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**ABSTRACT**

The empirical analysis in "International R&D Spillovers" (Coe and Helpman, 1995) is first revisited by applying modern panel cointegration estimation techniques to an expanded data set that we have constructed for the purpose of this study. The new estimates confirm the key results reported in Coe and Helpman about the impact of domestic and foreign R&D capital stocks on TFP. In addition, we show that domestic and foreign R&D capital stocks have measurable impacts on TFP even after controlling for the impact of human capital. Furthermore, we extend the analysis to include institutional variables, such as legal origin and patent protection, in order to allow for parameter heterogeneity based on a country's institutional characteristics. The results suggest that institutional differences are important determinants of total factor productivity and that they impact the degree of R&D spillovers.

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## ***1. Introduction***

The importance of international R&D spillovers has long been recognized, although estimates of their empirical significance at the macroeconomic level were often elusive. The search for R&D spillovers across countries received a boost in the 1990s with the development of new growth models by Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992), and by the application of the ideas from these models together with new empirical techniques to expanded data sets by Coe and Helpman (1995) and Coe, Helpman, and Hoffmaister (1997). The then-new endogenous growth models focused on commercially-oriented innovation efforts by profit-seeking firms as a major engine of technological progress and productivity growth, in contrast to the exogenous treatment of technological progress in neoclassical theory.<sup>1</sup>

In “International R&D Spillovers,” Coe and Helpman (1995) (hereafter CH) presented new estimates of R&D spillovers. Whereas many earlier studies of R&D spillovers had been based on sectoral or industry data for single countries,<sup>2</sup> CH used pooled macroeconomic data for 21 OECD countries plus Israel over the 1971-90 time period. They estimated equations explaining a country’s total factor productivity (TFP) as a function of the domestic R&D capital stock and a measure of the foreign R&D capital stock, where all the measures of R&D capital were constructed from the business sectors’ R&D activities. While equations relating output or TFP to the domestic R&D capital stock had been estimated previously, the extension to include an explicit measure of the foreign R&D capital stock was new. In another innovation, CH focused their estimation on long-run relationships, taking advantage of the attractive econometric properties of cointegrated equations. This was one of the early empirical studies to estimate panel cointegrating equations, despite the fact that, at that time, “the econometrics of pooled cointegration [were] not yet fully worked out” (CH, 1995, p. 870).

“International R&D Spillovers” inspired a large number of empirical studies, which can be grouped into three broad categories: studies addressing the appropriate definition of the foreign R&D capital stock, studies proposing additional determinants of TFP, and studies proposing alternative econometric techniques. Keller (2004) reviews a large part of this literature. To place the current paper in context, however, we briefly discuss some of the empirical studies based on panel estimates at the aggregate level.

For each of the 22 countries in their sample, CH defined a foreign R&D capital stock as the weighted average of the country’s 21 trading partners’ domestic R&D capital stocks, using bilateral import shares as weights. Subsequent papers proposed a number of alternative definitions of the foreign R&D capital stock, based on different methods for aggregating

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<sup>1</sup> See the discussion in Helpman (2004) and Ha and Howitt (2007).

<sup>2</sup> For example, the studies reviewed by Griliches (1992) are for agriculture or industry.

trading partners' domestic R&D capital stocks into a foreign R&D capital stock. The main differences between these methods is in the weights applied to foreign R&D capital stocks. These include equal weights (Keller, 1998),<sup>3</sup> weights based on bilateral export shares (Funk, 2001), weights based on the fraction of trading partners' output exported to the recipient country (Lichtenberg and van Pottelsberghe de la Potterie, 1998), weights based on inward and outward FDI flows (van Pottelsberghe de la Potterie and Lichtenberg, 2001) and stocks (Zhu and Jeon, 2007), weights based on the bilateral technological proximity between countries (Park, 1995; Guellec and van Pottelsberghe de la Potterie, 2004), weights based on indirect trade (Lumenga-Neso *et al.*, 2005), and weights based on information technology (Zhu and Jeon, 2007).

Keller (1998) and Coe and Hoffmaister (1999) demonstrated that a measure of foreign R&D capital defined as a simple average of trading partners' domestic R&D capital stocks performed about the same as the definition using bilateral import weights. Lichtenberg and van Pottelsberghe de la Potterie (1998) argued that CH's weighting scheme is subject to an aggregation bias, in that a merger between countries would always increase the stock of foreign R&D capital, and showed that a measure based on the fraction of bilateral trading partners' output exported to the recipient country yielded somewhat better results than the measure used in CH.<sup>4</sup> Funk (2001) presented results, using newly developed panel estimation techniques, showing that a definition of foreign R&D capital based on bilateral export shares performed better than CH's definition, suggesting the importance of R&D spillovers emanating from exporters' customers. More recently, Lee (2006) has shown, based on a different data set and modern panel cointegration techniques, that a definition of foreign R&D capital based on inward FDI or bilateral technological proximity do a better jobs than other definitions.

A number of other studies have focused on various explanatory variables in addition to the domestic and foreign R&D capital stocks. Determinants of TFP that have been shown to be significant, cointegrated, or to improve explanatory power, include human capital (Engelbrecht, 1997; Khan and Luintel, 2006), the import share (Coe and Hoffmaister, 1999;

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<sup>3</sup> Keller (1998) proported to show that a foreign R&D capital stock defined with "random" weights, which he noted were similar to equal weights, explained TFP developments as well or better than CH's bilateral import weights. Coe and Hoffmaister (1999) demonstrated analytically in the case of two trading partners and numerically for  $n$  trading partners that Keller's weights are essentially simple averages with a random error. Coe and Hoffmaister (1999) also showed that when three alternative sets of random weights are used to construct foreign R&D capital stocks, the estimated spillover elasticities are extremely small and the estimated equations explain less of the variation in TFP than if CH's original definition based on bilateral import shares, as would be expected if truly random weights were used.

<sup>4</sup> Lichtenberg and van Pottelsberghe de la Potterie (1998) also correctly pointed out that CH's indexation of the R&D capital stocks was problematic in CH's specification where the foreign R&D capital stock was interacted with the import share. Coe and Hoffmaister (1999) showed that correcting this has little effect on the estimated coefficients.

Edmond, 2001), productivity catch-up (Engelbrecht, 1997), measures of government funded R&D and the business cycle (Guellec and van Pottelsberghe de la Potterie, 2004), and infrastructure and stocks of inward and outward FDI (Khan and Luintel, 2006).

With advances in the econometrics of panel cointegration, a number of studies applied new techniques that were not available at the time of CH's research. Kao *et al.* (1999), for example, re-examined the econometric foundations of CH's results using newly developed techniques.<sup>5</sup> Although a number of Kao *et al.*'s (1999) estimates generally confirmed the results in CH, their dynamic OLS estimates, which they considered to be superior to the other estimation techniques, indicated that the estimated coefficients on the foreign R&D capital stock were insignificant. A number of other studies based on panel cointegration techniques found that TFP was cointegrated with domestic and foreign R&D capital, although the latter was often defined in one of the alternative ways discussed above (Lichtenberg and van Pottelsberghe de la Potterie, 1998; Edmond, 2001; Funk, 2001; Guellec and van Pottelsberghe de la Potterie, 2004; and Lee, 2006).

Panel cointegration techniques are particularly well suited for the study of the impact of R&D capital on total factor productivity for a number of reasons. One is the focus on the long-run relationships, which would be obscured if, for example, the equations were estimated on first differences rather than on the levels of variables. A second is the increased power that comes from exploiting commonalities across countries, given the limited number of time-series observations. A third, important reason is that, under cointegration, parameter estimates are super consistent, and hence are robust to problems such as omitted variables, simultaneity, and endogeneity.<sup>6</sup> Thus, using panel cointegration techniques to estimate the long-run effect of domestic and foreign R&D capital on TFP overcomes the endogeneity problem, thereby avoiding the difficult task of finding valid instruments for R&D capital, which would be necessary if the focus was on the short-run relationship.

Estimating R&D spillovers on a pooled dataset highlighted the issue of heterogeneity in parameter estimates. CH incorporated some heterogeneity in their pooled estimates by estimating separate elasticities of TFP with respect to domestic R&D capital for the G7 and for the smaller countries and by including fixed effects (i.e., country-specific constants). In addition, heterogeneity in the effect of foreign R&D on TFP was introduced by interacting the foreign R&D capital stock with the import share. In contrast to pooled estimates, which generally assume homogeneity of parameter estimates, group mean estimates average single country (i.e., time-series) estimates, thereby allowing for full heterogeneity. Edmond (2001) applied group mean estimates to the CH data set and found that TFP was cointegrated with domestic and foreign R&D capital if the latter was defined as a simple sum of trading partners' R&D capital stocks, but not if it was defined with bilateral import shares as in CH.

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<sup>5</sup> See also Harris and Sollis (2003, chapter 7).

<sup>6</sup> Pedroni and Urbain (2008) provide a summary of the recent panel cointegration literature. See also Stock (1987) and Stock and Watson (1993).

Luintel and Khan (2004), based on a different sample, conclude that pooling was not valid, although they did find cointegration between TFP and domestic and foreign R&D capital. Khan and Luintel (2006), on the other hand, addressed heterogeneity in their pooled estimates by interacting both domestic and foreign R&D capital stocks with a variety of other determinants of productivity.

The purposes of this paper are twofold. The first is to revisit the empirical analysis in CH using a data set updated to 2004 and expanded to 24 countries, and applying panel cointegration estimation techniques not available in the early 1990s. We find that the estimates based on the new data set and using modern econometric techniques give broadly similar results as those reported in CH. There is, moreover, robust evidence of cointegration between total factor productivity, domestic R&D capital, foreign R&D capital based on a number of definitions, and a measure of human capital. Measures of foreign R&D capital incorporating information about bilateral imports, such as those used by CH and Lichtenberg and van Pottelsberghe de la Potterie (1998), perform better than a measure based on equal weights. These results are obtained using either dynamic OLS on the pooled data or using dynamic OLS group mean estimates.

The second aim of the paper is to expand the empirical analysis to examine the impact of institutional factors that are now viewed as important determinants of economic growth. In particular, we study the impact of these institutions on the degree of R&D spillovers and the contribution of domestic R&D capital to TFP, thereby allowing for heterogeneity in parameter estimates. The paper thus contributes to the broader growth literature emphasizing the importance of institutions for economic growth.<sup>7</sup> We find evidence that countries where the ease of doing business and the quality of tertiary education systems are relatively high tend to benefit more from their own R&D efforts, from international R&D spillovers, and from human capital formation. We also find that strong patent protection is associated with higher levels of total factor productivity, higher returns to domestic R&D, and larger international R&D spillovers. Finally, we find evidence that the origins of a country's legal system also has an influence on the extent to which it benefits from its own and foreign R&D.

The next two sections summarize the key features of our data and present a brief overview of the econometric techniques of panel cointegration. Section 4 revisits the empirical analysis in CH and addresses some of the issues raised in the subsequent literature. Section 5 presents evidence on the importance of institutions for the effectiveness of domestic R&D and the extent of international R&D spillovers. Section 6 concludes.

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<sup>7</sup> The literature on institutions and economic growth is very large; see Helpman (2004, chapter 7) for an overview.

## 2. Data

The database used in CH, which covered the period 1971-90, has been reconstituted with revised data and updated to 2004.<sup>8</sup> The increase in the time-series dimension from 20 to 34 annual observations is important in the context of our cointegration analysis focusing on long-run relationships. The database has also been expanded to include Korea and Iceland, which brings a welcome increase in the cross-country variance in the data. Summary statistics for the data are presented in Table 1 and data for selected countries are shown in Figures 1-5. A brief description of the main features of the data follows; details about data sources and definitions are provided in an annex.

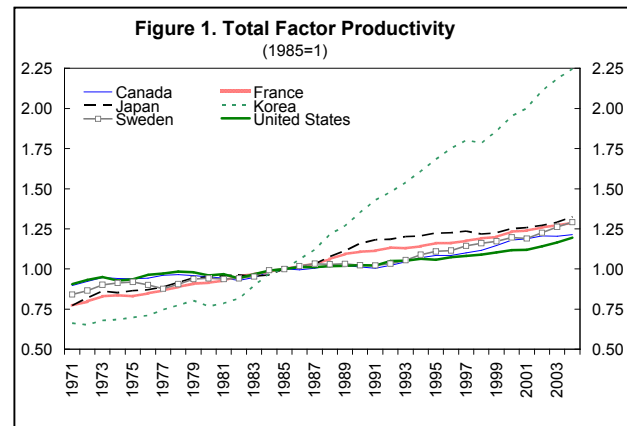
Table 1. Summary Statistics

	$F_{04}/F_{71}$	$S^d_{04}/S^d_{71}$	$S^{f-biw}_{04}/S^{f-biw}_{71}$	$m_{04}$	$m_{71}$	$H_{04}$	$H_{71}$
Australia	1.46	5.83	2.71	20.78	12.97	10.78	10.03
Austria	1.74	11.67	3.76	46.06	27.24	9.09	6.97
Belgium	1.80	5.48	2.63	79.82	47.25	8.87	8.30
Canada	1.35	7.80	2.65	34.16	19.80	11.63	8.95
Denmark	1.69	6.92	2.35	40.32	30.57	10.27	8.81
Finland	2.16	13.58	2.75	32.49	25.18	10.40	6.65
France	1.67	4.59	2.17	25.40	15.45	8.71	5.90
Germany	1.55	5.26	2.53	33.18	19.32	9.89	8.16
Greece	1.31	119.54	3.17	29.70	16.68	8.88	5.29
Iceland	2.09	3,632.56	2.93	40.25	43.85	9.07	6.31
Ireland	3.72	13.48	3.85	69.13	41.19	9.20	6.56
Israel	1.18	52.59	2.46	42.71	53.14	9.37	7.69
Italy	1.51	5.10	1.95	24.58	15.39	7.32	5.23
Japan	1.72	10.99	2.05	11.42	8.96	9.94	6.98
Korea	3.39	4,660.24	2.93	39.73	25.58	10.76	4.96
Netherlands	1.57	2.30	3.24	59.29	46.78	9.46	7.61
New Zealand	1.15	4.88	3.09	29.77	22.42	11.69	9.69
Norway	2.42	9.91	2.85	28.52	37.53	11.89	7.43
Portugal	1.83	3.15	1.60	36.48	26.42	5.21	2.51
Spain	1.44	22.46	1.19	29.97	12.46	7.75	4.65
Sweden	1.54	7.39	2.13	37.80	22.89	11.46	7.66
Switzerland	1.10	2.17	2.91	38.65	30.07	10.56	8.28
United Kingdom	1.79	1.90	2.75	28.36	21.05	9.61	7.73
United States	1.32	2.69	6.26	15.29	5.53	12.31	9.83
Average	1.77	358.85	2.79	36.41	26.16	9.76	7.17
Standard deviation	0.64	1,176.61	0.96	15.50	12.93	1.61	1.81

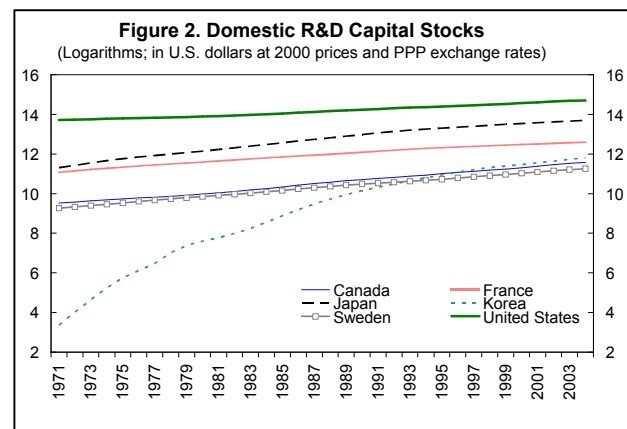
Note:  $S^{f-biw}$  is defined using bilateral import weights.  $m$  is in percent of GDP.  $H$  is in years of schooling.

<sup>8</sup> Data for Germany refer to West Germany until 1990 and to unified Germany thereafter.

Total factor productivity ( $F$ ), defined as the log of output minus a weighted average of labor and capital inputs using factor shares as weights, increased by an average of 77 percent from 1971-2004 in the 24 countries in our sample. In a number of countries, the growth of TFP over this period was much higher, increasing by a factor of more than three in Ireland and Korea and more than doubling in Finland, Iceland, and Norway. At the other extreme, TFP rose by only 10 to 20 percent in Israel, New Zealand, and Switzerland over the same 34 years. There was a clear acceleration in TFP after 1990 in Australia, Canada, Sweden, and the United States. In all countries, TFP exhibits a positive trend, as illustrated in Figure 1 for a selection of countries.



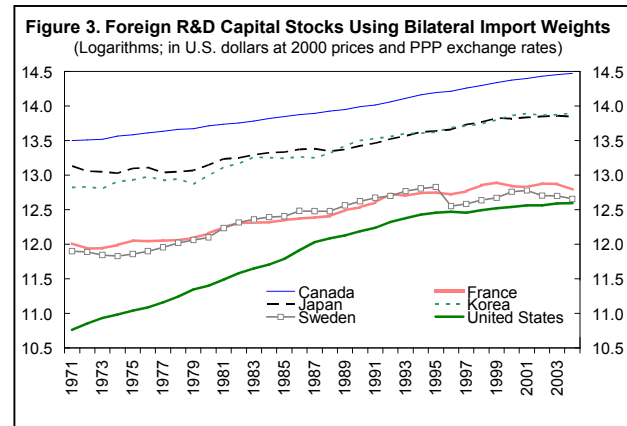
Compared with the rise in TFP, the increase in domestic R&D capital stocks ( $S^d$ ), measured in constant dollars for the business sector, was much larger and much more variable across countries. Starting from very low levels in 1971, R&D capital in Iceland and Korea increased sharply in the following 3½ decades, as it did, albeit to a much smaller extent, in Greece, Israel, and Spain; in all of these countries there is a clear deceleration in domestic R&D capital stocks after 1990. In general, the increase in domestic R&D capital over this period tended to be smallest in the largest countries, with the notable exceptions of Canada, Japan, and Spain. The slowest expansion of R&D capital was in the United Kingdom, Switzerland, and the Netherlands. Domestic R&D capital stocks display a clear, monotonic upward trend, as shown in Figure 2.



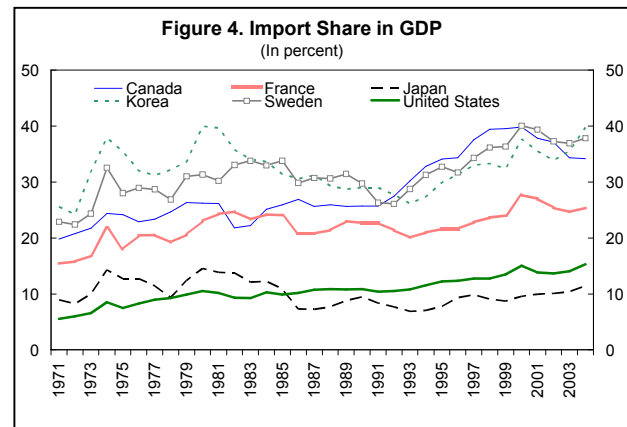
Not surprisingly, increases in foreign R&D capital stocks ( $S^{f-biw}$ ) are much more uniform across countries. This uniformity reflects (i) their construction as the bilateral-import weighted average of each countries' 23 trading partners' domestic R&D capital stocks, and (ii) the fact that the countries where increases in domestic R&D capital stocks were unusually large are also countries where bilateral import weights tend to be relatively small. The United States' foreign R&D capital stock increased the most, reflecting the fact that all other countries' foreign R&D capital includes the U.S. domestic R&D capital stock, often with relatively large weights, which increased relatively little in percentage terms. Similar factors explain why foreign R&D capital increased relatively little in Japan, Spain, and a number of continental European countries. The increase in foreign R&D capital is relatively smooth



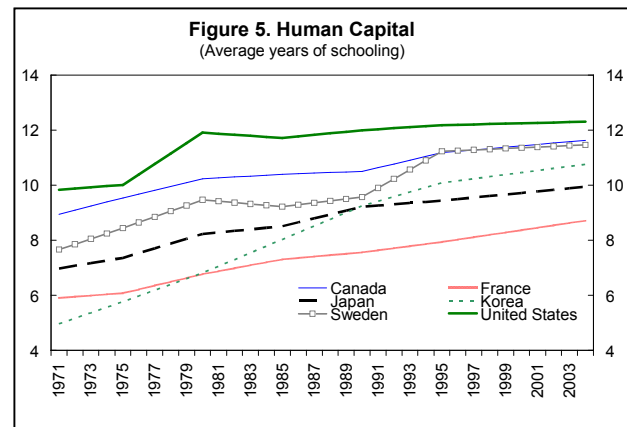
and, for most countries, monotonic, as shown in Figure 3. For comparison with other studies, alternative measures of foreign R&D capital have also been constructed based on the definition proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998) ( $S^{f-LP}$ ) and on a simple average ( $S^{f-avg}$ ); summary statistics for both are presented in appendix Table A6.



There is considerable diversity in imports of goods and services as a percent of GDP ( $m$ ), both in terms of levels—in 2004, the import share was about 80 percent in Belgium but only 10-15 percent in Japan and the United States—and in terms of changes from 1971-2004. On average import shares rose about 10 percentage points over this period. In Austria and Spain, however, the increase was about 18 percentage points, and in Belgium and Ireland it was about 30 percentage points. The import share declined from 1971-2004 in Iceland, Israel, and Norway, in the latter two countries by about 10 percentage points. Import shares have been relatively volatile, and for most countries there is little evidence of a trend, as is apparent in Figure 4.



Human capital ( $H$ ), proxied by average years of schooling, increased in all countries from 1971-2004. The largest increase over this period was in Korea and Portugal where the average years of schooling more than doubled from relatively low levels in 1971. In Australia and Belgium, where average years of schooling were already relatively high in 1971, the increase was less than one year. For many countries, the increase in human capital tended to be larger in the earlier part of the period, as shown in Figure 5.



### 3. Econometric Preliminaries

Panel cointegration techniques have become increasingly popular for a number of reasons. As with time series cointegration, estimates from a cointegrated panel are robust to a variety of problems that often plague empirical work, including endogeneity, omitted variables, and measurement error (Banerjee, 1999; Phillips and Moon, 2000; and Baltagi and Kao, 2000). Moreover, panel cointegration techniques can be implemented with shorter data spans than their time series counterparts and statistical inference is simplified because limiting distributions are standard normal.<sup>9</sup>

Before estimating the long-run cointegrating relationships, the relevant variables are pre-tested for unit roots and cointegration. We use so-called second-generation *panel unit root tests*, which are analogous to time-series augmented Dickey-Fuller tests. These tests allow for heterogeneous dynamics and include tests proposed by Levin, Lin, and Chu (2002, LLC) and Im, Pesaran, and Shin (2003, IPS). The null hypothesis for both of these tests is a unit root for each country  $i$ , but the tests differ in their assumption regarding the coefficient on the lagged level of the dependent variable (which is in first difference form),  $\rho_i$ , and the alternative hypothesis. The LLC test is a pooled panel (within-dimension) test that treats  $\rho_i$  as common across countries under both the null and alternative hypotheses. In contrast, the IPS test is a group mean (between-dimension) test that treats  $\rho_i$  as heterogeneous among countries under both the null and alternative hypotheses. In both cases the test is one-sided.

The LLC and IPS panel unit test results are presented in Table 2. The unit root tests are done for the three alternative definitions of foreign R&D capital and for a measure of patent protection (PP), which is one of the institutional variables discussed in Section 5. With the exception of the import share ( $m$ ) all variables, including the import share interacted with the alternative measures of the foreign R&D capital stocks, have a unit root, i.e., all are nonstationary.

	LLC	IPS
$\log F$	3.99	4.85
$\log S^d$	5.87	7.17
$\log S^{f-biw}$	2.73	2.57
$\log S^{f-LP}$	2.01	2.51
$\log S^{f-avg}$	3.53	4.75
$m$	-1.94 **	-1.36
$m \cdot \log S^{f-biw}$	0.39	-0.72
$m \cdot \log S^{f-LP}$	1.16	0.47
$m \cdot \log S^{f-avg}$	0.73	-0.24
$\log H$	2.19	2.14
$\log PP$	0.76	0.68

Notes: Columns LLC and IPS report the Levin-Lin-Chu (2002) and Im-Pesaran-Shin (2003) unit root tests. Significance levels at the 10, 5, and 1 percent levels for the one-tailed tests are indicated by \*, \*\*, and \*\*\*. The null hypothesis of a unit root is rejected if the test statistic is significant.

A number of *panel cointegration tests* have been proposed, analogous to time series cointegration tests (Pedroni, 2004).<sup>10</sup> The null hypothesis is that all of the countries in the

<sup>9</sup> This paper refers to panel cointegration as a stable long-run relation between the dependent variable and the independent variables in countries in a panel. This concept is distinct from cross-member cointegration whereby the dependent variable in one country is cointegrated with the dependent variable of another country in the panel (Evans, 1998).

<sup>10</sup> These differ from panel unit root tests due to the estimated regressor effect (Pedroni, 1999); panel cointegration tests coincide with residual-based panel unit root tests when cointegrating vectors are identical for all panel members and regressors are exogenous (Pedroni, 1995).

panel are not cointegrated; the alternative hypothesis is that all countries are cointegrated.<sup>11</sup> Similar to panel unit tests, panel cointegration tests come in two varieties: pooled (within dimension) tests and group mean tests. Monte Carlo simulations suggest that, while both varieties are conservative—rejecting the null hypothesis less than expected by the marginal significance level—at sample sizes such as the one in this study, pooled tests are less so. The degree of size distortion also depends on the specific test used, with t-type statistics being less conservative than rho-type statistics. Both tests are one-sided.

Panel cointegration tests corresponding to the panel analogues of the time series rho-statistic, t-statistic, and the ADF tests—Phillips and Perron (1988), Phillips and Ouliaris (1990), and Dickey and Fuller (1979)—are reported in Table 3. In the first two sets of panel unit root tests, pooled PP-rho tests reject the null hypothesis when the various measures of  $\log S^f$  are interacted with  $m$  but not when  $\log S^f$  is included alone. When  $\log H$  is added, however, the interaction with  $m$  is not required for cointegration. The same holds for the last two sets of tests when the variables are extended to also include  $\log PP$ . Regardless of the number of variables included in the tests, evidence of cointegration is found for both pooled and group mean tests. Taken together, cointegration typically requires including the interaction of  $m$  and  $\log S^f$ , and thus these models form the basis for the empirical results reported below.<sup>12</sup> These

Table 3. Panel Cointegration Tests  
(1971-2004, 24 countries)

	Pooled tests			Group mean tests		
	PP rho	PP	ADF	PP rho	PP	ADF
$\log TFP, \log S^d, \log S^{f-biw}$	-0.72	-1.19	-1.71 **	0.96	-0.20	-1.64 *
$\log TFP, \log S^d, \log S^{f-LP}$	-0.93	-1.48	-1.78 **	0.71	-0.55	-1.57 *
$\log TFP, \log S^d, \log S^{f-avg}$	-0.84	-1.35	-1.88 **	0.82	-0.39	-1.62 *
$\log TFP, \log S^d, m \cdot \log S^{f-biw}$	-1.79 **	-2.26 **	-3.75 ***	-0.12	-1.57 *	-3.85 ***
$\log TFP, \log S^d, m \cdot \log S^{f-LP}$	-1.46 *	-1.91 **	-2.03 ***	0.11	-1.19	-2.06 **
$\log TFP, \log S^d, m \cdot \log S^{f-avg}$	-2.41 ***	-3.17 ***	-4.43 ***	-0.98	-2.85 ***	-4.65 ***
$\log TFP, \log S^d, \log S^{f-biw}, \log H$	-1.71 **	-2.46 ***	-3.01 ***	-0.30	-2.05 **	-3.72 ***
$\log TFP, \log S^d, \log S^{f-LP}, \log H$	-1.45 *	-1.83 **	-2.53 ***	-0.17	-1.47 *	-3.73 ***
$\log TFP, \log S^d, \log S^{f-avg}, \log H$	-2.00 **	-2.80 ***	-3.37 ***	-0.46	-2.28 **	-4.45 ***
$\log TFP, \log S^d, m \cdot \log S^{f-biw}, \log H$	-1.49 *	-2.10 **	-1.71 **	-0.47	-1.94 **	-3.67 ***
$\log TFP, \log S^d, m \cdot \log S^{f-LP}, \log H$	-1.59 *	-2.22 **	-1.74 **	-0.57	-2.13 **	-3.59 ***
$\log TFP, \log S^d, m \cdot \log S^{f-avg}, \log H$	-1.54 *	-2.15 **	-1.72 **	-0.53	-2.01 **	-3.63 ***
$\log TFP, \log S^d, \log S^{f-biw}, \log H, \log PP$	-0.87	-2.42 ***	-2.90 ***	0.60	-2.04 **	-5.17 ***
$\log TFP, \log S^d, \log S^{f-LP}, \log H, \log PP$	-0.87	-2.42 ***	-2.90 ***	0.60	-2.04 **	-5.17 ***
$\log TFP, \log S^d, \log S^{f-avg}, \log H, \log PP$	-0.90	-2.45 ***	-3.14 ***	0.58	-2.02 **	-5.25 **
$\log TFP, \log S^d, m \cdot \log S^{f-biw}, \log H, \log PP$	-0.44	-1.68	-2.89 ***	1.16	-1.00	-3.61 ***
$\log TFP, \log S^d, m \cdot \log S^{f-LP}, \log H, \log PP$	-0.08	-1.01	-2.51 ***	1.32	-0.44	-3.64 ***
$\log TFP, \log S^d, m \cdot \log S^{f-avg}, \log H, \log PP$	-0.93	-2.70 ***	-3.66 ***	0.64	-2.26 **	-6.00 ***

Notes: Columns PP rho, PP, and ADF report the Philips-Perron rho tests, the Philips-Perron t-tests, and the augmented Dickey-Fuller tests. Significance levels at the 10, 5, and 1 percent levels for the one-tailed tests are indicated by \*, \*\*, and \*\*\*. The null hypothesis of no cointegration is rejected if the test statistic is significant.

<sup>11</sup> This assumption follows previous empirical work that assumes that R&D spillovers extend to all countries. If the data generating process does not imply that all countries cointegrate, then the alternative hypothesis would be that a substantial number of countries cointegrate.

<sup>12</sup> As a robustness check, estimates without the interaction are reported in the appendix.

results also suggest stable long-run relations can be estimated using either pooled or group mean estimation techniques.

In the following sections, we use pooled and group mean dynamic OLS (Kao and Chiang, 2000; Pedroni, 2001) to estimate long-run relationships. These single-equation methods extend to panel data the time-series dynamic OLS (DOLS) estimates proposed by Stock and Watson (1993).<sup>13</sup> Panel DOLS is fully parametric in their treatment of endogeneity and autocorrelation and, just as their time-series analogues, are asymptotically equivalent to full information maximum likelihood estimators. In pooled samples, Kao and Chiang (2000) found that panel DOLS have less size distortion than fully modified OLS for panels proposed by Pedroni (2000).

#### ***4. “International R&D Spillovers” Revisited***

Grossman and Helpman (1991) provide theoretical underpinnings for the empirical specifications used below with the aid of two canonic models of endogenous growth: the love of variety approach due to Romer (1990) and the quality ladders approach due to Grossman and Helpman (1991) and Aghion and Howitt (1992). In the love of variety approach an expansion of the range of available inputs raises total factor productivity, and investment in the development of new inputs raises the stock of knowledge, which reduces future R&D costs. As a result, there are spillovers from current R&D to future R&D activities. In an international context these spillovers cross national borders, implying that R&D of one country impacts not only the future R&D costs of domestic firms, but also the future R&D costs of foreign firms. The extent to which foreign firms benefit from these spillovers may depend on the economic relations between the countries, such as the volume of their bilateral trade or the characteristics of the traded products.

In the quality ladders approach an improvement in the quality of an input raises its productivity by a fixed proportional factor, which defines a rung size in the quality ladder. As a result, today’s improvement of a product enables future innovators to begin their own improvements from a higher quality level, and therefore contributes a larger *absolute* addition to the quality of the input at comparable costs. Consequently there are R&D spillovers. Naturally, these spillovers apply to all innovators who build on the quality of the available products, domestic and foreign alike. The degree to which foreign innovators can improve on a domestic product may depend, however, on the bilateral economic relations between the countries, as in the case of expanding variety. Grossman and Helpman (1994) discuss the application of these ideas to the construction of knowledge stocks, and argue that

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<sup>13</sup> Single-equation methods assume that the model can be expressed in triangular form so that normalizing the cointegration vector identifies the vector of interest. General vector error correction models (VECMs) with multiple equations are typically not feasible with panel data given the large number of parameters. Although restricted VECMs are feasible (Groen and Kleibergen, 2003), they are not used as often as the single-equation methods used here.

empirically observed investment rates in R&D can generate observed levels of total productivity growth in the United States. These insights guided the empirical specification in Coe and Helpman (1995), which we also adopt below.

Coe and Helpman (1995) estimated three specifications. The simplest is,

$$\log F_i = \alpha_i^0 + \alpha_i^d \log S_i^d + \alpha_i^f \log S_i^f + \varepsilon_i, \quad (1)$$

where  $i$  is a country index,  $F$  is total factor productivity,  $S^d$  is the real domestic R&D capital stock,  $S^f$  is the real foreign R&D capital stock, and  $\varepsilon$  is a well-defined error; time subscripts have been omitted. A second specification allows the impact of domestic R&D to differ between the largest seven economies and the others,

$$\log F_i = \alpha_i^0 + \alpha_i^d \log S_i^d + \alpha_i^{dG7} G7 \cdot \log S_i^d + \alpha_i^f \log S_i^f + \varepsilon_i, \quad (2)$$

where  $G7$  is a dummy variable equal to one for the G7 countries and zero otherwise. The third specification allows the impact of foreign R&D to vary with the level of imports by interacting the import share with the foreign R&D capital stock,

$$\log F_i = \alpha_i^0 + \alpha_i^d \log S_i^d + \alpha_i^{dG7} G7 \cdot \log S_i^d + \alpha_i^{fm} m_i \cdot \log S_i^f + \varepsilon_i, \quad (3)$$

where  $m$  is the share of imports in GDP.

Table 4 presents panel estimates of the three specifications.<sup>14</sup> The columns labeled *CH* report the OLS estimation results reported in CH based on pooled data for 1971-90 for 22 countries for each of the three specifications.<sup>15</sup> After the *CH* columns, dynamic OLS estimation results are reported using (i) the revised data for the same 1971-90 time period and for the same 22 countries, (ii) the updated data for 1971-2004 for the same 22 countries, and (iii) the updated data expanded to 24 countries. As in CH, all equations include unreported fixed effects, and foreign R&D capital is defined as a bilateral-import weighted average of trading partners domestic R&D capital. The equations estimated on the updated and expanded data set are cointegrated, as shown in Table 3.

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<sup>14</sup> As noted, the data for Germany are for West Germany until 1990 and for unified Germany thereafter. Excluding Germany makes virtually no difference compared with the reported estimation results, which include Germany.

<sup>15</sup> CH did not report standard errors for the OLS coefficient estimates because they are biased and their distribution is not asymptotically normal, although CH did note that the estimated standard errors were all small relative to the coefficient estimates, with t-statistics of four or larger.

Table 4. Specification in Coe and Helpman (1995) with Expanded Sample  
(DOLS, within, fixed effects)

years	1971-1990		1971-2004		1971-1990		1971-2004		1971-1990		1971-2004	
	22	22	22	24	22	22	22	24	22	22	22	24
number of countries	<i>CH</i>				<i>CH</i>				<i>CH</i>			
$\log S^d$	0.097	0.076	0.069	0.095	0.089	0.072	0.069	0.096	0.078	0.102	0.114	0.134
		<i>11.63</i>	<i>12.72</i>	<i>17.88</i>		<i>11.17</i>	<i>12.91</i>	<i>17.92</i>		<i>17.58</i>	<i>26.43</i>	<i>32.79</i>
$G7 \cdot \log S^d$					0.134	0.084	0.056	0.017	0.156	0.114	0.098	0.067
						<i>5.00</i>	<i>4.80</i>	<i>1.17</i>		<i>6.57</i>	<i>8.20</i>	<i>4.94</i>
$\log S^{f-biw}$	0.092	0.186	0.206	0.213	0.060	0.165	0.185	0.206				
		<i>11.37</i>	<i>17.00</i>	<i>15.68</i>		<i>10.06</i>	<i>14.46</i>	<i>14.13</i>				
$m \cdot \log S^{f-biw}$									0.294	0.041	0.045	0.065
										<i>6.45</i>	<i>8.85</i>	<i>12.58</i>
Standard error	0.049	0.004	0.006	0.009	0.046	0.004	0.006	0.009	0.044	0.004	0.007	0.010
$R^2$	0.56	0.84	0.76	0.81	0.62	0.85	0.77	0.81	0.65	0.83	0.73	0.80
$R^2$ adjusted	0.53	0.83	0.75	0.80	0.60	0.84	0.76	0.80	0.63	0.82	0.72	0.79
annual observations	20	20	34	34	20	20	34	34	20	20	34	34
pooled observations	440	440	748	816	440	440	748	816	440	440	748	816

Notes: The dependent variable is  $\log(\text{total factor productivity})$ . Columns labelled *CH* are the OLS regression results reported in Coe and Helpman (1995). T-statistics in italics below coefficient estimates.

Dynamic OLS estimates on the revised data for the same time period and countries give broadly comparable results to those reported in CH. The estimated coefficients on  $\log S^d$  are similar to those in CH, but the estimated coefficients on  $\log S^{f-biw}$  increase substantially in the first two specifications. The coefficients on  $m \cdot \log S^{f-biw}$  in the third specification are not comparable since  $S^{f-biw}$  was transformed into an index in CH, as discussed above, whereas  $S^{f-biw}$  is not transformed in the new results reported here. Standard errors are smaller by a factor of about 0.1, which mainly reflects that total factor productivity, the dependent variable, is indexed on a more recent base year, implying that the mean of the dependent variable is smaller in the updated data set than in CH. When the sample is extended to 2004 and to 24 countries, the main changes are that the estimated coefficients on  $G7 \cdot \log S^d$  decline sharply, becoming insignificant in the second specification when the sample is extended to 24 countries; the elasticities of TFP with respect to foreign R&D capital increase; and the elasticity with respect to domestic R&D capital tends to fall in the G7 countries but increase in the non-G7 countries.

These estimates confirm the key empirical results from CH. Econometric techniques not available in the early 1990s indicate that there is robust evidence that total factor productivity, domestic R&D capital, and foreign R&D capital are cointegrated, and that both measures of R&D capital are significant determinants of TFP. Broadly consistent results are obtained from a revised data set for the same time period and countries used by CH and for the updated and expanded dataset.

The specifications in CH focus on domestic and foreign R&D capital as the key long-run determinants of TFP, consistent with the theoretical model. Another important determinant of productivity is human capital (Engelbrecht, 1997). Including a measure of human capital becomes more important as the time period is lengthened, since for most economically advanced countries measures of human capital tend to change slowly, and as countries such as Korea, which have invested heavily in human capital formation since the early 1970s, are included in the analysis.<sup>16</sup> This is confirmed by regressions on the updated and expanded dataset, which indicate that human capital is cointegrated with TFP and domestic and foreign R&D capital, and that human capital is a significant determinant of TFP under a variety of specifications. From a broader perspective, other theoretical models would suggest a number of additional determinants of TFP, as emphasized by Khan and Luintel (2006), although lack of data availability precluded the inclusion of many potential candidates in this study.<sup>17</sup>

Table 5 presents estimates including the logarithm of human capital ( $H$ ) as an additional explanatory variable, and compares dynamic OLS within estimates, i.e., DOLS estimates on the pooled data, with DOLS mean group estimates. As noted, the estimated coefficients on human capital are highly significant in all specifications and with both estimation techniques.

Table 5. Dynamic OLS Within and Mean Group Estimates with Human Capital (1971-2004, 24 countries)

	within	mge	within	mge	within	within
$\log S^d$	0.098 <i>6.13</i>	0.144 <i>30.13</i>	0.066 <i>3.15</i>	0.195 <i>23.49</i>	0.062 <i>3.14</i>	0.095 <i>6.20</i>
$G7 \cdot \log S^d$					-0.019 <i>-1.23</i>	0.012 <i>0.63</i>
$\log S^{f-biw}$	0.035 <i>3.14</i>	0.018 <i>9.47</i>			0.121 <i>5.05</i>	
$m \cdot \log S^{f-biw}$			0.116 <i>5.11</i>	0.018 <i>1.91</i>		0.042 <i>3.27</i>
$\log H$	0.725 <i>8.33</i>	0.523 <i>6.16</i>	0.747 <i>9.88</i>	0.513 <i>7.28</i>	0.756 <i>9.83</i>	0.695 <i>7.81</i>
Standard error	0.092	0.018	0.089	0.019	0.088	0.091
$R^2$	0.76	0.94	0.78	0.94	0.78	0.77
$R^2$ adjusted	0.76	0.93	0.77	0.93	0.78	0.77

Notes: The dependent variable is  $\log(\text{total factor productivity})$ . T-statistics in italics below coefficient estimates. Within estimates include fixed effects.

<sup>16</sup> Coe *et al.* (1997) include human capital in their analysis of R&D spillovers from developed countries in the north to developing countries in the south.

<sup>17</sup> We did include measures of publicly financed R&D, distance to frontier, and a variety of other variables, but did not find that these were significant or robust determinants of total factor productivity in our data set.

The DOLS within estimates include regressions comparable to the three specifications reported in Table 4. Including  $\log H$  reduces the size of the estimated coefficients on  $\log S^{f-biw}$ , but not on  $m \cdot \log S^{f-biw}$ , and makes the estimated coefficients on  $G7 \cdot \log S^d$  insignificant; all other estimated coefficients remain highly significant.<sup>18</sup>

The mean group estimates, which are based on DOLS time-series estimates for each country, are broadly similar to the DOLS within estimates, with all of the estimated coefficients remaining correctly signed and significant. The main differences are that, compared with the “within” estimates, in the mean group estimates the estimated coefficients on  $\log S^d$  are larger while the coefficients on  $\log S^{f-biw}$  and on  $m \cdot \log S^{f-biw}$  are smaller, and the measures of goodness of fit are better. Of course, the MGE results are averages of the estimated equations for the individual countries, each of which are only based on 34 annual observations, and some of the estimated coefficients in these country-specific equations are incorrectly signed or insignificant, or both.

Foreign R&D capital in the results presented thus far is defined as a bilateral import share weighted average of the domestic R&D capital stocks of trading partners ( $S^{f-biw}$ ), as in CH. Table 6 presents estimation results using two alternative definitions: bilateral imports as the fraction of trading partners’ output multiplied by trading partners’ domestic R&D capital

Table 6. Alternative Definitions of Foreign R&D Capital  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.098 <i>6.13</i>	0.095 <i>6.04</i>	0.098 <i>6.10</i>	0.098 <i>6.15</i>	0.087 <i>5.61</i>	0.090 <i>5.67</i>
$m \cdot \log S^{f-biw}$	0.035 <i>3.14</i>			0.226 <i>2.20</i>		-0.025 <i>-0.63</i>
$m \cdot \log S^{f-LP}$		0.052 <i>3.33</i>			0.194 <i>2.62</i>	0.098 <i>1.76</i>
$m \cdot \log S^{f-avg}$			0.037 <i>2.97</i>	-0.205 <i>-1.81</i>	-0.104 <i>-1.76</i>	
$\log H$	0.725 <i>8.33</i>	0.708 <i>8.08</i>	0.718 <i>8.13</i>	0.765 <i>8.83</i>	0.685 <i>7.78</i>	0.676 <i>7.84</i>
Standard error	0.092	0.091	0.092	0.092	0.090	0.090
$R^2$	0.76	0.76	0.76	0.76	0.77	0.77
$R^2$ adjusted	0.76	0.76	0.76	0.76	0.77	0.77

Notes: The dependent variable is  $\log(\text{total factor productivity})$ . T-statistics in italics below coefficient estimates.

<sup>18</sup> Experiments entering  $\log H$  interacted with either  $\log S^d$ ,  $\log S^{f-biw}$ , or  $m \cdot \log S^{f-biw}$  did not yield results that were correctly signed and significant across a variety of specifications.



( $S^{f-LP}$ ), as proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998), and a simple average of trading partners' domestic R&D capital ( $S^{f-avg}$ ). To keep the presentation concise, results are only presented for the specification with the import share interacted with foreign R&D capital; estimation results for the specification with foreign R&D capital not interacted with import shares are presented in appendix Table A1.

Regression estimates using either of the three definitions are very similar, as shown in the first three columns of Table 6. When  $m \cdot \log S^{f-biw}$  or  $m \cdot \log S^{f-LP}$  is included in the same regression with  $m \cdot \log S^{f-avg}$ , the estimated coefficients on the former remain significant while the coefficients on the latter become negative and insignificant. While this mainly reflects multi-colinearity, it also suggests that the definition of foreign R&D capital based on either bilateral import shares or the definition proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998), which is also based on bilateral imports, perform somewhat better than the definition based on a simple average. When  $m \cdot \log S^{f-biw}$  and  $m \cdot \log S^{f-LP}$  are included in the same regression, the estimated coefficients become negative or insignificant. However, in the alternative specification without the interaction with the import share, the estimated coefficient on  $\log S^{f-biw}$  remains significant whereas the coefficient on  $\log S^{f-LP}$  is insignificant, as shown in the final regression in Table A1. Our interpretation of these results is that foreign R&D capital defined with bilateral-import weights ( $S^{f-biw}$ ) performs somewhat better than the definition proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998) ( $S^{f-LP}$ ), both of which perform much better than a simple average. In the next section, we only report results with foreign R&D capital defined with bilateral-import weights; results based on the LP measure are broadly similar.

## ***5. Institutions and International R&D Spillovers***

Institutions are increasingly viewed as key determinants of total factor productivity and, hence, of economic growth. In this section we test if the estimated parameters on domestic and foreign R&D capital and on human capital vary among countries according to various proxies for institutions. Thus we seek to account for heterogeneity based country-specific institutions rather than by estimating country-specific parameters based on limited time-series observations.

We focus on four institutions that have been emphasized in the literature:<sup>19</sup>

- The ease of doing business, which is an average ranking of countries according to the ease of doing the following ten actions: starting a business, dealing with licenses, employing workers, registering property, getting credit, protecting investors, paying

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<sup>19</sup> We also tested for the importance of various other institutions, such as measures of financial development, labor market institutions, governance, and ease of trading across borders, but did not find significant differences in the estimated coefficients.

- taxes, trading across borders, enforcing contracts, and closing a business (World Bank, 2007).
- The quality of tertiary education, which is a composite measure of the extent to which tertiary institutions have: freedom to manage resources, including the selection of students, autonomy to decide on the sources and structure of funding, and staff personnel policies; freedom in setting objectives, including deciding on course content; and are accountable, including various types of evaluation (Oliveira Martins *et al.*, 2007).<sup>20</sup>
  - The strength of intellectual property rights, as measured by an index of patent protection (Park and Lippoldt, 2005).
  - The origins of legal systems in either French, German, Scandinavian, or English law (La Porta *et al.*, 1999; La Porta *et al.*, 2008).

Table 7. Institutional Variables

	Ease of doing business			Quality of tertiary education		Patent protection		Legal origins
	WB rank	rank in 24	rank	value	rank	1971	2004	
Australia	8	6	Hi	7.83	Hi	2.04	4.17	English
Austria	30	19	Lo	6.24	Mid	2.64	4.33	German
Begium	20	14	Mid	5.89	Lo	3.07	4.67	French
Canada	4	3	Hi	6.88	Mid	2.91	4.67	English
Denmark	7	5	Hi	6.66	Mid	2.50	4.67	Scandinavian
Finland	14	12	Mid	6.98	Hi	2.30	4.64	Scandinavian
France	35	20	Lo	5.42	Lo	3.23	4.67	French
Germany	21	15	Mid	4.95	Lo	3.01	4.50	German
Greece	109	24	Lo	3.01	Lo	2.33	4.23	French
Iceland	12	10	Mid	6.21	Mid	1.67	3.48	Scandinavian
Ireland	10	8	Hi	6.90	Hi	2.20	4.67	English
Israel	26	18	Lo	n.a.	Mid	2.94	4.13	English
Italy	82	23	Lo	6.18	Lo	2.82	4.67	French
Japan	11	9	Mid	7.46	Hi	2.48	4.67	German
Korea	23	17	Lo	6.90	Hi	2.15	4.29	German
Netherlands	22	16	Mid	6.18	Lo	3.30	4.67	French
New Zealand	2	1	Hi	7.85	Hi	2.70	4.01	English
Norway	9	7	Hi	6.18	Lo	2.47	4.13	Scandinavian
Portugal	40	22	Lo	6.54	Mid	1.33	4.30	French
Spain	39	21	Lo	6.31	Mid	2.61	4.33	French
Sweden	13	11	Mid	6.46	Mid	2.58	4.54	Scandinavian
Switzerland	15	13	Mid	5.66	Lo	2.80	4.33	German
United Kingdom	6	4	Hi	7.53	Hi	2.66	4.54	English
United States	3	2	Hi	6.88	Hi	3.83	4.88	English
Average			Mid	6.40	Mid	2.61	4.42	
Standard deviation				1.03		0.53	0.31	

Notes: For ease of doing business (World Bank, 2007) and quality of tertiary education (Oliveira Martins, *et al.*, 2007) rank indicates if country is in the top (Hi), middle (Mid), or bottom (Lo) third of the 24 countries. An estimate of the quality of tertiary education is not available for Israel, which is assumed to be in the middle category. Patent protection (Park and Lippoldt, 2005) is an index with values from 1 (low) to 5.

<sup>20</sup> Values for Belgium, Canada, and the United States are population-weighted averages of the, respectively, linguistic, provincial, and state groups reported in Oliveira Martins *et al.* (2007). An estimate of the quality of tertiary education is not available for Israel, which is assumed to be in the middle group in Table 7.

Each of these institutional variables could potentially affect the degree to which domestic and foreign R&D capital affects total factor productivity. In the quality ladders approach, for example, a given R&D effort could result in larger quality improvements in countries where the quality of tertiary education is relatively high since these countries may produce more productive researchers than other countries. Similarly countries where the ease of doing business is relatively high or intellectual property rights are well protected may encourage more entrepreneurial R&D that results in larger quality improvements for a given R&D effort. Different legal systems may also affect the type or productivity of R&D.

The values for the institutional variables are reported in Table 7. Except for the index of patent protection, the other measures of institutions are either time invariant or not available as a time series. Although for most countries, changes over time in the ease of doing business and the quality of tertiary education are likely to be modest at best, they are not necessarily constant. However, our tests only assume that the rankings across countries of these two institutional variables remain constant over time: we do this by dividing the sample into groups of eight countries with the highest, middle, and lowest rank or score, and use these rankings to define dummy variables (*Hi*, *Lo*) that are interacted with the determinants of total factor productivity.

Estimation results for the ease of doing business are reported in Table 8. To facilitate comparisons, the first regression in the table is identical to the first regression in Table 6. The estimated coefficients on the interaction of the *Hi* ease of doing business dummy and each of the determinants of TFP is positive and highly significant. Thus countries where it is

Table 8. Ease of Doing Business  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.098 <i>6.13</i>	0.068 <i>4.79</i>	0.061 <i>4.15</i>	0.089 <i>6.16</i>
$m \cdot \log S^f$	0.035 <i>3.14</i>	0.031 <i>3.00</i>	0.040 <i>4.18</i>	0.042 <i>3.83</i>
$\log H$	0.725 <i>8.33</i>	0.741 <i>10.32</i>	0.878 <i>11.12</i>	0.683 <i>5.44</i>
	$Hi \cdot \log S^d$	0.101 <i>4.36</i>	$Hi \cdot m \cdot \log S^f$	0.047 <i>2.52</i>
			$Hi \cdot \log H$	0.442 <i>3.02</i>
	$Lo \cdot \log S^d$	-0.007 <i>-0.43</i>	$Lo \cdot m \cdot \log S^f$	-0.040 <i>-2.40</i>
			$Lo \cdot \log H$	-0.108 <i>-0.92</i>
Standard error	0.092	0.080	0.083	0.083
$R^2$	0.76	0.82	0.80	0.80
$R^2$ adjusted	0.76	0.81	0.80	0.80
<i>Memo:</i>				
Coefficient	Hi	$\log S^d$ 0.169	$m \cdot \log S^f$ 0.087	$\log H$ 1.125
ranges	Lo	$\log S^d$ 0.061	$m \cdot \log S^f$ 0	$\log H$ 0.575

Notes: The dependent variable is  $\log$  (total factor productivity).  $S^f$  is defined using bilateral import weights. *Hi* and *Lo* are dummy variables for the ease of doing business, defined in Table 7. T-statistics in italics below coefficient estimates.

relatively easy to do business—i.e., the top third countries in the ranking in Table 7—benefit more from their own R&D efforts, from international R&D spillovers, and from their own investment in human capital formation than do other countries. Conversely, countries where it is relatively hard to do business benefit less from their own R&D efforts and investment in human capital and significantly less from international R&D spillovers than do countries ranked in either the middle or the high group. Indeed, the estimates suggest that countries where the ease of doing business is lowest do not benefit at all from international R&D spillovers. It is clear that country differences in the ease of doing business imply substantial heterogeneity in the estimated coefficients, as summarized in the memorandum items in Table 8 reporting the highest and lowest estimated coefficients for each variable.

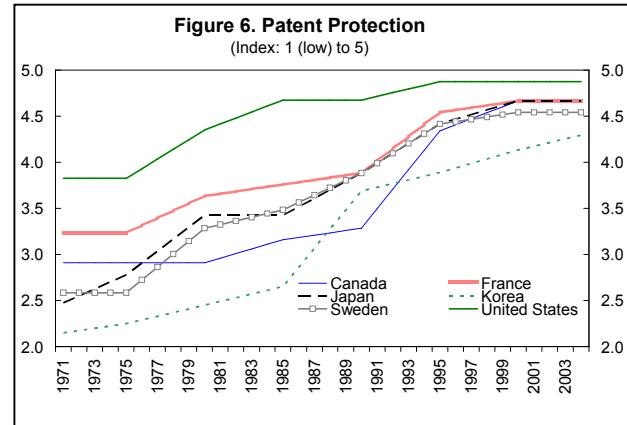
Broadly similar results are obtained for the quality of tertiary education, as shown in Table 9. Countries where the quality of tertiary education is relatively high benefit more from their own R&D efforts, from international R&D spillovers, and from their own investment in human capital formation than do other countries. Indeed, these estimates imply that only countries where the quality of tertiary education is in the highest one-third benefit from international R&D spillovers, with countries in the middle and lowest group deriving no significant benefits from foreign R&D. There is also no significant difference between the middle and the lowest group in terms of the impact of own R&D and human capital. Differences in the quality of tertiary education also imply substantial heterogeneity in the estimated coefficients.

Table 9. Quality of Tertiary Education Systems  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.098 <i>6.13</i>	0.067 <i>6.25</i>	0.072 <i>5.54</i>	0.082 <i>6.95</i>			
$m \cdot \log S^f$	0.035 <i>3.14</i>	0.036 <i>3.47</i>	0.012 <i>1.14</i>	0.040 <i>4.10</i>			
$\log H$	0.725 <i>8.33</i>	0.698 <i>7.94</i>	0.813 <i>11.37</i>	0.488 <i>5.29</i>			
	$Hi \cdot \log S^d$	0.102 <i>7.84</i>	$Hi \cdot m \cdot \log S^f$	0.101 <i>6.95</i>			
			$Hi \cdot \log H$	0.939 <i>9.33</i>			
	$Lo \cdot \log S^d$	-0.013 <i>-0.53</i>	$Lo \cdot m \cdot \log S^f$	0.012 <i>0.75</i>			
			$Lo \cdot \log H$	0.201 <i>1.66</i>			
Standard error	0.092	0.088	0.082	0.087			
$R^2$	0.76	0.78	0.81	0.79			
$R^2$ adjusted	0.76	0.78	0.81	0.78			
<i>Memo:</i>							
Coefficient	Hi	$\log S^d$	0.169	$m \cdot \log S^f$	0.113	$\log H$	1.427
ranges	Lo	$\log S^d$	0.054	$m \cdot \log S^f$	0.012	$\log H$	0.488

Notes: The dependent variable is  $\log(\text{total factor productivity})$ .  $S^f$  is defined using bilateral import weights.  $Hi$  and  $Lo$  are dummy variables for the quality of tertiary education, defined in Table 7. T- statistics in italics below coefficient estimates.

There has been a strengthening of intellectual property rights over the past 3½ decades in all of the countries in our sample, as shown in Table 7 and Figure 6. In general, the variance across countries is not large, and the strengthening over time has been most pronounced among countries where patent protection was initially weakest. In 1971 the index of patent protection averaged 2.61, on a scale of 1 to 5, and ranged from a low of 1.33 in Portugal to a high of 3.83 in the United States. By 2004 the average had increased to 4.42 and the range had narrowed to a low of 3.48 in Iceland and to a high of 4.88 in the United States.



Patent protection is a significant additional determinant of total factor productivity, as shown in the second regression in Table 10. Patent protection might also affect TFP through its impact on R&D: by encouraging innovators to work on risky projects where the potential return is higher, for example, strengthened patent protection may result in an R&D capital stock that has a larger impact on TFP. This is supported in the third and fourth regressions in Table 10, which suggest that countries where patent protection is relatively strong tend to benefit more from a given level of domestic and, to a lesser extent, foreign R&D capital compared with countries where patent protection is relatively weak.<sup>21</sup> Given that the

Table 10. Patent Protection  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.098 <i>6.13</i>	0.056 <i>4.86</i>	0.043 <i>4.04</i>	0.057 <i>5.84</i>	0.042 <i>3.66</i>
$m \cdot \log S^f$	0.035 <i>3.14</i>	0.031 <i>4.19</i>	0.026 <i>3.25</i>	0.022 <i>2.66</i>	0.027 <i>3.31</i>
$\log H$	0.725 <i>8.33</i>	0.452 <i>7.48</i>	0.413 <i>7.55</i>	0.402 <i>7.20</i>	0.415 <i>7.51</i>
$\log PP$		0.251 <i>6.52</i>			
$PP \cdot \log S^d$			0.008 <i>8.86</i>		0.009 <i>2.48</i>
$PP \cdot m \cdot \log S^f$				0.008 <i>8.63</i>	-0.001 <i>-0.23</i>
Standard error	0.092	0.083	0.081	0.081	0.081
$R^2$	0.76	0.80	0.81	0.81	0.81
$R^2$ adjusted	0.76	0.80	0.81	0.81	0.81

Notes: The dependent variable is  $\log(\text{total factor productivity})$ .  $S^f$  is defined using bilateral import weights. T-statistics in italics below coefficient estimates.

<sup>21</sup> If patent protection is included in the same regression with either or both of the capital stocks interacted with patent protection, it was either insignificant or incorrectly signed.

differences in patent protection across countries is not large, and that patent protection has strengthened and converged, the heterogeneity of the estimated coefficients implied by the last three equations in Table 10 is not large and decreases over time. In the fourth equation, for example, the range of the lowest and highest estimated coefficients on  $m \cdot \log S^f$  is about 0.03-0.05 in 1971 and 0.05-0.06 in 2004.

Countries with different legal systems may offer different degrees of investor protection, including patent protection, which could be reflected in the estimated coefficients on R&D capital. To test for this, dummy variables for countries whose legal systems originate in French (*Fr*), German, and Scandinavian (*Sc*) law (cf. Table 7) were interacted with the domestic and foreign R&D capital stocks.<sup>22</sup> The estimated coefficients for countries with legal systems based on German law were not significantly different from those based on English law. The results reported in Table 11 suggest that countries with French- and Scandinavian-based legal systems benefit less from a given level of domestic R&D capital than other countries. This result comes through strongly in the basic specification as well as in specifications where patent protection enters separately or interacted with the domestic

Table 11. Legal Origins and Patent Protection  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.098 <i>6.13</i>	0.113 <i>7.84</i>	0.094 <i>5.91</i>	0.080 <i>4.21</i>	0.060 <i>5.38</i>	0.072 <i>3.32</i>	0.060 <i>2.83</i>
$m \cdot \log S^f$	0.035 <i>3.14</i>	0.054 <i>5.00</i>	0.046 <i>3.44</i>	0.047 <i>4.16</i>	0.051 <i>6.06</i>	0.044 <i>3.48</i>	0.043 <i>3.35</i>
$\log H$	0.725 <i>8.33</i>	0.950 <i>12.55</i>	0.726 <i>7.96</i>	0.831 <i>10.10</i>	0.474 <i>8.47</i>	0.816 <i>11.05</i>	0.799 <i>11.00</i>
$\log PP$				0.162 <i>3.39</i>	0.242 <i>6.63</i>		
$PP \cdot \log S^d$						0.005 <i>3.53</i>	0.006 <i>4.55</i>
$Fr \cdot \log S^d$		-0.154 <i>-9.95</i>		-0.154 <i>-10.24</i>		-0.147 <i>-9.40</i>	$PP \cdot Fr \cdot \log S^d$ -0.042 <i>-8.30</i>
$Sc \cdot \log S^d$		-0.052 <i>-3.88</i>		-0.048 <i>-3.51</i>		-0.037 <i>-2.53</i>	$PP \cdot Sc \cdot \log S^d$ -0.011 <i>-2.07</i>
$Fr \cdot m \cdot \log S^f$			-0.048 <i>-1.14</i>		-0.056 <i>-4.25</i>		
$Sc \cdot m \cdot \log S^f$			-0.001 <i>-0.02</i>		-0.068 <i>-4.31</i>		
Standard error	0.092	0.084	0.090	0.076	0.081	0.076	0.076
$R^2$	0.76	0.80	0.77	0.83	0.81	0.84	0.84
$R^2$ adjusted	0.76	0.80	0.77	0.83	0.81	0.84	0.84

Notes: The dependent variable is  $\log(\text{total factor productivity})$ .  $S^f$  is defined using bilateral import weights. *Fr* and *Sc* are dummy variables for countries whose legal origins are French and Scandinavian, respectively, defined in Table 7. T-statistics in italics below coefficient estimates.

<sup>22</sup> We found no evidence that the estimated coefficients on foreign R&D capital were different for trading partners with the same legal origin than for trading partners with different legal origins.

R&D capital stock. The estimated coefficients on foreign R&D capital interacted with the legal origins dummies are only significant in the specification where patent protection enters as a separate variable (compare columns 3 and 5). For countries with Scandinavian-based legal systems, the results suggest that the coefficient on domestic R&D capital is reduced by about one-half. For countries with French-based legal systems, however, the estimated coefficients imply that both domestic and foreign R&D capital have essentially no significant impact on total factor productivity.<sup>23</sup> Thus legal origins in French and, to a lesser extent, Scandinavian law imply considerable heterogeneity in parameters compared with countries with legal origins in English or German law.

## 6. Conclusions

The key results reported in Coe and Helpman (1995) are, in general, confirmed by estimation on an updated and expanded database using modern panel cointegration techniques not available in the early 1990s. There is robust evidence that total factor productivity, domestic R&D capital, and foreign R&D capital are cointegrated, and that both measures of R&D capital are significant determinants of TFP. Although not included in CH's analysis, there is strong evidence that human capital is also cointegrated and is an additional significant determinant of TFP, as emphasized by Engelbrecht (1997). Including human capital does, however, change the result in CH that the estimated coefficient on the domestic R&D capital stock is significantly higher in the G7 countries than in other countries. Regressions using the definition of foreign R&D capital based on either bilateral import shares, as in CH, or the definition proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998), which is also based on bilateral imports, perform equally well, and better than the definition based on a simple average.

When the equations are estimated individually for each country, the DOLS mean group estimates give broadly similar results to the DOLS estimates on the pooled data, although the estimated coefficients on foreign R&D capital decline substantially while those on domestic R&D capital rise somewhat. These two estimation techniques are based on extreme assumptions about parameter heterogeneity: the pooled estimates assume homogeneity, except for fixed effects, whereas the mean group estimates allow complete heterogeneity, albeit based on limited time-series observations.

We address the issue of parameter heterogeneity by extending the empirical analysis in Coe and Helpman (1995) to examine institutional sources of heterogeneity. We find evidence that countries where the ease of doing business and the quality of tertiary education systems are relatively high tend to benefit more from their own R&D efforts, from international R&D

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<sup>23</sup> The estimated coefficients on  $Fr \cdot \log S^d$  or  $Fr \cdot m \cdot \log S^f$  are negative and greater in absolute value than the estimated coefficients on  $\log S^d$  or  $m \cdot \log S^f$ , although the sums of the two coefficients may not be significantly different from zero.

spillovers, and from human capital formation. We also find that strong patent protection is associated with higher levels of total factor productivity, higher returns to domestic R&D, and larger international R&D spillovers. Finally, we find evidence that countries whose legal systems are based on French and, to a lesser extent, Scandinavian law benefit less from their own and foreign R&D capital than countries whose legal origins are based on English or German law.

These results on the importance of institutions are consistent with the broader growth literature emphasizing the importance of institutions for economic growth and suggest specific channels through which institutions may affect TFP and growth. A fruitful area for future research would be to extend the analysis in Coe, Helpman, and Hoffmaister (1997) to examine the role of institutions in explaining why some developing countries benefit more than others from international R&D spillovers from advanced countries.



## Appendix A: Alternative Specification

Regression results comparable to those presented in Table 6 and Tables 8-11 but based on an alternative specification where foreign R&D capital ( $\log S^f$ ) is not interacted with the import share ( $m$ )—i.e., based on equation (2) rather than equation (3), but without the  $G7$  dummy interacted with  $\log S^d$ —are presented in Tables A1-A5. In general, the results are similar to those discussed in the main text, although there are some noteworthy differences:

- In the alternative specification, foreign R&D capital defined with bilateral import shares ( $S^{f-biw}$ ) dominates foreign R&D capital defined as proposed by Lichtenberg and van Pottelsberghe de la Potterie (1998) ( $S^{f-LP}$ ) when both are entered in the same equation, whereas both were insignificant in the specification reported in the text (cf. the fourth equations in Tables 6 and A1).
- The evidence of a significantly lower coefficient on foreign R&D capital in countries where the ease of doing business is lowest is absent in the alternative specification (cf. the third equations in Tables 8 and A2).
- In the alternative specification, there is evidence of a significantly lower coefficient on foreign R&D capital in countries whose legal origins are French (cf. the third equations in Tables 11 and A5) and Scandinavian (cf. the fifth equations in Tables 11 and A5).

Table A1. Alternative Definitions of Foreign R&D Capital:  
Alternative Specification  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.066 <i>3.15</i>	0.083 <i>4.01</i>	0.079 <i>3.26</i>	0.074 <i>3.25</i>	0.078 <i>3.39</i>	0.061 <i>2.99</i>
$\log S^{f-biw}$	0.116 <i>5.11</i>			0.184 <i>3.81</i>		0.096 <i>3.61</i>
$\log S^{f-LP}$		0.082 <i>3.72</i>			0.074 <i>2.25</i>	0.035 <i>1.37</i>
$\log S^{f-avg}$			0.087 <i>2.82</i>	-0.109 <i>-1.74</i>	0.016 <i>0.36</i>	
$\log H$	0.747 <i>9.88</i>	0.627 <i>6.89</i>	0.670 <i>7.44</i>	0.870 <i>8.99</i>	0.615 <i>6.70</i>	0.680 <i>8.22</i>
Standard error	0.089	0.093	0.091	0.091	0.091	0.088
$R^2$	0.78	0.75	0.76	0.76	0.76	0.78
$R^2$ adjusted	0.77	0.75	0.76	0.76	0.76	0.78

Notes: The dependent variable is  $\log(\text{total factor productivity})$ . T-statistics in italics below coefficient estimates.

Table A2. Ease of Doing Business: Alternative Specification  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.066 <i>3.15</i>	0.055 <i>5.94</i>	0.065 <i>3.44</i>	0.07 <i>3.56</i>		
$\log S^f$	0.116 <i>5.11</i>	0.077 <i>4.96</i>	0.070 <i>2.36</i>	0.092 <i>3.92</i>		
$\log H$	0.747 <i>9.88</i>	0.691 <i>15.77</i>	0.753 <i>10.27</i>	0.646 <i>5.17</i>		
	<i>Hi</i> · $\log S^d$	0.105 <i>6.24</i>	<i>Hi</i> · $\log S^f$	0.080 <i>2.22</i>	<i>Hi</i> · $\log H$	0.393 <i>2.46</i>
	<i>Lo</i> · $\log S^d$	-0.013 <i>-1.35</i>	<i>Lo</i> · $\log S^f$	0.013 <i>0.37</i>	<i>Lo</i> · $\log H$	0.026 <i>0.23</i>
Standard error	0.089	0.080	0.086	0.085		
$R^2$	0.78	0.82	0.79	0.79		
$R^2$ adjusted	0.77	0.81	0.79	0.79		

*Memo:*

Coefficient	<i>Hi</i>	$\log S^d$	0.160	$\log S^f$	0.150	$\log H$	1.039
ranges	<i>Lo</i>	$\log S^d$	0.042	$\log S^f$	0.070	$\log H$	0.646

Notes: The dependent variable is  $\log$  (total factor productivity).  $S^f$  is defined using bilateral import weights. *Hi* and *Lo* are dummy variables for the ease of doing business, defined in Table 7. T-statistics in italics below coefficient estimates.

Table A3. Quality of Tertiary Education Systems: Alternative Specification  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.079 <i>3.26</i>	0.037 <i>2.63</i>	0.074 <i>3.53</i>	0.058 <i>3.27</i>		
$\log S^f$	0.087 <i>2.82</i>	0.110 <i>4.83</i>	0.014 <i>0.33</i>	0.089 <i>3.43</i>		
$\log H$	0.670 <i>7.44</i>	0.742 <i>10.29</i>	0.715 <i>9.42</i>	0.620 <i>7.29</i>		
	<i>Hi</i> · $\log S^d$	0.100 <i>7.20</i>	<i>Hi</i> · $\log S^f$	0.169 <i>4.20</i>	<i>Hi</i> · $\log H$	0.832 <i>7.28</i>
	<i>Lo</i> · $\log S^d$	-0.022 <i>-1.10</i>	<i>Lo</i> · $\log S^f$	0.051 <i>1.20</i>	<i>Lo</i> · $\log H$	0.042 <i>0.35</i>
Standard error	0.091	0.084	0.085	0.086		
$R^2$	0.76	0.80	0.79	0.79		
$R^2$ adjusted	0.76	0.80	0.79	0.79		

*Memo:*

Coefficient	<i>Hi</i>	$\log S^d$	0.137	$\log S^f$	0.183	$\log H$	1.452
ranges	<i>Lo</i>	$\log S^d$	0.015	$\log S^f$	0.014	$\log H$	0.620

Notes: The dependent variable is  $\log$  (total factor productivity).  $S^f$  is defined using bilateral import weights. *Hi* and *Lo* are dummy variables for the quality of tertiary education, defined in Table 7. T-statistics in italics below coefficient estimates.

Table A4. Patent Protection: Alternative Specification  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.066 <i>3.15</i>	0.035 <i>2.99</i>	0.035 <i>3.33</i>	0.048 <i>4.76</i>	0.045 <i>3.43</i>
$\log S^f$	0.116 <i>5.11</i>	0.1 <i>7.13</i>	0.055 <i>2.94</i>	0.051 <i>2.65</i>	0.051 <i>2.66</i>
$\log H$	0.747 <i>9.88</i>	0.464 <i>8.03</i>	0.45 <i>7.90</i>	0.427 <i>7.35</i>	0.429 <i>7.36</i>
$\log PP$		0.231 <i>6.11</i>			
$PP \cdot \log S^d$			0.007 <i>6.72</i>		0.002 <i>0.39</i>
$PP \cdot \log S^f$				0.008 <i>6.70</i>	0.006 <i>1.33</i>
Standard error	0.073	0.081	0.080	0.080	0.080
$R^2$	0.79	0.79	0.79	0.79	0.79
$R^2$ adjusted	0.78	0.79	0.79	0.79	0.79

Notes: The dependent variable is  $\log(\text{total factor productivity})$ .  $S^f$  is defined using bilateral import weights. T-statistics in italics below coefficient estimates.

Table A5. Legal Origins and Patent Protection: Alternative Specification  
(DOLS, within, fixed effects, 1971-2004, 24 countries)

$\log S^d$	0.066 <i>3.15</i>	0.098 <i>4.26</i>	0.062 <i>2.92</i>	0.061 <i>2.52</i>	0.032 <i>2.58</i>	0.064 <i>2.52</i>	0.054 <i>2.18</i>
$\log S^f$	0.116 <i>5.11</i>	0.082 <i>3.78</i>	0.136 <i>4.94</i>	0.064 <i>3.11</i>	0.114 <i>6.65</i>	0.024 <i>0.94</i>	0.027 <i>1.03</i>
$\log H$	0.747 <i>9.88</i>	0.969 <i>12.52</i>	0.793 <i>9.99</i>	0.819 <i>9.93</i>	0.494 <i>8.30</i>	0.82 <i>10.06</i>	0.809 <i>10.06</i>
$\log PP$				0.203 <i>4.07</i>	0.229 <i>6.21</i>		
$PP \cdot \log S^d$						0.006 <i>3.72</i>	0.007 <i>4.37</i>
$Fr \cdot \log S^d$		-0.127 <i>-7.37</i>		-0.132 <i>-8.07</i>		-0.129 <i>-8.08</i>	$PP \cdot Fr \cdot \log S^d$ -0.037 <i>-7.09</i>
$Sc \cdot \log S^d$		-0.055 <i>-3.73</i>		-0.05 <i>-3.39</i>		-0.038 <i>-2.36</i>	$PP \cdot Sc \cdot \log S^d$ -0.012 <i>-2.04</i>
$Fr \cdot \log S^f$			-0.082 <i>-1.91</i>		-0.064 <i>-2.43</i>		
$Sc \cdot \log S^f$			-0.056 <i>-1.37</i>		-0.013 <i>-0.51</i>		
Standard error	0.089	0.087	0.088	0.078	0.082	0.079	0.079
$R^2$	0.78	0.78	0.78	0.83	0.81	0.82	0.82
$R^2$ adjusted	0.77	0.78	0.78	0.82	0.81	0.82	0.82

Notes: The dependent variable is  $\log(\text{total factor productivity})$ .  $S^f$  is defined using bilateral import weights.  $Fr$  and  $Sc$  are dummy variables for countries whose legal origins are French and Scandinavian, respectively, defined in Table 7. T-statistics in italics below coefficient estimates.

## ***Appendix B: Data Sources and Definitions***

The database is similar to CH but updated to 2004 and expanded to include Korea and Iceland and estimates of human capital and a number of institutional variables. As noted in the text, data for Germany refer to West Germany from 1964-1990 and to unified Germany thereafter.

Total factor productivity ( $F$ ) in the business sector is defined as,

$$F = Y / ( K^\beta \cdot L^{(1-\beta)} ),$$

where  $Y$  is real value added in the business sector,  $K$  is capital stock,  $L$  is labor input (defined as business sector employment times average annual hours worked),  $\beta$  is the average labor share, and all variables are indices with 2000=1. All data are from the OECD's analytical database or the OECD Economic Outlook database except for Israel where the data were provided by Ms. Soli Peleg of the Central Bureau of Statistics. For Belgium, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, New Zealand, Portugal, Sweden, and the United States, the OECD only has capital stock estimates for the total economy; for the other countries, including Israel, the capital stock is for the business sector. For some countries missing data for business sector output or employment were filled in using the growth rate of the corresponding economy wide variable; missing data for the capital stock were filled in by assuming a constant scrapping rate and the perpetual inventory model; missing data for hours worked were filled in by assuming it remained constant at the last observation.

Data for business sector R&D expenditure ( $R\&D$ ) for most countries are from the OECD Directorate of Science Technology, and Industry, published in *Main Science and Technology Indicators*. For Korea, R&D data are from the Ministry of Science and Technology. For Israel, R&D data are from the Central Bureau of Statistics supplemented by estimates from 1970/71 to 1985/86 from Ms. Soli Peleg of the CBS.

Most countries do not have data for all years from 1970-2004, either because the data do not start until after 1970 or because there are gaps in the data, which were only collected every other year or even more sporadically. The OECD also publishes data on R&D expenditure for total industry ( $R\&D^I$ ) in the STAN database, and for some countries these data are available for more years than the data for the business sector ( $R\&D$ ). For these countries the correlation between  $R\&D$  and  $R\&D^I$  is very high (0.99 except for Australia where it is 0.72). The ratios of  $R\&D/R\&D^I$ , which are relatively stable and close to 1, were interpolated and used to estimate missing values of  $R\&D$  for those observations where only  $R\&D^I$  data were available. An analogous procedure was used for Austria, for which there are many more observations for total R&D expenditure than for  $R\&D$  in the business sector.

Business sector R&D expenditure in constant 2000 dollars valued at purchasing power parities ( $R\&DV$ ) were obtained by dividing  $R\&D$  by GDP deflators (2000=1) to convert from nominal to real,<sup>24</sup> and by multiplying by the 2000 purchasing power parity exchange rate in U.S. dollars per local currency. Missing observations for  $R\&DV$  were estimated using the predicted values from OLS regressions of  $\log R\&DV$  on  $\log GDPBV$  and  $\log IBV$ , where  $GDPBV$  is real value-added in the business sector and  $IBV$  is real non-residential private investment (for a few countries it was necessary to use aggregate GDP and total investment). If significant, a time trend ( $T$ ) and  $T^2$  were also included. The change in the predicted values from these regressions, which typically had  $R^2$ s of 0.95-0.99, were used to fill in the remaining missing observations for  $R\&DV$ .

R&D capital stocks in the business sector ( $S^d$ ), defined as beginning of year, were calculated using the perpetual inventory procedure,

$$S_t^d = (1-\delta)S_{t-1}^d + R\&DV_{t-1},$$

where the depreciation rate,  $\delta$ , is assumed to be 0.05.<sup>25</sup> The benchmarks are calculated as,

$$S_{1970}^d = R\&DV_{1970} / (\delta + g),$$

where  $g$  is the annual average logarithmic growth rate from 1970-1985, i.e.,  $g = \log(R\&DV_{1985}/R\&DV_{1970}) / 15$ . To take advantage of the availability of data on  $R\&DV$  from the early 1960s for the G7 countries, the benchmarks for G7 countries are calculated for 1962,  $g$  is calculated from 1963-1985, and the capital stocks are calculated from 1963. For the other countries the benchmarks are calculated for 1970 and the capital stocks from 1971.

A number of alternative measures of foreign R&D capital were defined for each of the 24 countries, each of which is based on the domestic R&D capital stocks of the countries' 23 trade partners. Following CH, the bilateral-import-share-weighted foreign R&D capital stock for country  $i$  is defined as,

$$S_i^{f-biw} = \sum_{j \neq i} w_{ij} S_j^d,$$

where  $w_{ij} = M_{ij} / \sum_{j \neq i} M_{ij}$ ,  $\sum_{j \neq i} w_{ij} = 1$ , and  $M_{ij}$  is country  $i$ 's imports of goods and services from country  $j$ . Bilateral imports, which are on a c.i.f. basis, are from the IMF Direction of Trade database. Lichtenberg and van Pottelsberghe de la Potterie (1998) propose an alternative definition of foreign R&D capital stocks

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<sup>24</sup> The lack of consistent data for wages prevented deflating nominal R&D expenditure by an average of PGDP and an index of wages, as was done in Coe and Helpman (1995).

<sup>25</sup> CH and other studies have found that empirical results are not sensitive to the assumed value for the depreciation rate.

$$S^{f-LP}_i = \sum_{j \neq i} (M_{ij} / Y_j) S^d_j,$$

where  $Y_j$  is nominal GDP in country  $j$ , from the IMF World Economic Outlook database. A final estimate of foreign R&D capital is the simple average of the domestic R&D capital stocks in the other 23 countries,

$$S^{f-avg}_i = \sum_{j \neq i} S^d_j / 23.$$

Summary statistics for  $S^{f-LP}$  and  $S^{f-avg}$  are presented in Table A6.

Human capital ( $H$ ) is proxied by a measure of average years of schooling from Barro and Lee (2000). The Barro-Lee data, which are reported for every five years to 2000, were interpolated to get annual series and extrapolated to 2004.

Openness ( $m$ ) is measured as the ratio of total imports of goods and services to GDP, with both series from the IMF World Economic Outlook database.

Sources for the institutional variables are given in the text.

	$S^{f-LP}_{04}/S^{f-LP}_{71}$	$S^{f-avg}_{04}/S^{f-avg}_{71}$
Australia	3.27	3.66
Austria	7.45	3.65
Belgium	5.36	3.66
Canada	4.04	3.63
Denmark	3.56	3.66
Finland	4.61	3.65
France	5.77	3.63
Germany	4.69	3.56
Greece	5.90	3.67
Iceland	4.60	3.67
Ireland	5.93	3.66
Israel	4.52	3.64
Italy	5.69	3.65
Japan	4.22	3.23
Korea	17.87	3.57
Netherlands	5.47	3.70
New Zealand	2.77	3.67
Norway	3.22	3.66
Portugal	6.64	3.67
Spain	11.14	3.64
Sweden	2.98	3.64
Switzerland	4.42	3.70
United Kingdom	6.53	3.88
United States	9.23	5.36
Average	5.83	3.71
Standard deviation	3.25	0.37

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