# Externalities and Interdependent Growth: Theory and Evidence

by

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**Abstract**: I formulate and estimate a model of externalities within countries and technological interdependence across countries. I find that external returns to scale to physical capital within countries are 8 percent; that a 10 percent increase of total factor productivity of a country's neighbors raises its total factor productivity by 6 percent; and that a 2 percent annual growth rate of labor productivity can be explained as an endogenous response to an exogenous 0.2 percent annual growth rate of total factor productivity in the steady-state.

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# 1 Introduction

Recent theoretical work on economic growth by Paul Romer (1986, 1990), Robert Lucas (1988), and others has successfully argued that aggregate externalities to physical and human capital within countries may help explain many of the observed patterns of growth across countries. But empirical work on economic growth has largely ignored aggregate externalities and returned to Robert Solow's (1956) growth model, see the work by Robert Barro and Xavier Sala-i-Martin (1992) or by Gregory Mankiw, David Romer, and David Weil (1992) for example. This is probably because the theoretical work on aggregate externalities does not explain how to tell external from internal returns to physical and human capital with the available cross-country data.

I argue that external and internal returns to physical and human capital can be easily told apart with the available cross-country data because the reasoning behind the theoretical work on aggregate externalities implies technological interdependence across neighboring countries. This argument defines my two objectives: First, to extend the theoretical work on growth with aggregate externalities within countries by Romer and Lucas for technological interdependence across countries. Second, to show how the degree of technological interdependence across countries, and internal and external returns to physical and human capital within countries, can be estimated with the available cross-country data.

The reasoning behind the theoretical work on aggregate externalities by Romer and Lucas is that private capital accumulation of households and firms generates technological ideas that cannot be fully appropriated by investors. These ideas diffuse and increase the productivity of many other households and firms. Romer and Lucas link the diffusion of ideas to spatial proximity but assume that ideas diffuse within countries only in their theoretical work. This is just a simplification of course: New Mexico is closer to Mexico than to Washington State and Sumatra closer to Malaysia than to Irian Jaya; national borders are arbitrary, often separating regions with similar cultural identities and economic characteristics; and the history of technology is full of ideas that went around the world traveling from one country to another, see Joel Mokyr (1990) and Arnold Pacey (1990) for example. I argue that eliminating this simplification and allowing technological ideas to cross national borders is simple and productive; it yields interesting theoretical conclusions about economic growth in a world of technologically interdependent countries and makes it easy to tell external from internal returns to physical and human capital using the available cross-country data.

This is why I extend the theoretical work on aggregate externalities within countries by Romer and Lucas and allow for technological ideas to be adopted and adapted by households and firms in neighboring countries. The aggregate level of technology in any country may therefore not only depend on externalities generated by capital accumulation within the country but also on the aggregate level of technology of its neighbors; all countries may become technologically interdependent as a result. At the theoretical level, this implies an increase in the steady-state growth rate of labor productivity for any exogenous growth rate of total factor productivity. It also implies a larger effect of investment on steady-state labor productivity. Another theoretical implication of international technological interdependence is that endogenous growth is possible despite decreasing aggregate returns to scale to capital at the country level.

But my main results are empirical. Modeling technological interdependence across countries allows me to estimate not only the degree of interdependence across countries but also the strength of external returns to physical and human capital within countries from the available cross-country data. This is because technological ideas generated by externalities to physical and human capital accumulation within a country, are adopted and adapted by neighboring countries and increase their aggregate level of technology and labor productivity indirectly. I can therefore use the geographic pattern of growth to tell external from internal returns to physical and human capital.

I estimate the model using data on 98 countries. Five interesting empirical results emerge. First, there is a high degree of technological interdependence across countries. My findings indicate that a 10 percent increase in the level of total factor productivity of any country's neighbors raises its level of total factor productivity by 6 percent. This estimate suggests that the well-known spatial correlation in income per capita—evident from the color-coded income per capita world maps in the first pages of almost every world atlas—is partially due to a spatial correlation of the aggregate level of technology. Second, there are strong and empirically significant external returns to private capital accumulation within countries. External returns to scale to capital within countries are 8 percent. Third, external returns to capital appear to be entirely due to physical capital. My estimates suggest that the social return to physical capital accumulation at the country level is 33 percent higher than the private return. Fourth, internal returns to scale to physical capital are 28 percent in the model with externalities within countries and international technological interdependence. This estimate is consistent with estimates of the physical capital share in national income available from national income data. The average physical capital share in the US over my sample period, for example, was 28.3 percent. Fifth, my estimates suggest that technological interdependence across countries and externalities within countries can explain a 2 percent steady-state annual growth rate of labor productivity as an endogenous response to an exogenous 0.2 percent annual growth rate of total factor productivity.

## 2 Model

The model describes a simple theory of economic growth in a world with $N$ technologically interdependent countries. Its main objective is to show how the degree of international technological interdependence across countries and the strength of external returns to physical and human capital within countries can be estimated using the available cross-country data. The model also shows that international technological interdependence increases the steady-state growth rate of labor productivity for any exogenous growth rate of total factor productivity; that it strengthens the effect of physical and human capital investment on steady-state labor productivity; and that it makes endogenous growth possible despite decreasing returns to scale to capital at the country level.

The model consists of many different firms in $N$ different countries. Any firm $f$ in any country $c$ produces its goods with human capital, physical capital, and labor hired in competitive factor markets. The average labor productivity of firm $f$ in country $c$ at time $t$, $Y_{fct}$, is related to physical capital per worker $K_{fct}$ and to human capital per worker $H_{fct}$ employed in the firm by the following production function in intensive form,

$$Y_{fct} = A_{ct}\left(K_{fct}^{\beta} H_{fct}^{1-\beta}\right)^{\alpha}, \tag{1}$$

where $A_{ct}$ describes the aggregate level of technology in country $c$ at time $t$, and $\alpha$ describes the returns to scale to capital at the firm level—with $\alpha\beta$ the returns to scale to physical capital at the firm level and $\alpha(1-\beta)$ the returns to scale to human capital at the firm level. I assume that all firms sell their goods in competitive markets and that production and investment take place at discrete intervals $t = 1, 2, \ldots, +\infty$.

Average labor productivity at the country level at time $t$, $Y_{ct}$, can now be calculated as an employment-weighted average of average labor productivity at the firm level; (1) and the assumption of competitive national markets for produced goods and employed inputs yields that a country's average labor productivity increases with the aggregate level of physical capital per worker $K_{ct}$ and the aggregate level of human capital per worker $H_{ct}$ available at time $t$ according to

$$Y_{ct} = A_{ct}\left(K_{ct}^{\beta} H_{ct}^{1-\beta}\right)^{\alpha}. \tag{2}$$

The aggregate level of technology $A_{ct}$ of any country $c$ will be endogenous in the model. I adapt the reasoning of Romer (1986, 1990) and Lucas (1988) and assume that each country's aggregate level of technology increases with the aggregate level of physical capital per worker $K_{ct}$ and the aggregate level of human capital per worker $H_{ct}$ available in that country. Romer and Lucas argue that private capital accumulation generates new technological ideas that cannot be fully appropriated by investors and increase the productivity of many other firms and households in the same country. I take this argument a step further and also allow for some of these technological ideas to spill over to neighboring countries. The aggregate level of technology in country $c$, $A_{ct}$, may therefore not only depend on externalities generated by physical and human capital accumulated in that country in or before period $t-1$, described by $K_{ct}^{\lambda}H_{ct}^{1-\lambda}$ with $0 \leq \lambda \leq 1$; it may also depend on the aggregate level of technology of its neighbors, $\{A_i \mid i \in M_c\}$ where $M_c$ denotes the set of countries neighboring country $c$. The particular functional form I assume for the aggregate level of technology in country $c$ is a geometrically weighted average of the externalities at the country level and the geometric average of the aggregate level of technology of neighbors;

$$A_{ct} = E_t(K_{ct}^{\lambda}H_{ct}^{1-\lambda})^{\gamma}(\prod_{i \in M_c} A_i^{1/N_c})^{\sigma} \tag{3}$$

for all countries $c = 1,\ldots,N$; $N_c$ denotes the number of countries neighboring country $c$; and I assume $\sigma < 1$. The degree of international technological interdependence is described by $\sigma$; $\sigma$ is the elasticity of country $c$'s aggregate level of technology with respect to the average level of technology of its neighbors. The strength of external returns to scale to capital at the country level is described by $\gamma$; $\gamma\lambda$ denotes external returns to scale to physical capital and $\gamma(1-\lambda)$ external returns to scale to human capital. The index $E_t$ captures technological ideas that are generated for reasons that are exogenous to the model; I assume that

$$(E_{t+1} - E_t) / E_t = \theta \tag{4}$$

in the steady state and refer to $\theta$ as the exogenous growth rate of total factor productivity.

It is straightforward to show that (3) characterizes the distribution of aggregate technology across countries at time $t$ if technology diffuses across countries according to

$$A_{c,s+\kappa} = E_t (K_{ct}^{\lambda} H_{ct}^{1-\lambda})^{\gamma} (\prod_{i \in M_c} A_{is}^{1/N_c})^{\sigma} , \qquad (5)$$

with $t \leq s < s+\kappa \leq t+1$ and if $\kappa$ is small;[1] (5) is certainly not the most realistic model of technology diffusion; but assuming that technology diffuses much more slowly—with a one period lag for example—would not change the predictions of the model in or close to the steady-state in any way.

The model described by equations (2), (3), and (4) reduces to the Solow growth model with human capital as described and estimated by Mankiw, Romer, and Weil (1992) when there are no externalities to capital accumulation within countries, $\gamma = 0$, and technological ideas do not cross national borders, $\sigma = 0$; but (2) and (3) allow for externalities within countries, $\gamma > 0$—which may be due to physical or human capital depending on the distribution parameter $\lambda$, $0 \leq \lambda \leq 1$—and international technological interdependence, $\sigma > 0$. The most evident benefit of this extension is that it allows me to estimate the degree of international technological interdependence $\sigma$. Less evidently, this extension allows me to estimate internal returns to scale to physical and human capital consistently and to estimate internal returns to scale to physical capital, $\alpha\beta$, and human capital, $\alpha(1-\beta)$, and external returns to physical capital, $\gamma\lambda$, and human capital, $\gamma(1-\lambda)$, separately.

International technological interdependence implies that countries cannot be analyzed in separation but must be analyzed as an interdependent system. This

[1] To see this, it is useful to collect the $N$ equations for the $N$ different countries in (5) and rewrite them in logarithms, $\boldsymbol{a}_{s+\kappa} \equiv \boldsymbol{z}_t + \sigma \boldsymbol{M} \boldsymbol{a}_s$, where $\boldsymbol{z}_t \equiv [z_{1t}, \ldots, z_{Nt}]' \equiv [\log E_t + \gamma(\lambda \log K_{1t} + (1-\lambda)\log H_{1t}), \ldots, \log E_t + \gamma(\lambda \log K_{Nt} + (1-\lambda)\log H_{Nt})]'$ with the prime denoting the transpose of the vector; $\boldsymbol{a}_t \equiv [a_{1t}, \ldots, a_{Nt}]' \equiv [\log A_{1t}, \ldots, \log A_{Nt}]'$; and $\boldsymbol{M}$ a $N \times N$ matrix which has non-zero entries $m_{ij} = 1/N_i$—with $N_i$ the number of neighbors of country $i$— whenever countries $j$ and $i$ are neighbors. The result follows immediately from the fact that $\boldsymbol{M}$ is a Markov-matrix and that $\sigma < 1$.

is why it is useful to rewrite the $N$ equations for the $N$ different countries in (2) and (3) in vector notation, denoting with bold-faced, lower-case variables the $N \times 1$ vectors of the logarithms of the corresponding upper-case variables, $\boldsymbol{y} \equiv [y_1,.....,y_N]' \equiv [\log Y_1,.....,\log Y_N]'$, with the prime denoting the transpose, and so on. With this notation, the $N$ equations in (2) become

$$\boldsymbol{y}_t = \boldsymbol{a}_t + \alpha(\beta \boldsymbol{k}_t + (1-\beta)\boldsymbol{h}_t), \tag{6}$$

while the $N$ equations in (3) become

$$\boldsymbol{a}_t = \boldsymbol{e}_t + \gamma(\lambda \boldsymbol{k}_t + (1-\lambda)\boldsymbol{h}_t) + \sigma \boldsymbol{M} \boldsymbol{a}_t, \tag{7}$$

where $\boldsymbol{M}$ is an $N \times N$ Markov-matrix which has non-zero entries $m_{ij} = 1/N_i$—with $N_i$ the number of neighbors of country $i$—whenever countries $j$ and $i$ are neighbors.

Solving equation (7) for the aggregate level of technology across countries $\boldsymbol{a}_t$ and substituting into equation (6), yields the distribution of average labor productivity at time $t$ across countries as a function of the distribution of physical capital $\boldsymbol{k}_t$ across countries, the distribution of human capital $\boldsymbol{h}_t$ across countries, and exogenous world technology $\boldsymbol{e}_t$,

$$\boldsymbol{y}_t = (1/(1-\sigma))\boldsymbol{e}_t + \alpha(\beta \boldsymbol{k}_t + (1-\beta)\boldsymbol{h}_t) + \gamma(\boldsymbol{I} - \sigma \boldsymbol{M})^{-1}(\lambda \boldsymbol{k}_t + (1-\lambda)\boldsymbol{h}_t), \tag{8}$$

where $\boldsymbol{I}$ is the $N \times N$ identity matrix. Equation (8) clearly shows that average labor productivity in country $c$ may not only depend on the amount of physical and human capital available in that country. When some technological ideas cross national borders, $\sigma > 0$, and some technological ideas are generated by capital accumulation, $\gamma > 0$, then the average labor productivity in country $c$ increases with capital accumulated in neighboring countries directly and in the rest of the world indirectly. This is because $\gamma > 0$ implies that non-rival, non-appropriable technological ideas are generated by capital accumulation in all other countries; these technological ideas get adopted and adapted elsewhere, traveling from one country to another if $\sigma > 0$ and increasing the aggregate level of technology and average labor productivity around the world.

## 2.1 Interdependence and Growth

International technological interdependence increases the steady-state growth rate of labor productivity for any exogenous growth rate of total factor productivity because it implies that all countries adopt and adapt technologies generated elsewhere. This effect of technological interdependence across countries is most easily seen by differencing (8) with respect to time; setting $\Delta y_{ct} = \Delta k_{ct} = \Delta h_{ct} = g$ for all countries—where $\Delta y_{ct} = y_{ct} - y_{c,t-1}$ and so on—making use of the fact that capital and output grow at the same rate in steady-state; and solving for the steady-state growth rate of average labor productivity $g$,

$$g = \frac{\theta}{(1-\alpha-\gamma)(1-\sigma')}, \tag{9}$$

where $\sigma' \equiv \sigma(1-\alpha)/(1-\alpha-\gamma)$ and where I have assumed that $\sigma' < 1$. Technological interdependence across countries, $\sigma > 0$ which implies $\sigma' > 0$, increases the steady-state growth rate of average labor productivity for any exogenous growth rate of total factor productivity. It is straightforward to show that the model with technological interdependence across countries permits endogenous growth, i.e. steady-state productivity growth without exogenous total factor productivity growth, if $(1-\alpha-\gamma)(1-\sigma') = 0$. In particular, endogenous growth is possible despite aggregate decreasing returns to scale to capital at the country level, $\alpha+\gamma<1$, if the degree of technological interdependence across countries is sufficiently high.

Equation (9) allows for a simple decomposition of the steady-state growth rate of average labor productivity $g$ into the exogenous impulse $\theta$—the exogenous growth rate of total factor productivity—and the endogenous response or propagation $g-\theta$; $g=\theta+(g-\theta)=\theta+m\theta$ where $m$ denotes the "growth multiplier,"

$$m \equiv \frac{1-(1-\alpha-\gamma)(1-\sigma')}{(1-\alpha-\gamma)(1-\sigma')}. \tag{10}$$

This decomposition of the steady-state growth rate of average labor productivity and the "growth multiplier" terminology is useful because it moves away from the crass distinction between endogenous growth models and exogenous growth models. There may be some technological change that is exogenous to the economic system and the "knife-edge" condition on technology that is always required in endogenous growth models to explain steady-state labor productivity growth in the absence of exogenous total factor productivity growth is unlikely to hold. The important question is the strength of the endogenous propagation mechanism of the growth model. For example, the Solow growth model with physical capital only, $\beta=1$, and with a share of physical capital in national income of roughly 1/3, which implies $\alpha\beta=1/3$, requires an exogenous annual growth rate of total factor productivity of 1.4 percent to explain an annual growth rate of labor productivity of 2 percent. This is because the growth multiplier of the Solow model is a low 1/2,

$$m = \frac{\alpha}{1-\alpha} \cong \frac{1/3}{1-1/3} = \frac{1}{2}.$$

The Solow model extended for human capital as estimated by Mankiw, Romer, and Weil (1992) requires an exogenous annual growth rate of total factor productivity of 0.7 percent to explain a 2 percent annual growth rate of labor productivity. Including human capital accumulation quadruples the growth multiplier relative to the standard Solow model. This is because the parameter for internal returns to capital, $\alpha$, now includes internal returns to physical capital, $\alpha\beta$, and internal returns to human capital, $\alpha(1-\beta)$; Mankiw, Romer, and Weil estimate that $\alpha\beta \cong \alpha(1-\beta) \cong 1/3$ which implies $\alpha \cong 2/3$ and

$$m = \frac{\alpha}{1-\alpha} \cong \frac{2/3}{1-2/3} = 2.$$

The model with externalities and technological interdependence estimated in this paper more than quadruples the growth multiplier relative to the model of Mankiw, Romer, and Weil and further reduces the exogenous impulse required to explain an annual growth rate of labor productivity of 2 percent. My estimates below indicate that an exogenous annual growth rate of total factor productivity of 0.2 percent is sufficient to explain a 2 percent annual growth rate of labor productivity.

## 2.2 Interdependence and Investment

International technological interdependence also increases the effect of investment on steady-state average labor productivity. This is most easily seen by relating the physical capital-output ratio and the human capital-output ratio to the physical capital investment rate $i_{Kc}$ and the human capital investment rate $i_{Hc}$ in country $c$ and solving for the steady-state distribution of average labor productivity as a function of investment rates.

In steady-state, capital and output grow at the same rate. Using the definition of investment rates, this implies that the physical capital-output ratio and human capital-output ratio are constant and related to investment rates by $i_{Kc}^{*}(Y_c^{*} / K_c^{*})-(n_c+d)=g$ and $i_{Hc}^{*}(Y_c^{*} / H_c^{*})-(n_c+d)=g$, where $d$ denotes the annual rate of depreciation of capital, $n_c$ the annual growth rate of the labor force in country $c$, and asterisks denote steady-state values. Steady-state capital-output ratios are therefore equal to

$$K_c^{*} / Y_c^{*} = i_{Kc}^{*} / (n_c + d + g) \tag{11}$$

and

$$H_c^{*} / Y_c^{*} = i_{Hc}^{*} / (n_c + d + g). \tag{12}$$

Taking logarithms of (11) and (12), substituting into (8), and solving for the steady-state distribution of average labor productivity across countries yields

$$\begin{aligned} \boldsymbol{y}_t^{*} &= \boldsymbol{e}_0 + gt\boldsymbol{i} \\ &+ \left((1-\alpha)\boldsymbol{I} - \gamma(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\right)^{-1}\left(\alpha\beta\boldsymbol{I} + \gamma\lambda(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\right)\left(\mathbf{log}\frac{\boldsymbol{i}_K^{*}}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right) \\ &+ \left((1-\alpha)\boldsymbol{I} - \gamma(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\right)^{-1}\left(\alpha(1-\beta)\boldsymbol{I} + \gamma(1-\lambda)(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\right)\left(\mathbf{log}\frac{\boldsymbol{i}_H^{*}}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right) \end{aligned} \tag{13}$$

where $\boldsymbol{i}$ denotes the $N \times 1$ unit vector, $\mathbf{log}(\boldsymbol{i}_K^{*} \boldsymbol{/} (\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}))$ the $N \times 1$ vector collecting the $\log(i_{Kc}^{*} / (n_c + d + g))$-terms and $\mathbf{log}(\boldsymbol{i}_H^{*} \boldsymbol{/} (\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}))$ the $N \times 1$ vector collecting the $\log(i_{Hc}^{*} / (n_c + d + g))$-terms for all $N$ countries; $\boldsymbol{e}_0 = \boldsymbol{i}e_0$

denotes the logarithm of the initial level of the exogenous component of total factor productivity.

Equation (13) allows me to calculate the elasticity of steady-state average labor productivity with respect to physical and human capital investment. Differentiating (13) with respect to log-investment rates and summing the effect of investment in countries $1,2,\ldots,N$ on average labor productivity in country $c$, I find that increasing physical and human capital investment across all countries by 10 percent increases steady-state average labor productivity by

$$\frac{(\alpha+\gamma)(1-\sigma'')}{(1-\alpha-\gamma)(1-\sigma')}\times 10 \text{ percent},$$

where $\sigma'' \equiv \sigma\alpha/(\alpha+\gamma)$ and $\sigma'$ is defined after equation (9). It is straightforward to show that $(1-\sigma'')/(1-\sigma')>1$ if $\sigma>0$ and $\gamma>0$ which implies that international technological interdependence increases the effect of investment on steady-state average labor productivity if there are externalities at the country level. My estimates below indicate that steady-state average labor productivity increases by 30 percent when investment in physical and human capital increases by 10 percent across all countries. For comparison, the estimates in Mankiw, Romer, and Weil would imply a 20 percent increase in steady-state average labor productivity, while the implied increase in steady-state average labor productivity would be 5 percent in the standard Solow model with physical capital only and a capital share in national income of 1/3.

## 2.3 Interdependence and Identification

My main objective is to use the model in the previous sections to estimate technological interdependence across countries and externalities to physical and human capital within countries with the available cross-country data on economic growth and investment. To do so, I take a log-linear approximation of the predicted growth rate of average labor productivity around the steady-state distribution of average labor productivity,

$$\Delta \boldsymbol{y}_{t+1} = g\boldsymbol{i} + (\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}) * ((1-\alpha)\boldsymbol{I} - \gamma(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1})(\boldsymbol{y}_t^* - \boldsymbol{y}_t) + \boldsymbol{u}_t, \tag{14}$$

where $\Delta \boldsymbol{y}_{t+1}$ denotes the growth rate of labor productivity across countries between period $t$ and period $t+1$; $\boldsymbol{y}_t^*$ denotes the steady-state distribution of average labor productivity across countries in (13); $(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})$ denotes the $N \times 1$ vector collecting the $n_c + d + g$-terms; "$*$" denotes the element-by-element product of two vectors; and $\boldsymbol{u}_t$ is proportional to the difference between exogenous productivity growth close to the steady-state $\Delta \boldsymbol{e}_t \equiv \boldsymbol{e}_t - \boldsymbol{e}_{t-1}$ and exogenous productivity growth in the steady-state $\boldsymbol{i}\theta$, i.e. $\boldsymbol{u}_t = (\Delta \boldsymbol{e}_t - \boldsymbol{i}\theta)/(1-\alpha-\beta)(1-\sigma')$. This log-linearization is immediately recognized as a simple generalization of the linearization in Mankiw, Romer, and Weil (1992)—the two equations become identical when $\gamma = \sigma = 0$.

With international technological interdependence, (13) and (14) can be combined to estimate the strength of external returns to scale to physical and human capital within countries from a simple cross-country growth regression, using data on economic growth and investment over some period of years. Without modeling international technological interdependence, internal and external returns to scale to capital cannot be estimated separately. This can be seen from (13) and (14) by setting $\sigma = 0$; (13) becomes

$$\Delta \boldsymbol{y}_{t+1} = g\boldsymbol{i} + (1-(\alpha+\gamma))(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}) * (\boldsymbol{y}_t^* - \boldsymbol{y}_t) + \boldsymbol{u}_t, \tag{15}$$

while (14) becomes

$$\begin{aligned}\boldsymbol{y}_t^* &= \boldsymbol{e}_t \\ &+ \left(1-(\alpha+\gamma)\right)^{-1}(\alpha\beta+\gamma\lambda)\left(\mathbf{log}\frac{\boldsymbol{i}_K}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right) \\ &+ \left((1-(\alpha+\gamma)\right)^{-1}\left((\alpha+\gamma)-(\alpha\beta+\gamma\lambda)\right)\left(\mathbf{log}\frac{\boldsymbol{i}_H}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right).\end{aligned} \tag{16}$$

Only the sum of internal and external returns to scale to physical capital, $\alpha\beta+\gamma\lambda$, and human capital, $\alpha(1-\beta)+\gamma(1-\lambda)$, enter into these equations. Internal and external returns to scale cannot be estimated separately because they both translate investment into growth in the same way at the country level. This is the main reason why modeling technological interdependence is important. But modeling international technological interdependence is also necessary to get consistent estimates of internal plus external returns to scale to capital at the country level. Not modeling the aggregate level of technology implies that the unmodeled and unobservable heterogeneity in the level of aggregate technology across countries will enter into equation (16) through $\boldsymbol{e}_t$. Because the initial aggregate level of technology is positively correlated with the initial average labor productivity $\boldsymbol{y}_t$, which is a regressor in (15), the least-squares estimate of aggregate returns to scale obtained from (15) and (16) will overestimate the true value of aggregate returns to scale to capital.

With technological interdependence, (13) and (14) can be used to estimate internal and external returns to scale to physical and human capital separately. Intuitively, this is because externalities increase the steady-state level of technology and labor productivity of neighbors indirectly if countries are technologically interdependent. I can therefore use the geographic pattern of growth to tell external from internal returns to physical and human capital.

## 3 Estimation

Substituting (13) into (14), I can in principle estimate $\alpha$, $\beta$, $\gamma$, $\lambda$, and $\sigma$ by non-linear least squares using data on investment rates, labor force growth rates, and average labor productivity over some period of years $s$. In practice, this looks hopeless at first because of the very strong non-linearities in both equations. But (13) into (14) simplifies to

$$
\begin{aligned}
(\boldsymbol{y}_t - \boldsymbol{y}_{t-s})/s = \quad & g\boldsymbol{i} \\
& +(et/s(1-\sigma))e_0(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}) \\
& -(1-\alpha-\gamma)(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\boldsymbol{y}_{t-s} \\
& +\sigma(1-\alpha)(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*(\boldsymbol{I}-\sigma\boldsymbol{M})^{-1}\boldsymbol{M}\boldsymbol{y}_{t-s} \\
& +\alpha(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*\left(\mathbf{log}\frac{\boldsymbol{i}_H}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right) \\
& +\alpha\beta(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*\left(\left(\mathbf{log}\frac{\boldsymbol{i}_K}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right)-\left(\mathbf{log}\frac{\boldsymbol{i}_H}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right)\right) \\
& +\gamma(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*(I-\sigma\boldsymbol{M})^{-1}\left(\mathbf{log}\frac{\boldsymbol{i}_H}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right) \\
& +\gamma\lambda(\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g})*(I-\sigma\boldsymbol{M})^{-1}\left(\left(\mathbf{log}\frac{\boldsymbol{i}_K}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right)-\left(\mathbf{log}\frac{\boldsymbol{i}_H}{\boldsymbol{n}+\boldsymbol{d}+\boldsymbol{g}}\right)\right) \\
& +\boldsymbol{v},
\end{aligned} \tag{17}
$$

where $v$ will capture both measurement error and the difference between average exogenous productivity growth between $t-s$ and $t$ and steady-state exogenous productivity growth.

Equation (17) is easily estimated in a two-step least squares approach. First, conditional on $\sigma$, the parameters $\alpha$, $\alpha\beta$, $\gamma$, and $\gamma\lambda$ can be estimated by restricted generalized linear least squares. Imposing the two conditionally linear coefficient restrictions on the third and fourth regressor, the estimates for $\alpha$, $\alpha\beta$, $\gamma$, and $\gamma\lambda$ are given by the coefficient on the fifth, sixth, seventh, and eighth regressor. Second, $\sigma$ can be estimated by a grid search. This two-step procedure is equivalent to non-linear least squares applied to (13) and (14).

### 3.1 Data

I use the same data to estimate (17) that Mankiw, Romer, and Weil (1992) use to estimate (15) and (16). This is for three reasons. First, it allows me to use the well-known results in Mankiw, Romer, and Weil as a benchmark; in particular, I can check my results in their special case and see whether the results change in the right direction. Second, it makes it clear that new results are because of the new model, not because of new data. Third, the data has not been updated for some countries and the widest possible data set is available over the period 1965-1985; the widest possible data set is desirable to get every country to have a sufficiently large number of neighbors that are included in the sample—which also explains why I use Mankiw, Romer, and Weil's largest sample with 98 countries.

All the data, except the data on human capital accumulation, is from the *Penn World Tables*. The proxy for human capital accumulation in (17) uses data from the *UNESCO Yearbook* and measures approximately the percentage of the working-age population in secondary school. The other important approximation is the use of income per equivalent adult for average labor productivity. For exact definitions of the data and the data, see the appendix of Mankiw, Romer, and Weil. Following Mankiw, Romer, and Weil, I set the sum of the steady-state growth rate and the capital depreciation rate in (17) equal to 8 percent.

I have defined two countries to be neighbors if they have a common land border. If they are separated by sea, they are defined as neighbors if the shortest distance between the two countries does not exceed 150 miles. Countries in the sample have 4 neighbors on average.

### 3.2 Results

The estimate for $\sigma$ is 58 percent; the hypothesis that there are no international technology spillovers (the Mankiw, Romer, and Weil model) is rejected at the 4 percent significance level. The estimates and the heteroskedasticity adjusted standard errors of all other parameters conditional on $\sigma$ equal to 58 percent are given in *Table* 1. This table also contains the estimates of Mankiw, Romer, and Weil.

The regression in (17) yields six especially interesting results:

(1) There is a high degree of technological interdependence across countries; the estimate of $\sigma$ indicates that a 10 percent increase in the level of total factor productivity of a country's neighbors raises its level of total factor productivity by 6 percent. This estimate suggests that the well-known spatial correlation in income per capita—evident from the color-coded income per capita world maps in the first pages of almost every world atlas—is partially due to a spatial correlation in the aggregate level of technology. The spatial correlation in

income per capita cannot be explained by the spatial correlation in investment rates only.

(2) There are strong and empirically significant aggregate external returns to scale to private capital accumulation at the country level. External returns to scale to capital within countries are 8 percent.

**Table 1:** The Model with Technological Interdependence Across Countries Compared to the MRW Model.

| **Estimated Coefficient** | **Estimates of the Model with International Technological Interdependence.** | **Estimates of the MRW Model.** |
|---|---|---|
| Internal Returns to Scale to (Physical and Human) Capital: $\alpha$ | 51 percent<br>(4 percent) | 71 percent |
| Internal Returns to Scale to Physical Capital: $\alpha\beta$ | 28 percent<br>(8 percent) | 48 percent<br>(7 percent) |
| External Returns to Scale to (Physical and Human) Capital: $\gamma$ | 8 percent<br>(2 percent) | not identified |
| External Returns to Scale to Physical Capital: $\gamma\lambda$ | 9 percent<br>(5 percent) | not identified |

**Notes:** Heteroskedasticity adjusted standard errors in brackets. The estimated equation is (17). The method is generalized non-linear least squares. MRW refers to Mankiw, Romer and Weil (1992).

(3) Surprisingly, aggregate external returns to scale within countries appear to be entirely due to physical capital. Estimated external returns to scale to physical

capital, 9 percent, are statistically equal to estimated external returns to scale to physical and human capital, 8 percent. There is no evidence for external returns to human capital. Taking into account that the private return to physical capital in production at the country level is $\alpha\beta(Y/H)$ while the social return to physical capital in production at the county level is $(\alpha\beta+\gamma\lambda)(Y/H)$, my estimates suggest that the social return to physical capital accumulation is 33 percent (37 percent/28 percent minus 1) higher than the private return.

(4) The estimate of aggregate returns to scale to physical and human capital—71 percent in Mankiw, Romer, and Weil—is 59 percent, 51 percent plus 8 percent. This suggests that the results in Mankiw, Romer, and Weil were biased upwards because of the positive correlation between the unobserved and unmodeled initial aggregate level of technology and the initial level of average labor productivity—see the discussion after equation (16).

(5) Internal returns to scale to human capital are 23 percent in both regressions; 51 percent minus 28 percent in the model with international technological interdependence. The coefficient on human capital investment remains unchanged when accounting for externalities within countries and technological interdependence across countries.

(6) Internal returns to scale to physical capital—estimated at a very high 48 percent in Mankiw, Romer, and Weil—are 28 percent in the model with externalities and international technological interdependence. This estimate is consistent with estimates of internal returns to scale to physical capital obtained indirectly through the share of physical capital in national income. Under some standard conditions—which are all satisfied in the model in this paper—internal returns to scale to physical capital are equal to the share of physical capital in national income. The estimate of the average share of physical capital in national income in the US between 1960 and 1985 in the National Income Accounts is

28.3 percent, almost exactly equal to my 28 percent estimate of internal returns to scale to physical capital.

There are two reasons why the estimate for internal returns to scale to capital drops from 48 percent in Mankiw, Romer, and Weil to 28 percent in (17) : First, the 48 percent estimate in Mankiw, Romer, and Weil comprises both internal and external returns to scale to physical capital; they cannot be estimated separately in their framework. Second, the estimate in Mankiw, Romer, and Weil was biased upwards because the unobserved and unmodeled heterogeneity in the aggregate level of technology is positively correlated with the initial level of average labor productivity.

To check the robustness of the results in *Table* 1, I have added continental dummies to the regression in (17). The most important dummy is for the African countries. African countries are generally poorer than say European countries and the dummy for African countries allows me to see whether the estimated technological interdependence in (17) arises because of the overall discrepancy between African and European income per capita. Adding this dummy did not significantly affect the estimates. Internal plus external returns to capital remain at 59 percent and external returns to capital at 8 percent. The Africa dummy turned out to be negative but insignificant at the 15 percent significance level. This suggest that international technological interdependence identified in (17) is of the local nature formulated in (3), and not because of differences in income per capita between broadly defined groups of countries.

### 3.3. Testing for Exogeneity

One problem with the regression in (17) and therefore the results is the potential endogeneity of the regressors. It would be desirable to test for exogeneity.

One simple way to do this is the following. The theory in the previous sections implies that internal returns to scale to physical capital, $\alpha\beta$, are equal to the physical capital share in national income. This is because profit-maximization, competitive markets for produced goods and employed inputs, and (1) imply that $r_{ct} + d = \alpha\beta(Y_{fct} / K_{fct})$, where $r_{ct}$ denotes the real interest rate in country $c$ at time $t$ and $d$ the annual depreciation rate of physical capital; re-arranging and aggregating over firms this yields

$$(r_{ct} + d)K_{ct} / Y_{ct} = \alpha\beta .$$

This is why the least-squares estimator for internal returns to scale to physical capital in (17) will be a consistent estimator of the share of physical capital in national income if the regressors in (17) are exogenous: A rejection of the hypothesis that the estimate of internal returns to scale to physical capital is equal to the share of physical capital in national income will therefore amount to a rejection of the hypothesis that the regressors are exogenous. This is why I test

$H_0$: $\alpha\beta$ = Share of Physical Capital in National Income Over the Sample Period.

The share of physical capital in national income in the US between 1960 and 1985 can be found in the National Income Accounts. The average share of physical capital in national income in the US was 28.3 percent with a standard deviation of 2.7 percent. This implies that the exogeneity of the regressors cannot be rejected at the 90 percent significance level.

### 3.4 Estimating the Growth Multiplier

The estimate of aggregate returns to scale to capital in *Table* 1 has fallen from 71 percent in Mankiw, Romer, and Weil (1992) to 59 percent. Equation (10) shows that—other things equal—this decreases the endogenous propagation mechanism of the growth model in the paper relative to the growth model in Mankiw, Romer, and Weil. Taking international technological interdependence into account, however, raises the growth multiplier,

$$m = \frac{1-(1-\alpha-\gamma)(1-\sigma')}{(1-\alpha-\gamma)(1-\sigma')} \cong \frac{1-(2/5)(1/4)}{(2/5)(1/4)} = 9\,.$$

This constitutes a more than fourfold increase relative to the growth multiplier in Mankiw, Romer, Weil. This high multiplier implies that a 2 percent annual growth rate of labor productivity can be explained as an endogenous response to an exogenous 0.2 percent annual growth rate of total factor productivity in the steady-state.

One way to put the growth multiplier of the model with technological interdependence across countries and externalities within countries into perspective is by asking what value for aggregate returns to scale to capital would result in such a strong endogenous response to exogenous total factor productivity growth in a model without international technological interdependence. Setting $\sigma = 0$ in (10) and solving the equation

$$\frac{\alpha+\gamma}{1-(\alpha+\gamma)} = 9$$

for $\alpha+\gamma$ yields $\alpha+\gamma = 0.9$: The estimated model with technological interdependence across countries has the same growth multiplier than a growth model with aggregate returns to scale to capital equal to 90 percent and no technological interdependence across countries.

## 4 Conclusion

This paper has extended the theoretical work on externalities at the country level by Romer (1986, 1990), Lucas (1988), and others and the empirical work by Mankiw, Romer, and Weil (1992) to account for technological interdependence across countries. This simple extension has proven to be productive both at the theoretical and the empirical level.

At the theoretical level, the paper has yielded some interesting conclusions about economic growth in a world of technologically interdependent countries. I have shown that international technological interdependence increases the steady-state average labor productivity growth rate for any exogenous growth rate of total factor productivity; that international technological interdependence strengthens the effect of investment on steady-state labor productivity; and that endogenous growth becomes possible despite decreasing aggregate returns to scale to capital at the country level.

But the more important conclusions of the paper are empirical. The paper has presented evidence on many of the important issues in modern growth theory: Exogenous versus endogenous growth, the strength of external returns to capital accumulation, human versus physical capital externalities, and the international diffusion of technology. I have found that international technological interdependence raises the endogenous propagation mechanism of the model considerably; a 2 percent steady-state annual growth rate of labor productivity can be explained as an endogenous response to an exogenous 0.2 percent annual growth rate of total factor productivity. I have also found strong external returns to physical capital and a high degree of international technological interdependence; the social return to physical capital is 33 percent higher than the private return and a 10 percent increase in the aggregate level of technology of a country's neighbors raises its level of technology by 6 percent. The empirical results seem reasonable and robust; endogeneity does not appear to be a serious problem. The most important indicator for this is the estimate of internal returns to scale to physical capital: I estimate internal returns to scale to physical capital at 28 percent which is almost exactly the average share of physical capital in national income in the US over my sample period.

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