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Measuring Knowledge Spillovers: A Non-appropriable Returns Perspective *

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A new approach is developed to measure knowledge spillovers by means of proportion of non-appropriable returns to social returns, assuming no specific forms of production and knowledge functions. It is complicated theoretically, but very simple and practical empirically. Using PWT 6.3, we find that: 1. the measure of spillovers is nonlinear to income; 2. spillovers do not exist when income is low, but do exist in higher income groups; 3. the elasticity of knowledge is nonlinear to income; 4. spillovers exist even when the elasticity of output to capital is roughly close to direct measure of capital's share.

Key Words: Knowledge spillovers; Measure; Non-appropriable returns; Capital's share; Dynamic OLS.
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1. INTRODUCTION

Since theoretical papers on knowledge spillovers (Arrow, 1962; Romer, 1986) appeared, a large amount of works have tried to measure spillovers empirically. Traditionally there are two approaches in the literature (Griliches, 1992). One is the estimation of the rate of return to innovations in limited industries or sectors(e.g., Bresnahan, 1986; Mansfield et al., 1977; Trajtenberg, 1989). The other is the estimation of social returns to research and development (R&D) capital or investment (e.g., Coe and Helpman, 1995; Coe, Helpman and Hoffmaister, 2009; Jones and Williams, 1998).

The first approach, as Griliches (1992) points out, suffers from doubts about representativeness in that it focuses only on successful inventions. In addition, the case-study method, stylized in this class of studies, might suffer from unacceptable cost if the externalities go to the whole economy rather than limited industries or sectors.

In order to overcome the weakness above, the second approach tries to construct an "overall" variable(e.g., output, TFP or their growth rates) and regress it on a knowledge variable or an R&D variable(e.g., R&D capital or the intensity of R&D investment). Recent developments of this approach include construction and extensions of the knowledge variable (Lang, 2009), and investigations of behavior and efficacy of knowledge variables (Kaiser, 2002; Nelson, 2009).

The second approach does provide a lot of information about externalities of knowledge. But it is not the whole story. Assume that the rates of social return to two innovations are both 30%. Can we tell which innovation has stronger external effects? The answer, evidently, depends on the rate of private return. Just as Romer (1986) and Griliches (1992) argue, the basic characteristic of knowledge spillovers is the difference between the private and social marginal products of capital stock(denoted by MPK_{private} and MPK_{social}, respectively), which is called *non-appropriable* returns to capital (Grossman and Helpman, 1991, pp.57).

Shen and Li (2009) is a first attempt to measure the non-appropriable returns empirically. Their paper implies that the ratio of non-appropriable returns to social returns can be derived theoretically. But a specific production function has to be assumed if they are intended to figure out the ratio empirically. A similar problem also appears in Romer (1986). The nature of problem is rooted in the fact that calculations of MPK_{private} and MPK_{social} depend on the form of the production function.

Is it possible to measure the non-appropriable returns when the production function takes a general form satisfying only neoclassical conditions? Is it practical in empirical studies? If the answers to these questions are yes, then how large is the proportion of non-appropriable returns to total returns?

The motivation of this paper is to provide a new approach to answer three questions above. In the paper, we try to derive generalized measures of relative difference between MPK_{private} and MPK_{social} to capture Romer (1986)'s knowledge spillovers based on physical capital. Although the expressions of measures seem to be complicated and disappointed theoretically, they prove simple and promising empirically. Applying this method to Penn World Table 6.3 (Heston, Summers, and Aten, 2009), we find that a large proportion of returns does spill over into the whole world and cannot be ignored under some conditions, contrasting sharply with Mankiw, Romer, and Weil (1992)'s conclusion of no substantial externalities to capital.

The rest is arranged as follows: section 2 derives measures of spillovers based on aggregate and average capitals, respectively. It answers the first two questions. Section 3 presents econometric models, describes the data and variables, and discusses the empirical results. It answers the third question. The last section concludes.

2. MODELS

2.1. Spillovers Based on Aggregate Capital

Romer (1986) and Barro and Sala-I-Martin (2004, pp.212-218) discuss details of knowledge spillovers based on aggregate capital stock. In order to obtain a simple expression of $MPK_{\text{private}}/MPK_{\text{social}}$, Romer (1986) chooses to assume a simple production function, $\tilde{f}(k, K) = k^v K^\gamma$. In this section, the production function of firm i is assumed to take a general form satisfying neoclassical conditions, that is, constant returns to scale with respect to capital and labor, positive and diminishing returns to private inputs and Inada conditions (Barro and Sala-I-Martin, 2004, pp.27):

$$Y_i = F(K_i, T(K)L_i) \tag{1}$$

where Y_i, K_i and L_i are the output, capital input, and identical and simple labor input of firm i, respectively. $K = \sum_i K_i$ is the aggregate physical capital stock. $T(K)$ is a generalized knowledge function (also known as a knowledge index) available to firm i. In Romer (1986) and Barro and Sala-I-Martin (2004), $T(K) = K$. In this paper, we just assume $T(K) \geq 1$ and $T'(K) \geq 0$. $T = 1$ means that simple labor input is employed in the production. If $T > 1$, simple labor input is augmented by knowledge. $T'(K) \geq 0$ implies the knowledge, available to firm i, does not decrease when other firms invest more on capital.

The per worker form of the production function can be expressed as

$$y_i = k_i f(T(K)/k_i) \tag{2}$$

where $y_i = Y_i/L_i$ is the output per worker, $k_i = K_i/L_i$ is the capital per worker, $f(x) \triangleq F(1, x)$. $f(T(K)/k_i)$ is just the average product of physical capital. The assumption of constant returns to scale implies there could be infinite number of firms in the market. Hence individual choice will not affect the aggregate capital, K. In steady state, all firms will make symmetric decisions because they are identical. Let a variable with a superscript * denote the variable in steady state. Then, $k_i = k^*(= K^*/L^*)$ for all i in steady state. The private marginal product of capital in steady state is

$$MPK_{\text{private}} = f(T(K^*)/k^*) - [T(K^*)/k^*]f'(T(K^*)/k^*) \tag{3}$$

In order to find the social marginal product of capital, just consider a centralized economy. For a social planner, the production function (2) becomes

$$y = kf(T(K)/k) \tag{4}$$

The social planner's marginal product of capital in steady state is

$$MPK_{\text{social}} = f(T(K^*)/k^*) - (1 - v_{\text{Aggr}})[T(K^*)/k^*]f'(T(K^*)/k^*) \tag{5}$$

where $v_{\text{Aggr}} \triangleq T'(K)K/T$ is the elasticity of the knowledge with respect to its argument.

The measure of spillovers, w, is defined as

$$w \triangleq (MPK_{\text{social}} - MPK_{\text{private}})\,/MPK_{\text{social}} \tag{6}$$

which is a proportion of non-appropriable returns to social returns. For the aggregate-capital based model, the measure, w_{Aggr}, is

$$w_{\text{Aggr}} = \frac{v_{\text{Aggr}}[T(K^*)/k^*]f'(T(K^*)/k^*)}{f(T(K^*)/k^*) - (1 - v_{\text{Aggr}})[T(K^*)/k^*]f'(T(K^*)/k^*)} \tag{7}$$

It is almost impossible to estimate w_{Aggr} by means of (7) unless $f(\cdot)$ and $T(\cdot)$ take specific forms. If we assume $T(K) = K^{\frac{\gamma}{1-\nu}}$ and $F(K_i, TL_i) = K_i^{\nu}(TL_i)^{1-\nu}$, then $y_i = k_i^{\nu}K^{\gamma}$ and $f(T/k) = (T/k)^{1-\nu}$. With these forms of functions, we have $w_{\text{Aggr}} = \gamma/(\nu + \gamma)$ which is just Romer (1986)'s case. Evidently w_{Aggr} is easy to estimate empirically in this case. But one may cast doubt on the assumptions about function forms. What if we know almost nothing about function forms? Fortunately, we find a new approach to estimate the w_{Aggr} of (7) without specifying function forms.

Consider Taylor series expansion of the production function (2) with respect to logarithmic variables around the steady state:

$$\begin{aligned}
\ln y_i =& \ln f(T(K^*)/k^*) + \frac{[T(K^*)/k^*]f'(T(K^*)/k^*)}{f(T(K^*)/k^*)}(\ln k^* - v_{\text{Aggr}} \ln K^*) \\
&+ \left(1 - \frac{[T(K^*)/k^*]f'(T(K^*)/k^*)}{f(T(K^*)/k^*)}\right) \ln k_i \\
&+ \frac{v_{\text{Aggr}}[T(K^*)/k^*]f'(T(K^*)/k^*)}{f(T(K^*)/k^*)} \ln K + \text{Higher Order Terms} \\
=& \beta_0 + \beta_1 \ln k_i + \beta_2 \ln K + \text{Higher Order Terms} \\
\approx& \beta_0 + \beta_1 \ln k_i + \beta_2 \ln K \qquad (8)
\end{aligned}$$

where

$$\begin{aligned}
\beta_0 &= \ln f(T(K^*)/k^*) + (1 - \beta_1)(\ln k^* - v_{\text{Aggr}} \ln K^*) \\
\beta_1 &= MPK_{\text{private}}/f(T(K^*)/k^*) \qquad (9) \\
\beta_2 &= (MPK_{\text{social}} - MPK_{\text{private}})\,/f(T(K^*)/k^*) \qquad (10)
\end{aligned}$$

Dropping higher order terms, we get the log-linearization expression (8). By (9) and (10), w_{Aggr} and v_{Aggr} can be written as

$$w_{\text{Aggr}} = \beta_2/(\beta_1 + \beta_2), \quad v_{\text{Aggr}} = \beta_2/(1 - \beta_1) \qquad (11)$$

Since $f(T(K^*)/k^*)$ is the average product of physical capital, we can reasonably assume it to be strictly positive unless nothing is produced. If $\beta_1 = 0$, then $MPK_{\text{private}} = 0$, which implies the capital does not enter into production function because of the assumption of positive returns to private inputs. If $\beta_2 = 0$, then $MPK_{\text{private}} = MPK_{\text{social}}$, which implies there are no externalities. After the β's are estimated, we can find w_{Aggr} and v_{Aggr} easily, whatever function forms $f(\cdot)$ and $T(\cdot)$ may take.

It is true that log-linearization above is a kind of simplification. If the equation (8) is used to describe the behavior of the economic system, nonlinearity is absolutely simplified. But the full characterization of economic system is not the purpose of our research. What we have done is to find tractable expressions of w_{Aggr} and v_{Aggr} while nonlinearity and complexity of them remain. That is, the measure of knowledge spillovers and elasticity of knowledge function which are aspects of a complex economic system can be expressed fortunately by functions of the arguments which are just coefficents on the linear terms. Therefore the log-linearization expression in (8) gives only the coefficients on the linear terms and cannot be regarded as a full description of a complex system.

2.2. Spillovers Based on Average Capital

Barro and Sala-I-Martin (2004, pp. 235) suggests that knowledge spillovers might come from average capital, that is, the knowledge, T, is now a function of capital per worker, k, of an economy. Therefore the production function (1) is changed into $Y_i = F(K_i, T(k)L_i)$. The per worker form is

$$y_i = k_i f(T(k)/k_i) \tag{12}$$

Following the same steps as the above, the private and social marginal products of capital in steady state are:

$$MPK_{\text{private}} = f(T(k^*)/k^*) - [T(k^*)/k^*]f'(T(k^*)/k^*) \tag{13}$$

$$MPK_{\text{social}} = f(T(k^*)/k^*) - (1 - v_{\text{Aver}})[T(k^*)/k^*]f'(T(k^*)/k^*) \tag{14}$$

where $v_{\text{Aver}} = T'(k)k^*/T(k^*)$. The measure of knowledge spillovers based on average capital, according to the definition (6), can be expressed as:

$$w_{\text{Aver}} = \frac{v_{\text{Aver}}[T(k^*)/k^*]f'(T(k^*)/k^*)}{f(T(k^*)/k^*) - (1 - v_{\text{Aver}})[T(k^*)/k^*]f'(T(k^*)/k^*)} \tag{15}$$

The log-linearization of production function (12) implies

$$\ln y_i \approx \gamma_0 + \gamma_1 \ln k_i + \gamma_2 \ln k \tag{16}$$

where

$$\begin{aligned}
\gamma_0 &= \ln f(T(k^*)/k^*) + (1 - v_{\text{Aver}})\frac{[T(k^*)/k^*]f'(T(k^*)/k^*)}{f(T(k^*)/k^*)} \ln(k^*) \\
&= \ln f(T(k^*)/k^*) + (1 - v_{\text{Aver}})(1 - \gamma_1)\ln(k^*) \\
\gamma_1 &= 1 - \frac{[T(k^*)/k^*]f'(T(k^*)/k^*)}{f(T(k^*)/k^*)} = \frac{MPK_{\text{private}}}{f(T(k^*)/k^*)} \\
\gamma_2 &= \frac{v_{\text{Aver}}[T(k^*)/k^*]f'(T(k^*)/k^*)}{f(T(k^*)/k^*)} = \frac{MPK_{\text{social}} - MPK_{\text{private}}}{f(T(k^*)/k^*)}
\end{aligned}$$

By means of γ's, w_{Aver} and v_{Aver} can be written as:

$$w_{\text{Aver}} = \gamma_2/(\gamma_1 + \gamma_2), \quad v_{\text{Aver}} = \gamma_2/(1 - \gamma_1) \tag{17}$$

whose expressions are similar to (11).

3. EMPIRICAL ANALYSIS

3.1. Econometric Models

Based on (8) and (16), we set up two econometric models as follows:

$$\ln y_{it} = \beta_{0,i} + \beta_1 \ln k_{it} + \beta_2 \ln K_{t-1} + \varepsilon_{it} \tag{18}$$

$$\ln y_{it} = \gamma_{0,i} + \gamma_1 \ln k_{it} + \gamma_2 \ln k_{t-1} + \epsilon_{it} \tag{19}$$

where i and t now stand for panel unit and year, respectively. Since our data set is based on Penn World Table 6.3 (constructed by Heston, Summers, and Aten, 2009), a panel unit now becomes an economy(a country or region). $\ln y_{it}$ is the logarithm of output per capita of unit i, year t. $\ln k_{it}$ is the logarithm of capital per capita of unit i, year t. $\ln K_{t-1}$ is the logarithm of total capital of a whole group in year $t-1$. $\ln k_{t-1}$ is the logarithm of capital per capita of a whole group in year $t-1$. ε_{it} and ϵ_{it} are random disturbances which include the higher order terms deleted in the log-linearization process. $\beta_{0,i}$ and $\gamma_{0,i}$ are fixed individual effects. β_1, β_2, γ_1, and γ_2 are our interested coefficients to be estimated. In the above econometric models, we use the $\ln K_{t-1}$ and $\ln k_{t-1}$ rather than $\ln K_t$ and $\ln k_t$ in that it takes some time for knowledge to spill over. In the appendix A.2.2, we also consider current spillovers whose results are similar to the lagged spillovers here.

3.2. Data and Variables

Penn World Table 6.3 (Heston, Summers, and Aten, 2009) includes real gross domestic product(GDP) per capita, investment share of real GDP per capita, and population. We measure y_{it} as the real GDP per capita, available in the data set, and k_{it} as the real capital per capita, which is equal to real capital divided by population. The data of real capital of an economy i in year t, $K_{i,t}$, are calculated by means of the perpetual-inventory method:

$$K_{i,t} = (1-\delta)K_{i,t-1} + I_{i,t-1} \quad t = 1, 2, \cdots \tag{20}$$

where δ is the rate of depreciation of capital and assumed to be 5%. $I_{i,t}$ is the investment which is calculated by:

$$\begin{aligned} \text{Investment } (I_{i,t}) = & \text{Real GDP per capita} \\ & \times \text{Investment share of Real GDP per capita} \\ & \times \text{Population} \end{aligned} \tag{21}$$

The initial value of physical capital is defined as (Coe and Helpman, 1995):

$$K_{i,0} = I_{i,0}/(g_i + \delta) \tag{22}$$

where $g_i = I_{i,t}/I_{i,t-1} - 1$ is the constant growth rate of investment, which is measured as the average annual growth rate of investment in the sample (see the appendix A.2.3 for discussions on g_i).

Penn World Table 6.3 includes 189 economies totally and covering the period 1950-2007 with 2005 as the base year. After data preparation (see the appendix A.1), there are totally 167 economies in the sample. Since economies with different income levels may behave differently, we classify all economies into four income groups according to the World Bank's classification[1]: the low income(group1), the lower middle income(group2), the upper middle income (group3), and the high income(group4). Group0 is defined as the total sample. For each group, we trim the data set to construct the largest balanced panel.

The real capital of a group in year t, K_t, is the summation of real capital of each economy of the group in year t. The real capital per capita of a group, k_t, equals to the real capital of the group divided by the total population of the group. The definition of variables are listed in table 6. The summary statistics of variables and dimensions of our data set are shown in table 7.

In order to check consistency of physical capital stock with other macroeconomic literature, such as Mankiw, Romer, and Weil (1992), we also calculate the average capital-output ratio assuming different δ's. The average ratio of group0 is about 7.6 for $\delta = 0.00$, 2.68 for $\delta = 0.05$, 1.66 for $\delta = 0.10$, and 1.20 for $\delta = 0.15$. Given $\delta = 0.05$, the average capital-output ratio is about 1.6 for group1, 2.8 for group2, 2.9 for group3 and 3.2 for group4. The behavior of capital-output ratio is consistent with Mankiw, Romer, and Weil (1992, pp.431) which argues that some countries have the ratio near 1 and some near 3. In the appendix A.2.1, we will show main conclusions in the paper are robust to the assumption of depreciation rate.

3.3. Results and Discussions

3.3.1. Nonstationarity Tests

In order to check nonstationarity of $\ln y_{it}$ and $\ln k_{it}$, we list the results of five familiar panel unit root tests(tables 12-16), that is, LLC (Levin, Liu, and Chu, 2002), HT (Harris and Tzavalis, 1999), Breitung (Breitung, 2000), IPS (Im, Pesaran, and Shin, 2003) and Hadri (Hadri, 2000) tests. LLC test rejects the null hypothesis that the panels contain a unit root, when a constant and trend terms are included. HT, Breitung and IPS tests, however, do not reject the null. Since the number of panel units is large compared with the number of years, results of HT, Breitung and IPS tests are more reliable than the result of LLC test. Moreover, Hadri test

[1]Refer to the web site: http://data.worldbank.org/about/country-classifications/.

rejects the null hypothesis that all panels are stationary, therefore supports nonstationarity of $\ln y_{it}$ and $\ln k_{it}$.

For $\ln K_t$ and $\ln k_t$, we use the augmented Dickey-Fuller(ADF) and Phillips-Perron(PP) unit root tests to check nonstationarity. On some occasions, ADF test rejects the null hypothesis that the variable contains a unit root. But PP test cannot reject the null under all situations. Thus we reasonably suspect $\ln K_t$ and $\ln k_t$ are nonstationary.

3.3.2. Cointegration Tests and Estimations

First, we check whether or not there is cointegration relationship in the aggregate-capital based model (18) and average-capital based model (19), respectively. The results from Pedroni (1999)'s cointegration test are listed in tables 17-21. Evidently, for each group, all statistics of Pedroni (1999)'s cointegration test reject, at 1% level, the null hypothesis that the estimated model is not cointegrated. Thus, cointegration relationships do exist in the models (18) and (19), respectively.

Second, we choose a reliable estimator to estimate the model's coefficients when there is cointegration relationship. Generally there are three estimators for a cointegrated panel regression: traditional OLS, fully modified OLS (FMOLS) and dynamic OLS (DOLS). Kao and Chiang (2000) argues that the traditional OLS estimator is biased asymptotically when a panel is nonstationary. Although the FMOLS estimator makes corrections for endogeneity and serial correlation, Monte Carlo simulations indicate the FMOLS estimator is also biased and the corrections seem to fail (Kao and Chiang, 2000). The DOLS estimator, however, reduces the bias substantially by adding the number of leads and lags, and therefore is robust to endogeneity, measurement errors and ommitted variables (Baltagi and Kao, 2000; Kao and Chiang, 2000). Thus the DOLS estimator is the best choice.

We list results of traditional OLS and DOLS estimates in the tables 1-5 for the purpose of comparison. Estimation and cointegration tests of this section are performed by Chiang and Kao (2002)'s GAUSS codes.

3.3.3. Discussions

The first, a large proportion of returns spilling over into the overall world does exist and cannot be ignored. For example, in table 1, the traditional OLS estimates of $\ln K_{t-1}$ and $\ln k_{t-1}$ are about 0.34 and 0.50, respectively, for group0. The implied w_{Aggr} and w_{Aver} are about 0.43 and 0.52, respectively. It implies that about 43% returns to investment in the

TABLE 1.

Estimation of Knowledge Spillovers for Total Sample (Group0)

	Aggregate-capital Based Model		Average-capital Based Model	
	OLS	DOLS	OLS	DOLS
$\ln k_{it}$	0.4582***	0.6833***	0.4582***	0.6833***
	(0.0134)	(0.0281)	(0.0134)	(0.0281)
$\ln K_{t-1}$	0.3446***	0.1747***	-	-
	(0.0177)	(0.0393)	-	-
$\ln k_{t-1}$	-	-	0.4999***	0.2463***
	-	-	(0.0256)	(0.0570)
implied v	0.6361***	0.5516***	0.9225***	0.7778***
	(0.0277)	(0.1076)	(0.0401)	(0.1564)
implied w	0.4292***	0.2036***	0.5218***	0.2650***
	(0.0175)	(0.0403)	(0.0178)	(0.0497)
R^2	0.5913	0.8838	0.5914	0.8838

Notes: The dependent variable is $\ln y_{it}$. v is the elasticity of knowledge to its argument. w is the measure of spillovers. Statistical inference on implied v and w is based on the Wald test with the null of $H_0 : v = 0$ and $H_0 : w = 0$, respectively. *** denotes statistical significance at the 1% level. Standard errors are in parentheses. The lengths of Lag and lead are 1 in dynamic OLS (DOLS) estimation.

TABLE 2.

Estimation of Knowledge Spillovers for Low Income Sample (Group1)

	Aggregate-capital Based Model		Average-capital Based Model	
	OLS	DOLS	OLS	DOLS
$\ln k_{it}$	0.1892***	0.3838***	0.1889***	0.3838***
	(0.0321)	(0.0695)	(0.0322)	(0.0695)
$\ln K_{t-1}$	0.2646***	0.0377	-	-
	(0.0288)	(0.0672)	-	-
$\ln k_{t-1}$	-	-	0.4935***	−0.0010
	-	-	(0.0539)	(0.1235)
implied v	0.3263***	0.0611	0.6085***	−0.0017
	(0.0341)	(0.1073)	(0.0637)	(0.2005)
implied w	0.5831***	0.0894	0.7232***	−0.0027
	(0.0552)	(0.1501)	(0.0456)	(0.3234)
R^2	0.2319	0.4543	0.2314	0.4544

Notes: See notes in table 1.

TABLE 3.

Estimation of Knowledge Spillovers for Lower Middle Income Sample (Group2)

	Aggregate-capital Based Model		Average-capital Based Model	
	OLS	DOLS	OLS	DOLS
$\ln k_{it}$	0.2853***	0.3287***	0.2850***	0.3287***
	(0.0185)	(0.0344)	(0.0185)	(0.0344)
$\ln K_{t-1}$	0.2638***	0.2969***	-	-
	(0.0183)	(0.0422)	-	-
$\ln k_{t-1}$	-	-	0.3186***	0.3522***
	-	-	(0.0220)	(0.0507)
implied v	0.3692***	0.4423***	0.4455***	0.5247***
	(0.0235)	(0.0590)	(0.0282)	(0.0708)
implied w	0.4804***	0.4746***	0.5278***	0.5173***
	(0.0280)	(0.0509)	(0.0279)	(0.0513)
R^2	0.5530	0.4170	0.5539	0.4170

Notes: See notes in table 1.

TABLE 4.

Estimation of Knowledge Spillovers for Upper Middle Income Sample (Group3)

	Aggregate-capital Based Model		Average-capital Based Model	
	OLS	DOLS	OLS	DOLS
$\ln k_{it}$	0.3722***	0.3493***	0.3771***	0.3495***
	(0.0300)	(0.0648)	(0.0301)	(0.0650)
$\ln K_{t-1}$	0.4922***	0.4827***	-	-
	(0.0454)	(0.1002)	-	-
$\ln k_{t-1}$	-	-	0.7703***	0.7568***
	-	-	(0.0729)	(0.1603)
implied v	0.7840***	0.7418***	1.2366***	1.1634***
	(0.0541)	(0.1176)	(0.0878)	(0.1887)
implied w	0.5694***	0.5801***	0.6714***	0.6841***
	(0.0389)	(0.0876)	(0.0353)	(0.0787)
R^2	0.6345	0.3941	0.6311	0.3939

Notes: See notes in table 1.

TABLE 5.

Estimation of Knowledge Spillovers for High Income Sample (Group4)

	Aggregate-capital Based Model		Average-capital Based Model	
	OLS	DOLS	OLS	DOLS
$\ln k_{it}$	0.6583***	0.5732***	0.6581***	0.5733***
	(0.0160)	(0.0436)	(0.0160)	(0.0437)
$\ln K_{t-1}$	0.2327***	0.3205***	-	-
	(0.0261)	(0.0711)	-	-
$\ln k_{t-1}$	-	-	0.2851***	0.4048***
	-	-	(0.0320)	(0.0873)
implied v	0.6809***	0.7510***	0.8340***	0.9487***
	(0.0609)	(0.1313)	(0.0745)	(0.1606)
implied w	0.2611***	0.3586***	0.3023***	0.4139***
	(0.0250)	(0.0637)	(0.0272)	(0.0658)
R^2	0.8292	0.6461	0.8293	0.6461

Notes: See notes in table 1.

aggregate-capital based model (or 52% in the average-capital based model) spills over. However the estimates are not unbiased when nonstationary varialbes occur in a panel regression. In addition, the higher order terms are dropped to get the log-linearization expression (8), which also might bias the traditional OLS estimates. On the contrary, the DOLS estimator is robust to endogeneity, measurement errors and ommitted variables (Baltagi and Kao, 2000; Kao and Chiang, 2000). DOLS results of group0 in table 1 show that the coefficients of $\ln K_{t-1}$ and $\ln k_{t-1}$ are about 0.17 and 0.25, respectively, and significant at 1% level. The implied w_{Aggr} in the aggregate-capital based model is about 20%(less than half of the traditional OLS estimate), which means 20% of returns to physical capital investment by an economy will spill over into the overall world if the externalities are based on aggregate capital. If the spillovers are based on average capital, then the implied w_{Aver} is about 27%.

The second, the measures are nonlinear to the level of income (in terms of per capita) which is theoretically rooted in (7) and (15). For the four subsamples(group1-4), tables 2-5 indicate spillovers are significant in all groups except the group1 which consists of only low income economies. The implied measure of aggregate-capital based spillovers, w_{Aggr}, is about 9% for group1, which is not significantly different from 0%, 47% for group2, 58% for group3 and 36% for group4. The w_{Aggr} of the group3 is the highest among all groups, which implies there might exist some nonlinear relationship between w_{Aggr} and the level of income per capita. This conclusion also applies to w_{Aver}.

The third, the elasticity of T to K or k is also estimated and nonlinearity of the knowledge function is supported although no specific form of the knowledge function is assumed. According to tables 1-5, the implied elasticity of knowledge function is statistically significant at 1% level in all groups except group1. The implied elasticities are about 0.55, 0.44, 0.74 and 0.75 for group0, group2, group3 and group4, respectively, in the aggregate-capital based model, and 0.78, 0.52, 1.16 and 0.95 for group0, group2, group3 and group4, respectively, in the average-capital based model. Generally it is less than 1 in groups except group3 in the average-capital model. Just like the measure, it appears that there exists a nonlinear relationship between the elasticity of knowledge and income level. From table 7, we find the mean of k_t monotonically increases with the income level. Thus it implies that the elasticity of knowledge may not be linear to k_t. If the labor scale is controlled, it will also not be linear to K_t. Unfortunately, existing literature on knowledge spillovers (e.g., Barro and Sala-I-Martin, 2004; Romer, 1986) unanimously assumes linearity of the knowledge function, that is, the elasticity of knowledge is 1.

The fourth, it should be noted that, in the group1, the DOLS estimator in table 2 has an inference different from the traditional OLS estimator. For a nonstationary panel, the OLS estimates of the coefficients of $\ln K_{t-1}$ and $\ln k_{t-1}$ provide spurious results significant at 1% level while the DOLS estimates suggest no externalities at all. Although it is possible that externalities depend on the national income per capita, the more reasonable explanation would be that capital stock is heterogeneous among countries with different level of income per capita. For example, the average of GDP per capita of group1 is about \$1379. One will guess that members of group1 might invest very little on R&D activities which exhibit stronger externalities than common physical capital.

The fifth, results also suggest that the existence of externalities of physical capital cannot be excluded only by observing capital's share in income (traditionally denoted by α) not substantially different from the elasticity of y to k. It is true that the elasticity of y to k equals to α in a neoclassical growth model. If evidences support this neoclassical equality, they will support no externalities, just as argued by Mankiw, Romer, and Weil (1992). This paper, however, finds that the estimated elasticities of y to k (the estimated β_1 or γ_1 in this paper) of group1, group2 and group3 are very close to 1/3 while positive externalities do exist in group2 and group3 except group1.[2] We are not intended to reject the neoclassical model. Our results just uncover a logical possibility that externalities *can* exist even if the elasticity of y to k roughly equals to the capital's share in income.[3]

How could it be true? In a global perspective, a country can be considered as an "individual" whose capital's share is just a private share. By the definition of (9), β_1 is corresponding to an *individual*'s elasticity of y to k. In the neoclassical model, β_1 equals the capital's share of that country. If there are knowledge spillovers, contributions of all inputs in other countries will benefit from spillovers. Thus the traditional definition of capital's share of a country is just the "private" share, not the social share. Unfortunately previous literature overlooked the difference, such as Mankiw, Romer, and Weil (1992). Therefore, we can not infer that there are no externalities of capital stock observing the fact that a private elasticity is equal to a private capital's share. In this paper, β_2 defined by (10) captures the difference between the "private" and "social" shares of capital investment. By $\hat{\beta}_1$ and $\hat{\beta}_2$, the implied social elasticity of y to k is just $\hat{\beta}_1 + \hat{\beta}_2$.

4. CONCLUSION

In summary, this paper finds a new approach to measure knowledge spillovers from a perspective of non-appropriable returns to capital stock without assuming any specific forms of the production and knowledge functions. The measure of spillovers is defined as the proportion of non-appropriable returns to social returns, whose theoretical expression is connected with coefficients of familiar regression models. It is very simple empirically although it appears rather complicated theoretically.

Externalities do exist and cannot be ignored under some circumstances. The implied measure is about 20% based on aggregate capital (or 27% based on average capital) in the sample of all economies. There are no significant externalities for the low income group. But for the other groups, the range of the measure is 35-58% (or 41-68%) in the aggregate-capital (or average-capital) based model. The results imply a nonlinear relationship between the measure and income level.

[2]Direct measures of the capital's share in income, α, are roughly 1/3, an empirical target in Mankiw, Romer, and Weil (1992). Moreover, Barro and Sala-I-Martin (2004, table 10.1, pp.439) collects some estimates of α whose range are 0.37-0.42 for OECD countries, 0.26-0.49 for east Asian countries, and 0.45-0.69 for Latin American countries.

[3]It is consistent with Howitt (2000) who argues that $\alpha < 1$ is possible for endogenous growth by calibration.

Although we know nothing about the form of the knowledge function, we can estimate the elasticity of knowledge to its argument. In most cases, it is less than 1. But for the upper middle income group, it is greater than 1 in the average-capital based model. The elasticity of knowledge function is also nonlinear to income level.

The paper provides a chance to rethink the traditional opinion about checking existence of externalities of capital. One cannot argue no externalities only by means of comparing the elasticity of output to capital with the direct measure of capital's share in income of a country. Actually, we find externalities do or do not exist when the estimated elasticity of output to capital is roughly close to the direct measure of capital's share in income.

Future research can be focused on knowledge externalities outside Romer (1986)'s domain and searching for a unified measure of externalities independent on theoretical models. Another interesting issue is to uncover the nonlinear relationships discussed in the paper. Finally, some important factors, which might affect the measure of knowledge spillovers, are not considered in the paper, such as institution environment (Aghion, 2004), division of labor (Yang and Zhang, 2000) and constitutional transition (Sachs, Woo, and Yang, 2000).

APPENDIX A

A.1. DATA PREPARATION

The following six aspects describe how the data set is prepared:

1. There are three countries, Nicaragua (group2),Saudi Arabia (group4) and Sierra Leone (group1), whose investment shares of GDP per capita are negative in some years (Heston, Summers, and Aten, 2009). But the corresponding observations are positive in Penn World Table 6.2 (Heston, Summers, and Aten, 2006), whose base year is 2000. These countries are excluded because the change of base year should not alter the sign of figures.

2. There are two countries whose average annual growth rates of investment are negative, that is, Russia(-0.89%, 1990-2007) and Tajikistan(-4.44%, 1993-2007). The phenomenon might be related to the collapse of USSR. If the negative g_i is used in equation (22), it assumes that the average growth rate of investment is negative before $t = 0$. Evidently this is counterfactual and we exclude Russia and Tajikistan.

3. There are two versions of China's data. Heston, Summers, and Aten (2009) thinks the version 2 is more reliable. Thus the version 2 is used in the paper.

4. We exclude Serbia and Timor-Leste because they have only one observation in year 2005.

5. Values of real GDP per capita and investment of Bahrain in 2007 are predicted by means of the average geometric growth rate calculated from the lastest ten observations available. In 2007, the predicted real GDP per capita is $27329.847 and the predicted investment is $4125.20 million.

6. Mankiw, Romer, and Weil (1992) suggests that the members of the Organization of the Petroleum Exporting Countries (OPEC) should be excluded because their growth facts are more related to natural resources than to standard inputs. These countries are Angola, Ecuador, Iran, Iraq, Nigeria, Algeria, Libya, Venezuela, Kuwait, Qatar, Saudi Arabia, and United Arab Emirates. Indonesia and Gabon were members of OPEC historically and also are excluded. Lesotho and Kiribati are excluded because a very large fraction of income comes from labor income abroad and has no relationship with domestic standard inputs, just as Mankiw, Romer, and Weil (1992) points out.

A.2. ROBUSTNESS

A.2.1. Assumptions of Depreciation Rate

The depreciation rate, δ, is assumed to be 5% in the main part. When δ deviates from 5%, are our conclusions robust? We list the implied w_{Aggr} and w_{Aver} in table 8 when the depreciation rate is assumed to be 0%, 5%, 10%, 15%, 20%, 25%, 30%, and 35%.

Evidently, the nature of conclusions above are not substantially changed. Positive externalities exist in all groups but the group1. Disturbing δ only affects the magnitude. When the δ decreases from 35% through 0%, the range of the implied w_{Aggr} is 16%-24%(Group0), 49%-62%(Group2), 60%-71%(Group3) and 28%-50%(Group4); the range of the implied w_{Aver} is 21%-22%(Group0), 54%-67%(Group2), 64%-78%(Group3) and 32%-56% (Group4). The implied v_{Aggr} and v_{Aver} are also robust to disturbing δ. The results are listed in table 9.

A.2.2. Lagged or Current Spillovers

The results above assume lagged spillovers which are reflected by $\ln K_{t-1}$ and $\ln k_{t-1}$ in the models (18) and (19). We also consider the current spillovers which occur in the current year rather than the lagged year.

That is, we estimate the following models for all groups:

$$\ln y_{it} = \beta_{0,i} + \beta_1 \ln k_{it} + \beta_2 \ln K_t + \varepsilon_{it}$$
$$\ln y_{it} = \gamma_{0,i} + \gamma_1 \ln k_{it} + \gamma_2 \ln k_t + \epsilon_{it}$$

The results are listed in the tables 10 and 11. With $\delta = 0.05$, the results in the table 10 imply that the measure of knowledge spillovers based on aggregate capital is about 21%(Group0), 46%(Group2), 59%(Group3) and 36%(Group4); the one based on average capital is about 27%(Group0), 50%(Group2), 69%(Group3) and 41%(Group4). The spillovers for group1 are not significant statistically at 10% level for both types of externalities. All the conclusions on current spillovers are similar to the ones on lagged spillovers except for magnitudes. In addition, the conclusions are also robust to assumptions of rate of depreciation. Conclusions on the elasticity of knowledge function under current spillovers are similar to the conclusions under lagged spillovers, as shown in the table 11.

A.2.3. Construction of Initial Capital Stock

The initial capital stock is constructed by (22). Theoretically, the g_i should be measured by the growth rate of investment before the time zero rather than the one after. In the main part of the paper, we use the average annual growth rate of investment in the sample to meaure g_i. If the economy is on a steady state before and after the year defined to be zero, the average growth rate before will be equal to the one after since a steady state is "a situation in which the various quantities grow at constant rates". (Barro and Sala-I-Martin, 2004, pp.33) In this circumstance, it is justified using average annual growth rate of investment in the sample to calculate the initial capital stock.

If the economy is not on a steady state before time zero while it is after, there is a problem. Generally the average growth rate is higher when an economy is not on a steady state than when it is on a steady state. Thus the initial stock capital is overestimated if average annual growth rate of investment in the sample is used. How does the overestimation affect the results? We fabricate a situation to elucidate the effect.

Assume $\delta = 0.05$, $I_0 = 1$, and $g = 0.08$ (0.08 is the mean growth rate of investment of all countries in the group0 during the sample period 1950-2007). Then the initial capital stock is $K_0 = 7.6923$. If the true average growth rate before the time zero is double, that is, $g' = 0.16$, then the true initial capital stock is $K'_0 = 4.7619 = 0.619K_0$. Suppose the annual investment is always 1. We calculate capital time series for K_0 and K'_0, respectively.

After 40 years, $K_{40} = 18.3351$ and $K'_{40} = 17.9387$. The relative magnitude of overestimation is about 2.2%. It implies the overestimation is attenuated greatly. If $\delta = 0.10$ is assumed, $K_{40} = 9.9621$ and $K'_{40} = 9.9140$. Although the relative magnitude of overestimation is 0.5%, the absolute levels of capital stock are almost half of the ones under the assumption $\delta = 0.05$.

Therefore the effect of overestimation of initial capital stock is very small when comparing with the effect of different assumptions of δ. When the main conclusions of the paper are robust to the assumption of δ, they are also reasonably considered to be robust to overestimation of initial capital stock. Therefore the measure of g_i in the paper is justified.

A.3. TABLES

TABLE 6.

Definition of Variables

Variable	Definition	Unit
y_{it}	Real GDP per capita of the economy i in the year t	USD1
k_{it}	Real capital per capita of the economy i in the year t	USD1
K_t	Real capital of the whole group in the year t	USD100,000 million
k_t	Real capital per capita of the whole group in the year t	USD1

Notes: The logarithm of the variable is used in regression models.

TABLE 7.

Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Group0	Total Sample of All Economies			
y_{it}	10929.6700	11534.1200	153.4389	77766.1900
k_{it}	33571.8800	40217.5300	29.0177	232014.4000
K_t	1394.7290	214.7331	1070.0850	1767.7040
k_t	30543.2700	3266.5240	25553.5300	36161.5100
Group1	Low Income Sample			
y_{it}	1378.8990	741.2192	153.4389	3774.3220
k_{it}	1877.8500	1525.2100	213.9011	7750.8280
K_t	13.9271	3.1496	9.8410	20.1640
k_t	1855.7960	231.4706	1577.0410	2327.5180
Group2	Lower Middle Income Sample			
y_{it}	4442.0550	1978.7500	967.3316	11388.4600
k_{it}	13091.2200	13229.8200	14.0414	70197.5200
K_t	212.9889	60.0819	126.3451	327.3533
k_t	9967.6490	2359.5080	6503.1130	14425.7600
Group3	Upper Middle Income Sample			
y_{it}	9144.1730	3613.4710	1887.2990	22580.7700
k_{it}	26623.6500	19087.7900	4136.3240	118732.7000
K_t	143.3169	17.8733	115.2701	174.4734
k_t	20956.9500	1650.1190	18300.2000	23837.8200
Group4	High Income Sample			
y_{it}	25046.8400	10373.2600	1112.7990	77766.1900
k_{it}	80053.1300	38004.1400	390.4237	232014.4000
K_t	957.6996	165.8362	706.3830	1245.7140
k_t	97870.1600	13943.1800	76808.9700	122023.3000

Notes: Groups of economies are constructed by the World Bank's classification. The time range is 1994-2007 for group0 and group3, 1993-2007 for group1 and group2, 1990-2007 for group 4. The number of panel units is 167 for group0, 39 for group1, 43 for group2, 38 for group 3, and 47 for group4. The unit of the variable is described in table 6. The depreciation rate of capital stock is assumed to be 5%.

TABLE 8.

The Implied Measure (w) Assuming Lagged Spillovers

δ	Group0	Group1	Group2	Group3	Group4
Aggregate-capital Based Model					
0%	0.2380 ***	0.2529	0.6193 ***	0.7112 ***	0.4961 ***
	(0.0493)	(0.2093)	(0.0657)	(0.1088)	(0.0724)
5%	0.2036 ***	0.0894	0.4746 ***	0.5801 ***	0.3586 ***
	(0.0403)	(0.1501)	(0.0509)	(0.0876)	(0.0637)
10%	0.1907 ***	0.0146	0.4817 ***	0.5906 ***	0.3307 ***
	(0.0386)	(0.1360)	(0.0460)	(0.0759)	(0.0601)
15%	0.1758 ***	−0.0122	0.4895 ***	0.5893 ***	0.3132 ***
	(0.0384)	(0.1235)	(0.0440)	(0.0682)	(0.0586)
20%	0.1650 ***	−0.0164	0.4935 ***	0.5884 ***	0.3005 ***
	(0.0383)	(0.1125)	(0.0430)	(0.0622)	(0.0584)
25%	0.1588 ***	−0.0122	0.4949 ***	0.5899 ***	0.2906 ***
	(0.0383)	(0.1037)	(0.0424)	(0.0576)	(0.0589)
30%	0.1560 ***	−0.0057	0.4948 ***	0.5933 ***	0.2826 ***
	(0.0382)	(0.0971)	(0.0419)	(0.0543)	(0.0600)
35%	0.1554 ***	0.0001	0.4939 ***	0.5977 ***	0.2757 ***
	(0.0380)	(0.0924)	(0.0416)	(0.0518)	(0.0614)
Average-capital Based Model					
0%	0.2246 ***	0.3446	0.6693 ***	0.7839 ***	0.5645 ***
	(0.0717)	(0.3005)	(0.0624)	(0.0896)	(0.0681)
5%	0.2650 ***	−0.0027	0.5173 ***	0.6841 ***	0.4139 ***
	(0.0497)	(0.3234)	(0.0513)	(0.0787)	(0.0658)
10%	0.2576 ***	−0.0700	0.5248 ***	0.6917 ***	0.3804 ***
	(0.0472)	(0.2730)	(0.0461)	(0.0689)	(0.0636)
15%	0.2393 ***	−0.0648	0.5332 ***	0.6799 ***	0.3601 ***
	(0.0472)	(0.2244)	(0.0439)	(0.0642)	(0.0630)
20%	0.2243 ***	−0.0470	0.5377 ***	0.6660 ***	0.3456 ***
	(0.0476)	(0.1911)	(0.0427)	(0.0611)	(0.0632)
25%	0.2151 ***	−0.0292	0.5396 ***	0.6539 ***	0.3349 ***
	(0.0479)	(0.1688)	(0.0420)	(0.0593)	(0.0642)
30%	0.2103 ***	−0.0143	0.5400 ***	0.6439 ***	0.3263 ***
	(0.0479)	(0.1536)	(0.0415)	(0.0587)	(0.0656)
35%	0.2085 ***	−0.0032	0.5395 ***	0.6352 ***	0.3190 ***
	(0.0478)	(0.1433)	(0.0411)	(0.0589)	(0.0674)

Notes: *** denotes statistical significance at the 1% level based on the Wald test. Standard errors are in parentheses. Groups are described in table 7.

TABLE 9.

The Implied Elasticity of Knowledge (v) Assuming Lagged Spillovers

δ	Group0	Group1	Group2	Group3	Group4
Aggregate-capital Based Model					
0%	0.5318 ***	0.1212	0.4674 ***	0.6372 ***	0.7474 ***
	(0.1023)	(0.1026)	(0.0707)	(0.0876)	(0.1029)
5%	0.5516 ***	0.0611	0.4423 ***	0.7418 ***	0.7510 ***
	(0.1076)	(0.1073)	(0.0590)	(0.1176)	(0.1313)
10%	0.5180 ***	0.0110	0.4716 ***	0.7807 ***	0.7562 ***
	(0.1073)	(0.1040)	(0.0579)	(0.1181)	(0.1414)
15%	0.4691 ***	−0.0100	0.4861 ***	0.7644 ***	0.7269 ***
	(0.1059)	(0.1004)	(0.0573)	(0.1103)	(0.1436)
20%	0.4331 ***	−0.0144	0.4906 ***	0.7454 ***	0.6955 ***
	(0.1046)	(0.0973)	(0.0566)	(0.1020)	(0.1448)
25%	0.4123 ***	−0.0112	0.4898 ***	0.7357 ***	0.6689 ***
	(0.1036)	(0.0945)	(0.0558)	(0.0961)	(0.1471)
30%	0.4026 ***	−0.0054	0.4865 ***	0.7346 ***	0.6470 ***
	(0.1029)	(0.0920)	(0.0550)	(0.0926)	(0.1504)
35%	0.3995 ***	0.0001	0.4820 ***	0.7392 ***	0.6285 ***
	(0.1025)	(0.0899)	(0.0543)	(0.0908)	(0.1543)
Average-capital Based Model					
0%	0.4931 ***	0.1883	0.5817 ***	0.9387 ***	0.9846 ***
	(0.1617)	(0.2028)	(0.0907)	(0.1284)	(0.1238)
5%	0.7778 ***	−0.0017	0.5247 ***	1.1634 ***	0.9487 ***
	(0.1564)	(0.2005)	(0.0708)	(0.1887)	(0.1606)
10%	0.7626 ***	−0.0489	0.5604 ***	1.2156 ***	0.9402 ***
	(0.1554)	(0.1809)	(0.0691)	(0.1937)	(0.1743)
15%	0.6917 ***	−0.0504	0.5790 ***	1.1334 ***	0.8971 ***
	(0.1527)	(0.1666)	(0.0682)	(0.1779)	(0.1775)
20%	0.6340 ***	−0.0399	0.5857 ***	1.0420 ***	0.8556 ***
	(0.1504)	(0.1568)	(0.0672)	(0.1613)	(0.1793)
25%	0.5986 ***	−0.0264	0.5860 ***	0.9693 ***	0.8224 ***
	(0.1488)	(0.1492)	(0.0662)	(0.1500)	(0.1825)
30%	0.5799 ***	−0.0134	0.5832 ***	0.9138 ***	0.7958 ***
	(0.1477)	(0.1433)	(0.0651)	(0.1436)	(0.1869)
35%	0.5718 ***	−0.0031	0.5787 ***	0.8698 ***	0.7738 ***
	(0.1468)	(0.1387)	(0.0642)	(0.1405)	(0.1919)

Notes: See notes in table 8.

TABLE 10.

The Implied Measure (w) Assuming Current Spillovers

δ	Group0	Group1	Group2	Group3	Group4
Aggregate-capital Based Model					
0%	0.2237 ***	0.2073	0.6314 ***	0.7326 ***	0.4879 ***
	(0.0469)	(0.2211)	(0.0619)	(0.0908)	(0.0724)
5%	0.2060 ***	0.0965	0.4600 ***	0.5892 ***	0.3580 ***
	(0.0384)	(0.1433)	(0.0508)	(0.0789)	(0.0631)
10%	0.2030 ***	0.0477	0.4587 ***	0.5973 ***	0.3326 ***
	(0.0367)	(0.1239)	(0.0468)	(0.0694)	(0.0592)
15%	0.1917 ***	0.0304	0.4641 ***	0.5987 ***	0.3175 ***
	(0.0364)	(0.1111)	(0.0448)	(0.0624)	(0.0574)
20%	0.1795 ***	0.0217	0.4682 ***	0.6003 ***	0.3068 ***
	(0.0366)	(0.1023)	(0.0437)	(0.0566)	(0.0567)
25%	0.1694 ***	0.0172	0.4708 ***	0.6032 ***	0.2984 ***
	(0.0368)	(0.0958)	(0.0430)	(0.0522)	(0.0568)
30%	0.1615 ***	0.016	0.4722 ***	0.6069 ***	0.2915 ***
	(0.0369)	(0.0909)	(0.0424)	(0.0489)	(0.0574)
35%	0.1556 ***	0.0161	0.4728 ***	0.6105 ***	0.2855 ***
	(0.0371)	(0.0872)	(0.0420)	(0.0465)	(0.0583)
Average-capital Based Model					
0%	0.2133 ***	0.0119	0.6855 ***	0.7914 ***	0.5387 ***
	(0.0683)	(0.5641)	(0.0571)	(0.0778)	(0.0718)
5%	0.2670 ***	−0.3362	0.5033 ***	0.6896 ***	0.4058 ***
	(0.0472)	(0.5232)	(0.0513)	(0.0705)	(0.0663)
10%	0.2707 ***	−0.1672	0.5016 ***	0.7021 ***	0.3774 ***
	(0.0443)	(0.3034)	(0.0471)	(0.0605)	(0.0634)
15%	0.2579 ***	−0.0585	0.5072 ***	0.7004 ***	0.3606 ***
	(0.0441)	(0.2103)	(0.0450)	(0.0544)	(0.0621)
20%	0.2430 ***	−0.0165	0.5117 ***	0.6978 ***	0.3489 ***
	(0.0446)	(0.1723)	(0.0438)	(0.0496)	(0.0618)
25%	0.2303 ***	0.0006	0.5147 ***	0.6971 ***	0.3401 ***
	(0.0451)	(0.1526)	(0.0429)	(0.0458)	(0.0622)
30%	0.2204 ***	0.0097	0.5165 ***	0.6975 ***	0.3330 ***
	(0.0455)	(0.1404)	(0.0422)	(0.0431)	(0.0630)
35%	0.2128 ***	0.0152	0.5175 ***	0.6979 ***	0.3269 ***
	(0.0458)	(0.1322)	(0.0417)	(0.0412)	(0.0642)

Notes: See notes in table 8.

TABLE 11.

The Implied Elasticity of Knowledge (v) Assuming Current Spillovers

δ	Group0	Group1	Group2	Group3	Group4
Aggregate-capital Based Model					
0%	0.4907 ***	0.0892	0.4747 ***	0.7280 ***	0.7494 ***
	(0.1034)	(0.0983)	(0.0697)	(0.0791)	(0.1031)
5%	0.5629 ***	0.0649	0.4206 ***	0.7820 ***	0.7550 ***
	(0.1091)	(0.1013)	(0.0593)	(0.1095)	(0.1300)
10%	0.5614 ***	0.0367	0.4339 ***	0.8110 ***	0.7660 ***
	(0.1084)	(0.0980)	(0.0576)	(0.1103)	(0.1399)
15%	0.5210 ***	0.0255	0.4424 ***	0.8007 ***	0.7438 ***
	(0.1065)	(0.0948)	(0.0564)	(0.1032)	(0.1420)
20%	0.4778 ***	0.0192	0.4466 ***	0.7887 ***	0.7174 ***
	(0.1046)	(0.0920)	(0.0553)	(0.0953)	(0.1427)
25%	0.4430 ***	0.0159	0.4482 ***	0.7831 ***	0.6940 ***
	(0.1030)	(0.0895)	(0.0544)	(0.0892)	(0.1441)
30%	0.4170 ***	0.0152	0.4482 ***	0.7823 ***	0.6740 ***
	(0.1019)	(0.0872)	(0.0535)	(0.0848)	(0.1462)
35%	0.3977 ***	0.0156	0.4471 ***	0.7841 ***	0.6570 ***
	(0.1011)	(0.0853)	(0.0527)	(0.0816)	(0.1489)
Average-capital Based Model					
0%	0.4617 ***	0.0041	0.6042 ***	1.0080 ***	0.9186 ***
	(0.1593)	(0.1962)	(0.0887)	(0.1174)	(0.1256)
5%	0.7901 ***	−0.1530	0.5002 ***	1.2112 ***	0.9248 ***
	(0.1579)	(0.1891)	(0.0708)	(0.1732)	(0.1592)
10%	0.8180 ***	−0.1048	0.5154 ***	1.2895 ***	0.9319 ***
	(0.1563)	(0.1682)	(0.0685)	(0.1758)	(0.1725)
15%	0.7636 ***	−0.0448	0.5259 ***	1.2560 ***	0.9016 ***
	(0.1527)	(0.1544)	(0.0668)	(0.1607)	(0.1755)
20%	0.7010 ***	−0.0141	0.5317 ***	1.2150 ***	0.8688 ***
	(0.1494)	(0.1455)	(0.0654)	(0.1450)	(0.1767)
25%	0.6501 ***	0.0005	0.5344 ***	1.1882 ***	0.8410 ***
	(0.1468)	(0.1388)	(0.0641)	(0.1331)	(0.1787)
30%	0.6120 ***	0.0091	0.5352 ***	1.1719 ***	0.8180 ***
	(0.1448)	(0.1336)	(0.0630)	(0.1249)	(0.1816)
35%	0.5836 ***	0.0147	0.5346 ***	1.1599 ***	0.7986 ***
	(0.1433)	(0.1294)	(0.0620)	(0.1191)	(0.1851)

Notes: See notes in table 8.

TABLE 12.

Unit Root Tests for Total Sample (Group0)

Option	Test	$\ln y_{it}$	$\ln k_{it}$	Test	$\ln K_t$	$\ln k_t$
c	LLC(2002), Adj-t^*	1.6743	−0.6562	ADF	−0.5158	−0.2018
c,t		−19.0485***	−7.5057***		−3.1571*	−3.2393*
c	HT(1999), z	8.6367	5.0007	PP	−0.7973	0.3461
c,t		6.0880	3.0755		−1.4115	−1.6134
c	Breitung(2000), λ^*	4.6288	0.9529			
c,t		1.9154	−1.1408			
c	IPS(2003), t-bar	−0.4028	−0.6618			
c,t		−1.9287	−1.4805			
c	Hadri(2000), z	83.9098***	89.0050 ***			
c,t		46.0396***	50.6282 ***			

Notes: ***, significant at 1% level; **, significant at 5% level; *, significant at 10% level. Lags are 3 years in Breitung(2000), ADF and PP. Lags in LLC(2002) are automatically selected according to Akaike information criterion(AIC) with the maximum of 3 years. There are no lags in HT(1999), IPS(2003) and Hadri(2000). ADF and PP are Augmented Dickey-Fuller and Phillips-Perron unit-root tests, respectively. The option, c, denotes inclusion of a constant term. The option, t, denotes inclusion of a trend term.

TABLE 13.

Unit Root Tests for Low Income Sample (Group1)

Option	Test	$\ln y_{it}$	$\ln k_{it}$	Test	$\ln K_t$	$\ln k_t$
c	LLC(2002), Adj-t^*	1.2373	−2.9472***	ADF	1.0905	2.1287
c,t		−3.8337***	−8.9121***		−1.5304	1.1728
c	HT(1999), z	2.5048	4.3518	PP	10.7360	9.4658
c,t		0.7966	7.5340		−0.0097	−0.2872
c	Breitung(2000), λ^*	1.1349	−1.2991*			
c,t		0.7719	0.5491			
c	IPS(2003), t-bar	−0.9795	−0.8710			
c,t		−2.8470***	−1.6364			
c	Hadri(2000), z	36.7196 ***	47.0368 ***			
c,t		23.6837 ***	33.6948 ***			

Notes: See notes in table 12.

TABLE 14.

Unit Root Tests for Lower Middle Income Sample (Group2)

Option	Test	$\ln y_{it}$	$\ln k_{it}$	Test	$\ln K_t$	$\ln k_t$
c	LLC(2002), Adj-t^*	5.4076	0.5655	ADF	0.4920	0.8420
c,t		-7.0114^{***}	-8.9659^{***}		-3.7201^{**}	-2.7055
c	HT(1999), z	6.5047	0.3413	PP	-0.5591	-0.1447
c,t		1.4438	3.9227		-1.8941	-1.7407
c	Breitung(2000), λ^*	3.5692	2.1976			
c,t		1.9844	-0.1267			
c	IPS(2003), t-bar	-0.3579	-0.8911			
c,t		-2.0574	-1.8158			
c	Hadri(2000), z	45.7609 ***	44.3176 ***			
c,t		23.1138 ***	29.9836 ***			

Notes: See notes in table 12.

TABLE 15.

Unit Root Tests for Upper Middle Income Sample (Group3)

Option	Test	$\ln y_{it}$	$\ln k_{it}$	Test	$\ln K_t$	$\ln k_t$
c	LLC(2002), Adj-t^*	8.5652	-2.6027^{***}	ADF	-0.4325	-0.3478
c,t		-6.4583^{***}	-6.3140^{***}		-4.3645^{***}	-4.1582^{***}
c	HT(1999), z	4.6935	5.2259	PP	-0.4947	-0.1944
c,t		2.5721	8.2510		-1.5646	-1.5666
c	Breitung(2000), λ^*	3.1853	1.0690			
c,t		1.8426	-1.0494			
c	IPS(2003), t-bar	0.0457	-1.1113			
c,t		-1.7033	-1.0845			
c	Hadri(2000), z	37.4999 ***	45.5424 ***			
c,t		19.4776 ***	29.6981 ***			

Notes: See footnotes in table 12.

TABLE 16.

Unit Root Tests for High Income Sample (Group4)

Option	Test	$\ln y_{it}$	$\ln k_{it}$	Test	$\ln K_t$	$\ln k_t$
c	LLC(2002), Adj-t^*	1.7281	4.6392	ADF	−1.0600	−0.3243
c,t		−8.4982***	−10.5151***		−1.4386	−3.1474*
c	HT(1999), z	6.5973	6.2711	PP	−1.2809	−0.2095
c,t		1.3305	7.8798		−1.4450	−1.6798
c	Breitung(2000), λ^*	4.8279	0.6943			
c,t		1.1477	0.4223			
c	IPS(2003), t-bar	0.1488	0.5523			
c,t		−2.8184***	−0.6430			
c	Hadri(2000), z	66.7367 ***	70.0638 ***			
c,t		21.8999 ***	32.9676 ***			

Notes: See footnotes in table 12.

TABLE 17.

Cointegration Tests for Total Sample (Group0)

Statistic	Aggregate-capital Based Model	Average-capital Based Model
Panel v-statistic	12.9849 ***	12.9722 ***
Panel rho-statistic	−42.8057***	−42.4781***
Panel t-statistic(Nonparametric)	−17.4309***	−17.3059***
Panel t-statistic(Parametric)	−586.9367***	−578.6917***
Group rho-statistic	−51.7832***	−51.6988***
Group t-statistic(Nonparametric)	−19.2158***	−19.1658***
Group t-statistic(Parametric)	−20.6868***	−20.6529***

Notes: ***, significant at 1% level. Tests are based on Pedroni (1999) and taken with a constant option.

TABLE 18.

Cointegration Tests for Low Income Sample (Group1)

Statistic	Aggregate-capital Based Model	Average-capital Based Model
Panel v-statistic	6.9510 ***	6.6458 ***
Panel rho-statistic	−16.1217***	−14.4916***
Panel t-statistic(Nonparametric)	−6.3426***	−5.6346***
Panel t-statistic(Parametric)	−112.0463***	−76.2654***
Group rho-statistic	−26.4349***	−26.1044***
Group t-statistic(Nonparametric)	−9.4454***	−9.3045***
Group t-statistic(Parametric)	−10.4600***	−10.5639***

Notes: See notes in table 17.

TABLE 19.

Cointegration Tests for Lower Middle Income Sample (Group2)

Statistic	Aggregate-capital Based Model	Average-capital Based Model
Panel v-statistic	9.0656 ***	8.7110 ***
Panel rho-statistic	−21.6423***	−21.2849***
Panel t-statistic(Nonparametric)	−8.8795***	−8.7499***
Panel t-statistic(Parametric)	−268.7395***	−264.3920***
Group rho-statistic	−27.3871***	−27.4281***
Group t-statistic(Nonparametric)	−9.8502***	−9.8660***
Group t-statistic(Parametric)	−10.7730***	−10.7929***

Notes: See notes in table 17.

TABLE 20.

Cointegration Tests for Upper Middle Income Sample (Group3)

Statistic	Aggregate-capital Based Model	Average-capital Based Model
Panel v-statistic	12.3222 ***	14.5561 ***
Panel rho-statistic	−20.0276***	−21.1673***
Panel t-statistic(Nonparametric)	−7.3956***	−7.7049***
Panel t-statistic(Parametric)	−205.0873***	−219.1217***
Group rho-statistic	−25.2256***	−25.2200***
Group t-statistic(Nonparametric)	−8.7203***	−8.7345***
Group t-statistic(Parametric)	−9.5586***	−9.5543***

Notes: See notes in table 17.

TABLE 21.

Cointegration Tests for High Income Sample (Group4)

Statistic	Aggregate-capital Based Model	Average-capital Based Model
Panel v-statistic	11.9456 ***	11.1886 ***
Panel rho-statistic	−25.4284***	−24.8948***
Panel t-statistic(Nonparametric)	−11.0007***	−10.7197***
Panel t-statistic(Parametric)	−372.2547***	−367.1304***
Group rho-statistic	−28.9856***	−28.8101***
Group t-statistic(Nonparametric)	−10.6175***	−10.5516***
Group t-statistic(Parametric)	−12.1060***	−12.0040***

Notes: See notes in table 17.

REFERENCES

Aghion, Philippe, 2004. Growth and Development: A Schumpeterian Approach. *Annals of Economics and Finance* **5(1)**, 1-25.

Arrow, Kenneth, J., 1962. The Economic Implications of Learning by Doing. *The Review of Economic Studies* **29(3)**, 155–173.

Baltagi, Badi, H. and Chihwa Kao, 2000. Nonstationary Panels, Cointegration in Panels and Dynamic Panels: A Survey. In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels*, *Advances in Econometrics*, vol. 15, edited by Badi H. Baltagi, Thomas B. Fomby, and R. Carter Hill. Elsevier Science Inc, 7–51.

Barro, Robert, J. and Xavier Sala-I-Martin, 2004. *Economic Growth*. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2nd ed.

Breitung, Jörg, 2000. The Local Power of Some Unit Root Tests for Panel Data. In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels*, *Advances in Econometrics*, vol. 15, edited by Badi H. Baltagi, Thomas B. Fomby, and R. Carter Hill. Elsevier Science Inc, 161–177.

Bresnahan, Timothy, F., 1986. Measuring the Spillovers from Technical Advance: Mainframe Computers in Financial Services. *The American Economic Review* **76(4)**, 742–755.

Chiang, Min-Hsien and Chihwa Kao, 2002. *Nonstationary Panel Time Series Using NPT 1.3 - A User Guide*. Center for Policy Research, Syracuse University.

Coe, David, T. and Elhanan Helpman, 1995. International R&D Spillovers. *European Economic Review* **39(5)**, 859-887.

Coe, David, T., Elhanan Helpman, and Alexander, W. Hoffmaister, 2009. International R&D Spillovers and Institutions. *European Economic Review* **53(7)**, 723–741.

Griliches, Zvi, 1992. The Search for R&D Spillovers. *The Scandinavian Journal of Economics* **94**, S29-S47.

Grossman, Gene, M. and Elhanan Helpman, 1991. *Innovation and Growth in the Global Economy*. Cambridge: MIT Press.

Hadri, Kaddour, 2000. Testing for Stationarity in Heterogeneous Panel Data. *The Econometrics Journal* **3(2)**, 148–161.

Harris, Richard D. F. and Elias Tzavalis, 1999. Inference for Unit Roots in Dynamic Panels Where the Time Dimension is Fixed. *Journal of Econometrics* **91(2)**, 201–226.

Heston, Alan, Robert Summers, and Bettina Aten, 2006. Penn World Table Version 6.2. Tech. rep., Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Heston, Alan, Robert Summers, and Bettina Aten, 2009. Penn World Table Version 6.3. Tech. rep., Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Howitt, Peter, 2000. Endogenous Growth and Cross-Country Income Differences. *The American Economic Review* **90(4)**, 829-846.

Im, Kyung, So, M. Hashem Pesaran, and Yongcheol Shin, 2003. Testing for Unit Roots in Heterogeneous Panels. *Journal of Econometrics* **115(1)**, 53–74.

Jones, Charles, I. and John, C. Williams, 1998. Measuring the Social Return to R&D. *The Quarterly Journal of Economics* **113(4)**, 1119–1135.

Kaiser, Ulrich, 2002. Measuring Knowledge Spillovers in Manufacturing and Services: An Empirical Assessment of Alternative Approaches. *Research Policy* **31(1)**, 125–144.

Kao, Chihwa and Min-Hsien Chiang, 2000. On the Estimation and Inference of a Cointegrated Regression in Panel Data. In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels*, *Advances in Econometrics*, vol. 15, edited by Badi H. Baltagi, Thomas B. Fomby, and R. Carter Hill. Elsevier Science Inc., 179–222.

Lang, Guenter, 2009. Measuring the Returns of R&D–An Empirical Study of the German Manufacturing Sector over 45 Years. *Research Policy* **38(9)**, 1438–1445.

Levin, Andrew, Chien-Fu Lin, and Chia-Shang James Chu, 2002. Unit Root Tests in Panel Data: Asymptotic and Finite-Sample Properties. *Journal of Econometrics* **108(1)**, 1–24.

Mankiw, N. Gregory, David Romer, and David N. Weil, 1992. A Contribution to the Empirics of Economic Growth. *The Quarterly Journal of Economics* **107(2)**, 407–437.

Mansfield, Edwin, John Rapoport, Anthony Romeo, Samuel Wagner, and George Beardsley, 1977. Social and Private Rates of Return from Industrial Innovations. *The Quarterly Journal of Economics* **91(2)**, 221–240.

Nelson, Andrew J. 2009. Measuring Knowledge Spillovers: What Patents, Licenses and Publications Reveal About Innovation Diffusion. *Research Policy* **38(6)**, 994–1005.

Pedroni, Peter, 1999. Critical Values for Cointegration Tests in Heterogeneous Panels with Multiple Regressors. *Oxford Bulletin of Economics and Statistics* **61(S1)**, 653–670.

Romer, Paul M. 1986. Increasing Returns and Long-Run Growth. *The Journal of Political Economy* **94(5)**, 1002–1037.

Sachs, Jeffrey, Wing Thye Woo, and Xiaokai Yang, 2000. Economic Reforms and Constitutional Transition. *Annals of Economics and Finance* **1(2)**, 423-479.

Shen, Kunrong and Jian Li. 2009. Measurement of Technology Spillovers. *Economic Research Journal* **4**, 77–89.

Trajtenberg, Manuel, 1989. The Welfare Analysis of Product Innovations, with an Application to Computed Tomography Scanners. *The Journal of Political Economy* **97(2)**, 444–479.

Yang, Xiaokai and Dingsheng Zhang, 2000. Endogenous Structure of the Division of Labor, Endogenous Trade Policy Regime, and a Dual Structure in Economic Development. *Annals of Economics and Finance* **1(1)**, 211-230.