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INTERNATIONAL R&D SPILLOVERS AND PRODUCTIVITY TRENDS IN THE ASIAN MIRACLE ECONOMIES

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This paper examines the importance of the domestic research and development stock and foreign knowledge spillovers on total factor productivity for six Asian miracle economies over the period from 1955 to 2006. The productivity effects of international knowledge spillovers through the following channels are considered: imports, exports, inward foreign direct investment, patents, geographical proximity, and the general channel. The general channel is a transmission mechanism where knowledge spillovers occur automatically and do not pass through any specific channel. The estimates show that knowledge has been transmitted through all the channels considered but that the import channel and the general channel have probably been the most important ones for the Asian miracle economies. (*JEL* O10, O30, O40)

I. INTRODUCTION

Recent developments in endogenous growth theories have led to an increased recognition of the role that domestic knowledge and international knowledge spillovers (IKS) play as the engines of growth in Organisation for Economic Co-operation and Development (OECD) countries. Empirical studies for these countries have shown that IKS through the channels of imports, exports, foreign direct investment (FDI), patent flows, geographic proximity, and through no specific channel are important for growth, as discussed in the next section and as reviewed in the survey by Keller (2004).

Given the central role played by the Asian miracle economies in the literature on growth and development, it is surprising how little attention has been given to the joint effects of domestic and international research and development (R&D) on productivity growth in these countries. This negligence may be due to the difficulties associated with finding long historical R&D data for these countries and the emphasis on capital deepening as the most important source of growth in the literature on the Asian miracles (for a critical review of the capital deepening hypothesis, see Easterly and Levine 2001).

There are other reasons to expect domestic and foreign R&D-based knowledge to have been important for growth in these economies. First, their ratio of R&D expenditures to total income has increased markedly in the period 1955–2006 and has on average been 1.4%, which is more than half that for the technology frontier countries (the United States, Germany, Italy,

ABBREVIATIONS

ADF: Augmented Dickey-Fuller
DOLS: Dynamic Ordinary Least Square
DS: Domestic Stock
DTF: Distance to the Frontier
FDI: Foreign Direct Investment
GDP: Gross Domestic Product
IKS: International Knowledge Spillovers
OECD: Organisation for Economic Co-operation and Development
PP: Phillips–Perron
R&D: Research and Development
SUR: Seemingly Unrelated Regression
TFP: Total Factor Productivity
TIPO: Taiwan Intellectual Property Office
UNESCO: United Nations Educational, Scientific, and Cultural Organization
WWII: World War II

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France, and the UK) over the same period.[1] Second, outward orientation has often been stressed as an important factor behind the success of the Asian growth miracles (Radelet, Sachs, and Lee 2001; Rodrik 1997). This opens up the possibility that knowledge spillovers through the channel of imports and exports are important for economic growth in the Asian miracle economies.

This paper examines the effects on total factor productivity (TFP) of the domestic stocks of knowledge and IKS for six Asian miracle economies, including China, India, Japan, Korea, Singapore, and Taiwan, over the period from 1955 to 2006. The following six international knowledge transmission channels are examined: (1) imports (Coe and Helpman 1995; Coe, Helpman, and Hoffmaister 1997, 2009; Keller 1998; Kneller and Stevens 2006; Lichtenberg and van Pottelsberghe de la Potterie 1998; Madsen 2007, 2008a, 2008b; Vamvakidis 1998, 2003); (2) exports (Falvey, Foster, and Greenaway 2004); (3) inward FDI (van Pottelsberghe de la Potterie and Lichtenberg 2001); (4) flows of patents between countries (Eaton and Kortum 1996, 1999); (5) geographical proximity (Keller 2002); and (6) general knowledge spillovers that are not passing through any particular channel.

This examination not only serves as a useful check on the importance of knowledge-driven growth in the Asian miracle economies, but also provides an assessment of the relative importance of the different channels through which knowledge is transmitted internationally. Almost all available studies of knowledge spillovers have focused exclusively on the mature OECD countries, whose growth has not come close to that of the Asian miracle economies over the last few decades.[2] Trade, inward FDI, and patent flows have grown markedly in the Asian miracle economies since World War II (WWII). Furthermore, variations in the growth in TFP, domestic knowledge, and IKS are substantially larger among these economies than in OECD countries, thus yielding much more identifying variation in the data. The Asian miracle economies, therefore, provide an important testing ground for discriminating between various channels of knowledge transmission.

This paper proceeds as follows. Section II reviews the literature and provides a discussion of the analytical framework that underlies our empirical modeling strategy. Data and construction of variables are discussed in Section III. Section IV presents the main results, and robustness checks are provided in Section V. Productivity growth estimates are provided in Section VI, and Section VII identifies and discusses the sources of growth in the Asian miracle economies. The last section concludes.

II. SIX CHANNELS OF INTERNATIONAL KNOWLEDGE SPILLOVERS

Easterlin (1981), Clark (1987), and Mokyr (2005) have shown that throughout history the same technologies and production methods have often been employed across the world. Important examples include general purpose technologies such as the steam engine, trains, the combustion engine, electricity, telecommunications, the internet, and radio transmission. However, not all countries make effective use of the technologies and methods that are developed in the frontier countries. This raises the question of the channels through which technologies are transmitted internationally. The following six channels of international knowledge transmission are considered in this paper: imports, exports, inward FDI, foreign patent flows, geographic proximity, and general (or no specified) channel.

First, consider knowledge transmitted through the channel of imports. According to the endogenous growth models of Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992), horizontally and vertically differentiated intermediate inputs are the key determinants of TFP. For horizontally differentiated intermediate inputs, an increasing variety of these inputs results in higher efficiency of economy-wide production. Vertically differentiated intermediate inputs possess different qualities and their effectiveness in final production depends on the

1. Real R&D as a percentage of real GDP is on average (unweighted) slightly above 1.36% for the miracle economies (China, India, Japan, Korea, Taiwan, and Singapore) during the period 1955–2006, while the percentage is 2.34 on average for the United States, Germany, Italy, France, and the UK over the same period.

2. An important exception is the study by Coe, Helpman, and Hoffmaister (1997), who investigate the influence on productivity of knowledge spillovers through the channel of imports from OECD countries to 77 developing countries. Their study differs from ours in several respects, where the most important difference is that they focus on knowledge spillovers through the channel of imports from North to South. As such, they do not consider: (1) the effect on productivity of domestic knowledge in developing countries; (2) international knowledge transmission through channels other than imports; and (3) knowledge spillovers between developing countries. Moreover, they use a much shorter sample period (1971–1990) than the present study (1955–2006).

number of times they have been improved. In both cases, the variety and quality of intermediate inputs critically depend on R&D investment, which suggests that TFP is a positive function of R&D stocks. Also in both, the variety and quality of intermediate inputs are predominantly explained by cumulative R&D and, therefore, TFP reacts positively to knowledge stock accumulation. This line of reasoning suggests that the TFP of a country depends on its own knowledge stock and cumulative knowledge stocks embodied in imported intermediate inputs. Thus, technology is transmitted internationally by the import-weighted stock of knowledge.

There in an extensive empirical literature on the nexus between TFP growth and IKS for OECD countries. Several empirical studies have investigated knowledge spillovers through the channel of imports including Coe and Helpman (1995), Engelbrecht (1997), Coe, Helpman, and Hoffmaister (1997, 2009), Keller (1998), Lichtenberg and van Pottelsberghe de la Potterie (1998), del Barrio-Castro, Lopez-Bazo, and Serrano-Domingo (2002), Lumenga-Neso, Olarreaga, and Schiff (2005), Kneller and Stevens (2006), Madsen (2007, 2008a, 2008b), and Acharya and Keller (2009). Most of these studies find that domestic as well as foreign knowledge spillovers through imports are significant determinants of the level of TFP.

However, in an interesting study Keller (1998) shows that a problem associated with spillover weighting schemes is that they may not capture the channel through which knowledge is actually transmitted. He shows that randomly created import shares may create results that are even better than those based on explicit weighting schemes. Keller (1998) finds that randomly generated import shares and no shares at all yield results similar to or stronger than those obtained by Coe and Helpman (1995). Keller (2000) argues that trade weights are not likely to be good measures of knowledge spillovers because total import streams may not be representative of trade in intermediate goods and because common trends and shocks in R&D and TFP may lead to a spurious relationship between the import-weighted knowledge stock and TFP. Acharya and Keller (2009) go beyond the implicit assumption of the Coe and Helpman (1995) approach that knowledge spillover elasticities are the same across all countries and, instead, focus on the individual transfer of technology through imports for six major OECD countries in which they find significant differences in the elasticity values.

Second, learning-by-exporting in which firms learn to improve the quality of their products and production processes through contact with more advanced foreign competitors in global export markets is another possible channel of technology transmission (Bernard and Jensen 1999; Clerides, Lach, and Tybout 1998; Falvey, Foster, and Greenaway 2004). Quite a few empirical studies have examined the relationship between growth and exports under the assumption that firms benefit from interacting with foreign customers because they impose higher standards than domestic customers (Keller 2004), and because trade induces more efficient use of labor and resources through learning (Falvey, Foster, and Greenaway 2004). However, only a limited number of studies, such as Falvey, Foster, and Greenaway (2004), have examined this channel of knowledge transmission.

Third, FDI is often assumed to be associated with positive technological externalities (Branstetter 2006; Keller and Yeaple 2009; van Pottelsberghe de la Potterie and Lichtenberg 2001). Several empirical studies have investigated the relationship between growth and FDI under the assumption that domestic producers may increase their productivity by learning from foreign producers (see, for survey, Keller 2004). However, only a few studies such as van Pottelsberghe de le Potterie and Lichtenberg (2001) and Bitzer and Kerekes (2008) have investigated the transmission of foreign knowledge through the channel of outward and inward FDI. These studies give mixed evidence of the importance of knowledge spillovers through these channels. van Pottelsberghe de la Potterie and Lichtenberg (2001) find that outward knowledge flows increase productivity in the source country but not in the recipient country. Bitzer and Kerekes (2008) find that spillovers of knowledge through inward FDI are significant determinants of productivity, while they could not find any effects from knowledge spillovers through outward FDI.

Fourth, foreign patent flows are another channel through which technology can be transmitted across borders and thus serve as a useful measure to construct the international knowledge diffusion variables. The role of foreign patents as a transmitter of international knowledge has been highlighted in the models developed by Eaton and Kortum (1996, 1999) and in the empirical findings of Madsen (2008a).

Information about the diffusion of international technology is embedded in foreign patents as they travel easily between countries and only the most commercially promising ideas are patented abroad (see Eaton and Kortum 1996; Lichtenberg and van Pottelsberghe de la Potterie 1998).

Fifth, knowledge spillovers through geographic proximity appear to be important channels of knowledge transmission based on the observation that countries with similar growth and income experiences are clustered in geographically concentrated areas such as East Asia, South Asia, Southeast Asia, North America, Western Europe, Africa, and South America. These geographically concentrated groups of countries often have close trade links, similar cultures, and high movements of labor across borders. The importance of geographical distance between trade partners has been highlighted in the trade and growth literature (e.g., Berthelona and Freund 2008; Eaton and Kortum 2001, 2002; Frankel and Romer 1999; Grossman 1998; Keller 2002). Grossman (1998) argues that geographic distance between two trade partners reflects not only transport costs but also unfamiliarity or informational barriers. Keller (2002) argues that with greater proximity people are more able to create knowledge through interaction and adopt and assimilate knowledge that has been developed elsewhere. Geographical proximity allows technological knowledge to be transmitted through informal contacts, such as conferences, speeches, visits, and seminars. Keller (2002) shows that knowledge spillovers are positively related to geographic proximity, but that the geographic distance has become less of a deterrent to knowledge spillovers over time. Using a framework closely related to Keller (2002), Bottazzi and Peri (2003) examine the technology spillovers between European regions and find evidence that spillovers tend to cluster geographically.

Finally, knowledge can travel internationally, independently of trade, FDI, patent flows, or geographic proximity. In one of the models considered by Rivera-Batiz and Romer (1991), some described in Grossman and Helpman (1991) and those of Parente and Prescott (1994), Howitt (2000), and Aghion and Howitt (2006), it is shown that ideas travel internationally but independently of trade in goods and geographic proximity because telecommunications, the internet, books, magazines, and other means of communication render technology, wherever it is developed, globally available. This follows from the assumption that, with free communication, each researcher builds on a knowledge stock that would not otherwise have been available. This channel is similar to Romer's (1990) model.

Following the lead of Coe and Helpman (1995), the effects of domestic and foreign knowledge spillovers on TFP are estimated as follows[3]:

(1)

$$\ln\text{TFP}_{it} = a_0 + a_1 \ln\text{DS}_{it} + a_2 \ln\text{IKS}_{it} + \varepsilon_{it}$$

where the subscripts i and t represent country and time period, respectively; TFP is total factor productivity, DS the domestic stock of knowledge, IKS a measure of international knowledge spillovers, and ε a stochastic error term. TFP is expected to be positively related to the DS and IKS. The model is estimated using annual data over the period from 1955 to 2006 for China, India, Japan, Korea, Singapore, and Taiwan. Note that fixed effect dummies are not included in the regressions because the Pedroni (2001) panel dynamic ordinary least square (DOLS) estimator, as discussed and used in the regressions below, is a group-mean estimator in which the coefficients are computed as the averages for each country, thereby allowing for full heterogeneity in the parameter estimates.

III. DATA AND CONSTRUCTION OF VARIABLES

TFP is computed as $\text{TFP} = Y/(K^{\alpha}L^{1-\alpha})$, where Y is real gross domestic product (GDP), L the number of employed persons multiplied by annual hours worked, and K the nonresidential capital stock, which is estimated using the perpetual inventory method for investment in nonresidential buildings and structures as well as machinery and equipment. A depreciation rate of 3% is used for nonresidential buildings and structures and 17% for machinery and equipment. Investment data from the earliest available years have been used to generate the capital stock for the year 1955. The initial capital stock is obtained by dividing initial investment by the sum of the depreciation and growth rates of real investment. Following the established practice in the literature α is set to 0.3 (see, e.g., Aghion and Howitt 2007).

IKS are measured using both R&D expenditure and the number of patents applied for.

3. The analysis was also performed with the inclusion of time dummies. The parameter estimates were largely unaffected and so these results are not reported for brevity.

The stock of knowledge is generated using the perpetual inventory method and a 20% depreciation rate following Madsen (2008a) and Pakes and Schankerman (1984). Following Coe and Helpman (1995), nominal R&D expenditure is deflated using an unweighted average of the economy-wide value-added price deflator and hourly earnings. The number of patents applied for, rather than patents granted, is used because the granting frequencies vary significantly across countries and over time (Griliches 1990). Patents are measured as patents applied for or patents granted to residents. Patents applied for by foreign residents are not included in the patent data because they are usually duplicates of domestic patent applications and, furthermore, applications are usually made for the same patent in several countries (OECD 2003).

The use of patent data provides a valuable complement to R&D-based indicators. The advantage of using patents is that they are decomposed into patents filed by residents and nonresidents, which enables one to distinguish between ideas that are outcomes of domestic and foreign R&D activity, respectively. An additional advantage of using patents, as opposed to R&D, as indicators of innovative activity is that the outcome of informal R&D is sometimes patented. Bound et al. (1984) find that small firms patent proportionally more than large firms despite the fact that the latter have a disproportional share of R&D activity, which suggests that patents are perhaps a more inclusive measure of innovative activity than R&D expenditure. The problem associated with measuring innovative activity by patents data is that not all innovations, such as non-codifiable innovations, are patented and that the value of patents varies substantially across patents (Keller 2004). The law of large numbers will, to some extent, alleviate the problems associated with the heterogeneity of the value of patents.

The advantage of using R&D data is that they measure the resources that go into the development of new technologies and, as such, are able to discriminate between large and small innovations by assuming that the importance of innovations is proportional to the effort that is put into the innovations. The disadvantage of using R&D expenditure is that it is measured in nominal terms and, thus far, official R&D deflators are not published. Furthermore, total R&D expenditure is used here in the absence of more disaggregated R&D figures, although Guellec and van Pottelsberghe de la Potterie (2004) have shown that private sector R&D spending leads to higher productivity advances than public R&D spending. Finally, R&D expenditure, as a measure of technology, does not account for the random nature of innovations (Keller 2004).

A. Measurement of International Knowledge Spillovers

The six measures of IKS discussed in the previous section are measured as follows. The first measure, known as knowledge spillovers through the channel of imports ($\text{IKS}_{it}^{\text{im}}$), is based on the approach of Lichtenberg and van Pottelsberghe de la Potterie (1998), as follows:

$$\text{(2a)} \qquad \text{IKS}_{it}^{\text{im}} = \sum_{j=1}^{26} (M_{ijt}/Y_{jt})\text{DS}_{jt},\ i \neq j$$

where M_{ijt} is country i's imports from the exporting country j at time t; Y_{jt} is exporter j's GDP at time t; and DS_{jt} is exporter j's real R&D or patent stock at time t, that is, it is the knowledge stock of 20 OECD countries, which are listed in the Appendix, and the six Asian countries considered in this study, excluding the country under consideration.

Following Falvey, Foster, and Greenaway (2004), knowledge spillovers through the channel of exports ($\text{IKS}_{it}^{\text{ex}}$) is specified as follows:

$$\text{(2b)} \qquad \text{IKS}_{it}^{\text{ex}} = \sum_{j=1}^{26} (X_{ijt}/Y_{jt})\text{DS}_{jt},\ i \neq j$$

where X_{ijt} is country i's exports to the importing country j at time t.

Following van Pottelsberghe de le Potterie and Lichtenberg (2001) and Bitzer and Kerekes (2008), knowledge spillovers based on the channel of bilateral flows of FDI between countries ($\text{IKS}_{it}^{\text{FDI}}$) are constructed as follows:

$$\text{(2c)} \qquad \text{IKS}_{it}^{\text{FDI}} = \sum_{j=1}^{26} (F_{ijt}/K_{jt})\text{DS}_{jt},\ i \neq j$$

where F_{ijt} is recipient country i's nominal FDI stock from country j at time t and K_{jt} is country j's nonresidential capital stock at current prices. Data on FDI stock are directly available from the statistical sources over the period 1985–2006. FDI stock is used because FDI flow fluctuates excessively over time. Using the stock as opposed to the flow of FDI acknowledges the fact that countries that have previously invested heavily in country i will continue to transmit knowledge to country i even if the flow of FDI is zero because they are still operating their plants in the recipient country.

Knowledge spillovers through the channel of flows of patents between countries ($\text{IKS}_{it}^{\text{pat}}$) are estimated as follows:

$$\text{(2d)} \qquad \text{IKS}_{it}^{\text{pat}} = \sum_{j=1}^{26} (A_{ijt}/\text{TA}_{it})\text{DS}_{jt,}i \neq j$$

where A_{ijt} is the number of patent applications filed in country i by residents from country j at time t and TA_{it} the total number of patent applications in country i at time t. Patents applied for in country i by residents from country j are not directly impacting country i's TFP, but rather indirectly affecting the weight attributed to country j in knowledge spillovers. Patent applications flowing from country j to country i provide a sufficient metric for knowledge spillovers given that patents provide useful indications of potential technological collaborations between the receiving country and the residency of the patentee.

Knowledge spillovers through the channel of geographical proximity between trade partners ($\text{IKS}_{it}^{\text{prox}}$) are captured by the following measure in which knowledge spillovers are proportional to the square root of the *inverse* relative geographical distance:

$$\text{(2e)} \qquad \text{IKS}_{it}^{\text{prox}} = \sum_{j=1}^{26} \sqrt{(\text{TD}_i/D_{ij})}\text{DS}_{jt}, i \neq j$$

where TD_i is the total geographical distance in kilometers between the capital city of county i and the capital cities of all other countries, and D_{it} is the geographical distance in kilometers between the capital city of country i and the capital city of country j. Thus, the ratio TD_i/D_{ij} reflects the geographical proximity between countries i and j. A higher value of the ratio is expected to carry a larger weight of knowledge spillovers to country i from country j. Knowledge spillovers are proportional to the squared root of the geographical proximity measure because distance becomes proportionally less important as an impediment to knowledge transmission the further away a country is from the knowledge center.

Finally, foreign knowledge that transmits independently of trade in goods, FDI, patent flows, and geographic proximity ($\text{IKS}_{it}^{\text{nw}}$) is considered. No weighting scheme is used to construct this measure. The world stock of knowledge available to a particular Asian economy in our sample is simply the sum of all knowledge stocks in OECD countries and the Asian six excluding the country in question:

$$\text{(2f)} \qquad \text{IKS}_{it}^{\text{nw}} = \sum_{j=1}^{26} \text{DS}_{jt}.\ i \neq j.$$

The summary statistics of all variables used in the analysis are provided in Table 1. The data are obtained from various domestic and international sources, as detailed in the Appendix. Some of the growth rates are very large because most of the countries considered here started from a very low base. This can, particularly, be seen from the marked growth in IKS^{ex} for Korea and IKS^{FDI} for China. TFP increased by an average of 3.5 times over the period 1955–2006. Taiwan, as the strongest performer, has experienced a 5.7-fold increase in TFP over the period, while India, as the poorest performer in the group, has only experienced a 1.6-fold increase in TFP. In terms of growth in domestic R&D stock, there is a wide disparity across countries ranging from a factor of 45 to 445. Singapore and Taiwan have experienced a marked increase in domestic R&D stock over the last few decades, while the increase has been relatively modest for Japan and Korea. Similarly, there are great cross-country variations in the growth of IKS. The dispersion across countries is wide regardless of whether foreign R&D expenditure or foreign patent counts data are used. In most cases, China has experienced the largest, and India and Japan the smallest increase in foreign knowledge stock.

IV. EMPIRICAL ESTIMATES

The panel cointegration tests are performed using the approach of Pedroni (2004), which is based on the traditional Engle-Granger approach. Pedroni (2004) provides seven tests for cointegration that allow for heterogeneous intercepts and trend coefficients across cross sections. To derive the long-run estimates, the between-dimension (or group-mean) panel dynamic DOLS estimator of Pedroni (2001), which allows for the presence of heterogeneity of the cointegrating vectors, is used. This single-equation panel estimator is extended from the time series DOLS estimator of Stock and Watson (1993). One lag and one lead of the contemporaneous values of the explanatory variables in first differences are included in the estimates to

TABLE 1
Summary Statistics

	China	India	Japan	Korea	Singapore	Taiwan
TFP_{2006}/TFP_{1955}	5.0	1.6	3.6	2.5	2.7	5.7
DS_{2006}/DS_{1955}	74.0	131.1	44.8	74.2	445.4	295.3
$IKS^{im}_{2006}/IKS^{im}_{1955}$	331.8	6.9	41.9	119.5	40.1	162.8
$IKS^{ex}_{2006}/IKS^{ex}_{1955}$	309.3	5.9	85.4	826.0	343.6	248.9
$IKS^{FDI}_{2006}/IKS^{FDI}_{1985}$	583.4	20.0	6.2	13.3	14.8	10.5
$IKS^{pat}_{2006}/IKS^{pat}_{1955}$	45.2	7.4	9.2	22.1	15.2	10.2
$IKS^{prox}_{2006}/IKS^{prox}_{1955}$	9.2	8.2	8.1	10.0	8.9	9.7
$IKS^{nw}_{2006}/IKS^{nw}_{1955}$	7.9	8.0	7.4	8.0	8.2	8.1

Notes: IKS refers to international knowledge spillovers. The IKS measures reported here are constructed based on R&D stock. The construction and definition of the variables are defined in the text. The Appendix provides the sources of data. Data for IKS^{FDI} span from 1985 to 2006 because of unavailability of data prior to 1985.

capture the dynamics about the long-run equilibrium.

The results of regressing Equation (1) using R&D expenditures for knowledge stock are reported in Table 2. The regressions show that TFP, domestic R&D stock, and all measures of IKS form a robust long-run relationship. Using the 10% decision rule, evidence of cointegration is supported by Pedroni's cointegration tests. The results indicate that both domestic R&D stock and all IKS variables are significant determinants of TFP. Their coefficients are statistically significant at the 1% level in all cases. The average domestic R&D stock elasticity of TFP of 0.16 is only slightly higher than the average coefficient of foreign knowledge spillovers of 0.15.

The results of estimating Equation (1) using patents for knowledge stock are presented in Table 3. There is again evidence of cointegration and all coefficients are consistently significant at the 1% level. The coefficients of domestic and IKS are, on average, 0.18 and 0.17, respectively, which are comparable to the estimates using R&D data. The explosive growth in exports during the considered period is partly responsible for the low coefficients of IKS^{ex} in the regressions in Tables 2 and 3. The coefficients of IKS^{prox} and IKS^{nw} are substantially higher than the coefficient estimates of the other spillover variables, which is consistent with the estimates in Table 2. Compared to other regressions, the null hypothesis of no cointegration is rejected the most for the equations involving spillover variables IKS^{im}, IKS^{prox}, and IKS^{nw} in Tables 2 and 3. This result gives some support for the possibility that imports, proximity, and no specific channel are the best weighting schemes for knowledge spillovers, an issue that will be investigated further below.

The similarity between the results in Tables 2 and 3 in terms of cointegration tests and parameter estimates is truly remarkable in the sense that we arrive at almost the same conclusion regardless of whether innovative activity is measured as research output (patents) or input (R&D). This probably suggests that both R&D and patents are reliable indicators of innovations, that R&D has been deflated by a reasonably good deflator, and that the quality of the data is reliable.

Compared to the literature, the coefficient of domestic R&D knowledge stock is in most cases higher than the corresponding estimates for OECD countries (i.e., Acharya and Keller 2009; Branstetter 2006; Coe and Helpman 1995; Coe, Helpman, and Hoffmaister 2009; Guellec and van Pottelsberghe de la Potterie 2004; Keller 1998; Madsen 2007). This probably reflects the fact that R&D productivity is higher at the take-off phase during which the growth rate is high and that a substantial fraction of R&D activity is used to adapt and improve the technology that has been developed at the frontier. The coefficient of knowledge spillovers through imports is slightly lower or of the same magnitude compared to the estimates of Coe and Helpman (1995), Engelbrecht (1997), Acharya and Keller (2009), and Coe, Helpman, and Hoffmaister (2009) for OECD countries. The finding that IKS^{FDI} is positive and significant contrasts with the finding of van Pottelsberghe de la Potterie and Lichtenberg (2001), but is consistent with the results of Falvey, Foster, and Greenaway (2004), Branstetter (2006), and

TABLE 2

Mean Group Panel DOLS Estimates of $\ln\text{TFP}_{it} = a_0 + a_1\ln\text{DS}_{it} + a_2\ln\text{IKS}_{it}$, Measuring Knowledge by R&D

Measure of International Knowledge Spillovers (IKS)	Coefficient of Domestic Knowledge ($\hat{a}_1$)	Coefficient of International Knowledge Spillover ($\hat{a}_2$)	Pedroni's Test Statistics Supporting Evidence of Cointegration
(1) $\text{IKS}_{it}^{\text{im}}$	0.235**	0.082***	G^a, G^p, P^a, P^p
(2) $\text{IKS}_{it}^{\text{ex}}$	0.189***	0.065***	G^a, P^a, P^p
(3) $\text{IKS}_{it}^{\text{FDI}}$	0.135***	0.122***	P^v
(4) $\text{IKS}_{it}^{\text{pat}}$	0.164***	0.066***	P^a, P^v
(5) $\text{IKS}_{it}^{\text{prox}}$	0.115***	0.301***	G^a, G^p, P^a, P^p, P^r, P^v
(6) $\text{IKS}_{it}^{\text{nw}}$	0.140***	0.261***	G^a, G^p, P^a, P^p, P^r, P^v

Notes: The sample period is 1955–2006 and the number of observations is 312 for all but one regression. For row (3) which involves the use of FDI flows data as the weighting scheme, the sample is restricted to 1985–2006 because of data unavailability. The Pedroni (2004) cointegration tests provide seven test statistics: group augmented Dickey-Fuller (ADF) (G^a), group Phillips–Perron (PP) (G^p), group rho (G^r), panel ADF (P^a), panel PP (P^p), panel rho (P^r), and panel v (P^v) statistics. The optimal lag length is chosen using the Schwarz's Bayesian criterion. A 10% significance level is used as the decision rule to establish evidence of cointegration. Foreign knowledge stock is based on R&D expenditure.

***1% significance level.

TABLE 3

Mean Group Panel DOLS Estimates of $\ln\text{TFP}_{it} = a_0 + a_1\ln\text{DS}_{it} + a_2\ln\text{IKS}_{it}$, Measuring Knowledge by Patents

Measure of International Knowledge Spillovers (IKS)	Coefficient of Domestic Knowledge ($\hat{a}_1$)	Coefficient of International Knowledge Spillover ($\hat{a}_2$)	Pedroni's Test Statistics Supporting Evidence of Cointegration
(1) $\text{IKS}_{it}^{\text{im}}$	0.142***	0.131***	G^a, G^p, P^a, P^p, P^r, P^v
(2) $\text{IKS}_{it}^{\text{ex}}$	0.128***	0.088***	G^a, G^p, P^p
(3) $\text{IKS}_{it}^{\text{FDI}}$	0.179***	0.101***	G^a, G^p, P^a, P^p
(4) $\text{IKS}_{it}^{\text{pat}}$	0.329***	0.107***	G^a, G^p, P^a, P^p, P^v
(5) $\text{IKS}_{it}^{\text{prox}}$	0.124***	0.234***	G^a, G^p, P^a, P^p, P^r, P^v
(6) $\text{IKS}_{it}^{\text{nw}}$	0.152***	0.362***	G^a, G^p, P^a, P^p, P^r, P^v

Notes: The sample period is 1955–2006 and the number of observations is 312. The Pedroni (2004) cointegration tests provide seven test statistics: group augmented Dickey-Fuller (ADF) (G^a), group Phillips–Perron (PP) (G^p), group rho (G^r), panel ADF (P^a), panel PP (P^p), panel rho (P^r), and panel v (P^v) statistics. The optimal lag length is chosen using the Schwarz's Bayesian criterion. A 10% significance level is used as the decision rule to establish evidence of cointegration. Foreign knowledge stock is based on patents.

***1% significance level.

Bitzer and Kerekes (2008). The finding that the coefficient of IKS^{pat} is significant stands in contrast to the results of Madsen (2007), who shows that it is insignificant for OECD countries.

Finally, the data for China may be unreliable because of the possible presence of structural breaks. China opened its economy in 1978 and its knowledge sector has grown rapidly since then. This may have created an endogenous break in the cointegrated relationship given in Equation (1). To cater for this we conduct the cointegration test of Gregory and Hansen (1996) for China where the possibility of a one-time regime shift is allowed for in the cointegrated relationship of the benchmark model consisting of $\ln\text{TFP}_t$, $\ln\text{DS}_t$, and IKS_t^{im} or any of the other measures of knowledge spillovers. However, there is still supportive evidence of cointegration for China at the 5% level of significance in all cases. Furthermore, Hansen (1992) notes that evidence of parameter instability, which can be induced by the presence of structural breaks, should prevail when evidence of cointegration is absent. The above findings for evidence of cointegration remain unchanged when this approach is used to evaluate the stability of the parameters, suggesting that the findings are not sensitive to breaks in the time series. Hence, the panel estimates are unlikely to be influenced by structural breaks in the Chinese data.

V. ROBUSTNESS CHECKS

This section checks the robustness of the results to inclusion of control variables, the use of different TFP measures, alternative depreciation rates for R&D stock, various sample periods, allowance for interaction between openness and IKS, exclusion of OECD countries from the sample (i.e., Japan and Korea), and the distinction between IKS from Asia and OECD countries, where Japan and Korea are included in the Asian sample.

The stock of knowledge is based on R&D data following most of the literature on knowledge spillovers. International R&D spillovers through the channel of imports ($\text{IKS}_{it}^{\text{im}}$) is the only spillover variable used in this section in order to keep the exposition simple and to conserve space and because it is the channel of knowledge spillover that is used mostly in the literature.[4] The results remain unaltered if geographic proximity or the no weighting measures are used as the spillover variable instead of import weights.

A. Adding Control Variables

Thus far, it has been assumed that technological progress has been driven by the domestic and international knowledge stock. However, it is unlikely that the knowledge stock is the only variable that has been driving technological progress in the Asian miracle economies. To cater for that the following control variables are sequentially added to Equation (1): human capital, financial development, trade openness, and age structure. It is natural to include human capital in the TFP regressions because innovation-driven endogenous growth models are based on R&D and human capital. Through education the population can better organize work, communicate, and, to some extent, innovate and, therefore, bring the economy up to a higher productivity level. Furthermore, as recognized by Coe, Helpman, and Hoffmaister (1997, 2009), human capital is likely to be particularly important in the Asian miracle economies where there have been large investments in education.

Financial development is included as a control variable because it is often considered important for economic development and technological progress (see, for example, Ang 2011a; Ang and McKibbin 2007). Financial development reduces transaction costs and, therefore, renders trade easier and more efficient. Furthermore, the more financially developed a country is the easier is the access to credit, which in turn increases the investment in human capital, physical capital, and R&D. Trade openness is included in the set of control variables because trade is often assumed to enhance productivity through various channels (see Madsen 2009b). Finally, age structure is included as a control variable because middle-aged workers, judged from the life-cycle profile of salaries, are likely to be more productive than younger and older workers (Luong and Hébert 2009).

The regression results are included in Table 4. Common to all regressions is that the coefficients of domestic and foreign spillover are consistently highly significant and they are quite similar across different regressions. The coefficients of domestic knowledge stock are, on average, 0.17, which is slightly lower than the regression in the first row in Table 2. This is probably because the control variables have taken some of the explanation of TFP away from the domestic knowledge stock. The average coefficient of IKS is 0.10, which is comparable to the regression in the first row in Table 2. All the regressions are cointegrated according to at least some of Pedroni's (2004) cointegration tests.

Considering the regression in the first row in Table 4, the coefficient of human capital is quite significant and its size is comparable to the estimates of Engelbrecht (1997); however, it is much lower than the coefficient estimates of 0.52–0.76 by Coe, Helpman, and Hoffmaister (2009). In contrast to the regressions of del Barrio-Castro, Lopez-Bazo, and Serrano-Domingo (2002), the coefficient of the knowledge spillover variable remains significant. After including a measure of human capital, del Barrio-Castro, Lopez-Bazo, and Serrano-Domingo (2002) find that the coefficient of the knowledge spillover variable reduces in magnitude and becomes statistically insignificant. Although Engelbrecht (1997) and Coe, Helpman, and Hoffmaister (2009) also find that the magnitude of the coefficient of the knowledge spillover shrinks when human capital is included in the regression, it remains statistically significant in their estimates.

Next consider regressions (2) and (3) in which financial development and trade openness are included as an additional regressor,

4. An exception is the estimates in panel D of Table 5 in which international spillover based on the export (rather than import) channel has been used to interact with export intensity for consistency. See more details in Section V.E.

TABLE 4

Including Control Variables ($\ln\text{TFP}_{it} = a_0 + a_1\ln\text{DS}_{it} + a_2\ln\text{IKS}_{it} + a_3\ln\text{CV}_{it}$)

Additional Control Variable Included (CV)	Coefficient of Domestic Knowledge ($\hat{a}_1$)	Coefficient of International Knowledge Spillover ($\hat{a}_2$)	Coefficient of the Control Variable ($\hat{a}_3$)	Pedroni's Test Statistics Supporting Evidence of Cointegration
(1) Human capital	0.084***	0.092***	0.177***	G^a, P^a, P^p
(2) Financial development	0.196***	0.101***	0.011	G^p, P^a, P^p
(3) Trade openness	0.181***	0.089***	0.025**	G^a, P^a, P^p, P^v
(4) Age structure: 20–34	0.133***	0.129***	−0.278***	G^a, P^a, P^p, P^v
(5) Age structure: 35–49	0.192***	0.074***	0.489***	G^a, P^v
(6) Age structure: 50–64	0.208***	0.126***	−0.868***	G^a, P^v

Notes: The knowledge stock is based on R&D, and the spillover variables are weighted by imports. Human capital is measured as the average number of years of schooling; financial development refers to the ratio of private credit to GDP; trade openness is measured by the sum of exports and imports over GDP; and the age structure is the number of people in the respective age group as a proportion of the working age population (aged 20–64). Sources of data are described in the Appendix. The sample period is 1955–2006 and the number of observations is 312. The Pedroni (2004) cointegration tests provide seven test statistics: group augmented Dickey-Fuller (ADF) (G^a), group Phillips–Perron (PP) (G^p), group rho (G^r), panel ADF (P^a), panel PP (P^p), panel rho (P^r), and panel v (P^v) statistics. The optimal lag length is chosen using the Schwarz's Bayesian criterion. A 10% significance level is used as the decision rule to establish evidence of cointegration.

***1% significance level; **5% significance level.

respectively. The coefficient of financial development is insignificant while the coefficient of trade openness is positive and significant at the 5% level. Finally, consider the regressions in the last three rows in Table 4 in which the age structure is included. The age structure is measured as the proportion of the labor force in the age groups 20–34, 35–49, and 50–64. The estimates give support to the hypothesis that workers in middle age are more productive than the younger and older age cohorts. The coefficients of the fraction of workers in the young and old age cohorts are significant but negative, suggesting that these age groups are less productive than the average worker. Conversely, the coefficient of the fraction of workers in the middle age cohort is positive and highly significant, indicating that this cohort has above average productivity.

B. Using Alternative TFP Measures

The following three alternative TFP measures are used: TFP estimated with land (A^T), human capital (A^H), and both land and human capital ($A^{T \cdot H}$) as the factors of production, as follows:

$$\text{(3a)} \qquad A^T = Y/K^{\alpha(1-as)}T^{\alpha \cdot as}L^{1-\alpha},$$

$$\text{(3b)} \qquad A^H = Y/K^{\alpha}(L \cdot H)^{1-\alpha},$$

$$\text{(3c)} \qquad A^{T \cdot H} = Y/K^{\alpha(1-as)}T^{as}(L \cdot H)^{1-\alpha},$$

where capital's income share (α) of 0.3 is maintained while the share of capital income going to land (as) is allowed to change because of the diminishing role of agriculture during the modernization. Following Denison (1967), as is measured by the share of agricultural output in total GDP. Total land area is measured by the sum of arable land, permanent cropland, and permanent pasture. Human capital is measured as educational attainment, that is, the average number of years of schooling of the adult population over the age of 25.

The estimates in panel A of Table 5 show that domestic as well as IKS continue to be significant determinants of TFP when alternative TFP measures are considered. Note, however, that compared with the estimates in Table 2 the magnitude of the coefficients drop substantially when educational attainment is included in the TFP estimates. This result is quite intuitive as the marked increase in educational attainment among the adult population has resulted in a slower increase in TFP than when education is not allowed for in the regressions.

C. Using Alternative Depreciation Rates for R&D Stock

The 20% depreciation rate for R&D stock that has been used in the regressions may seem to be on the high side. Panel B in Table 5 reports the estimates when 5% and 10% depreciation rates are used to construct the R&D stock variables. It is evident that both domestic and international knowledge stocks continue to have economically and statistically significant effects

TABLE 5
Further Sensitivity Analysis

Modification	Coefficient of Domestic Knowledge ($\hat{a}_1$)	Coefficient of International Knowledge Spillover ($\hat{a}_2$)	Pedroni's Test Statistics Supporting Evidence of Cointegration
A. Alternative TFP measure			
- TFP with land	0.262***	0.105***	G^a, P^a, P^p
- TFP with human capital	0.049**	0.032**	P^a
- TFP with land & human capital	0.079***	0.053***	G^a, P^a
B. Alternative depreciation rates for R&D stock			
- 5%	0.219***	0.093***	G^a, G^p, P^a, P^p
- 10%	0.261***	0.061***	G^a, G^p, P^a, P^p
C. Alternative sample period			
- 1955–1996	0.328***	0.336***	P^a
- 1965–2006	0.396***	0.323***	G^a, G^p, P^p
- 1975–2006	0.505***	0.098**	G^a
- 1985–2006	0.682***	0.099***	G^a, G^p, P^a, P^p, P^r
D. Including the trade interaction term with IKS			
- imports intensity	0.270***	0.142***	G^a, G^p, P^a, P^p
- exports intensity	0.271***	0.175***	G^p, P^v
E. Sample restriction			
- excluding Japan	0.203***	0.114***	G^a, G^p, P^a, P^p
- excluding Korea and Japan	0.201***	0.139***	G^a, G^p, P^a
F. Sources of international spillovers			
- Asia only	0.219***	0.038	—
- OECD only	0.266***	0.088***	G^a, G^p, P^a, P^p

Notes: The knowledge stock is based on R&D and international knowledge spillovers (IKS) are based on imports weights except the regression in second row of panel D in which IKS is multiplied by export intensity. The sample period is 1955–2006 and the number of observations is 312. The Pedroni (2004) cointegration tests provide seven test statistics: group augmented Dickey-Fuller (ADF) (G^a), group Phillips–Perron (PP) (G^p), group rho (G^r), panel ADF (P^a), panel PP (P^p), panel rho (P^r), and panel v (P^v) statistics. The optimal lag length is chosen using the Schwarz's Bayesian criterion. A 10% significance level is used as the decision rule to establish evidence of cointegration.

**5% significance level; ***1% significance level.

on TFP. On average, the estimates are quite similar to those found in Table 2 in which the coefficients were found to be 0.235 for domestic knowledge stock and 0.082 for IKS based on the import channel. This suggests that the estimates are not largely driven by the choice of the rate of depreciation for the knowledge stock.

D. Using Alternative Estimation Periods

Various estimation periods are considered in panel C, including the pre-Asian financial crisis period of 1955–1996, and later periods beginning from 1965, 1975, and 1985 during which the R&D activity is substantially higher than in earlier periods. Regardless of the chosen estimation period, the coefficients of DS and IKS are all significant at the 1% level and the null hypothesis of no cointegration is rejected according to at least one of the Pedroni tests. Interestingly, the coefficient of DS is increasing while the coefficient of IKS is decreasing over time as the economies develop. This does not necessarily mean that the significance of domestic knowledge is increasing with economic development as estimates for OECD countries typically have lower coefficients of domestic knowledge stock than those found in Table 5. One possibility is the presence of a hump-shaped profile in which the effects of domestic knowledge on TFP are increasing during the take-off phase but may decline thereafter.

E. Interaction with Trade Openness

IKS are multiplied by import and export intensity in panel D in Table 5. Note that the international spillover variable is weighted by the direction of exports in the regression in which IKS is multiplied by export intensity. Interaction between openness and international knowledge stock is often allowed for in the literature following the lead of Coe and Helpman (1995) to cater for the possibility that relatively open economies would benefit more from the transfers of knowledge across borders. Note, however, that the degree of import penetration has already been allowed for in the weighting scheme of Lichtenberg and van Pottelsberghe de la Potterie (1998), which stands in contrast to the weighting scheme of Coe and Helpman (1995) in which the weights add to one. Thus, when the weighting scheme of Lichtenberg and van Pottelsberghe de la Potterie (1998) is used, there is no need to interact IKS with trade openness. The results in panel D show that the coefficients of both DS and IKS remain highly significant, suggesting that the estimates are not affected by the interaction of IKS with trade openness.

F. Controlling for Country Sample Bias

Considering potential country selection bias, the regressions in panel E exclude Japan (first row) and Japan and Korea (second row). The regressions suggest that the parameter estimates are largely unaffected by their exclusion and there is continued support for cointegration.

G. Sources of Spillover Effects

Keller (2000) argues that spillover effects from high technology countries are higher than from other countries. In the regressions in panel F, the spillover variables are decomposed into spillovers from the Asian miracle economies only and OECD countries only. The Asian countries include the six countries considered in the present study and the OECD countries include the 20 listed in the Appendix. The coefficient of IKS for the Asian countries is insignificant and there is no evidence of panel cointegration (first row in panel F). The coefficient of knowledge spillovers from the OECD, by contrast, is highly significant and the variables are cointegrated (second row). These results suggest that Asia has only benefitted from imports of products embodying knowledge that is developed at the technology frontiers. The results support Keller's (2000) argument that the spillover effects from high technology countries are significantly higher than zero, whereas there is no evidence of positive spillover effects from the Asian miracle economies.

VI. GROWTH ESTIMATES

Thus far we have included one spillover variable at a time in the regressions in Table 2 because the high multicollinearity between the spillover variables renders horse race regressions unreliable. To enable discrimination between the spillover variables the following model is estimated in first differences to eliminate trends:

(4)

$$\begin{aligned}\Delta \ln \mathrm{TFP}_{it} &= b_0 + b_1 \Delta \ln \mathrm{DS}_{it} + b_2 \ln(\mathrm{R\&D}/Y)_{it} \\ &\quad + b_3 \ln \mathrm{DTF}_{it} + b_4 \Delta \ln h_{it} + b_5 \ln h_{it} \\ &\quad + b_6 \Delta \ln \mathrm{IKS}_{it}^{\mathrm{im}} + b_7 \Delta \ln \mathrm{IKS}_{it}^{\mathrm{ex}} + b_8 \Delta \ln \mathrm{IKS}_{it}^{\mathrm{FDI}} \\ &\quad + b_9 \Delta \ln \mathrm{IKS}_{it}^{\mathrm{pat}} + b_{10} \Delta \ln \mathrm{IKS}_{it}^{\mathrm{prox}} \\ &\quad + b_{11} \Delta \ln \mathrm{IKS}_{it}^{\mathrm{nw}} + v_{it},\end{aligned}$$

where R&D is the real R&D expenditure, Y the real GDP, R&D/Y the research intensity, DTF the distance to the frontier, h the human capital proxied by educational attainment, and v a stochastic error term. DTF is measured as TFP in the United States divided by TFP for country i. It is included as an additional variable to allow for the benefits of backwardness, following the historical analysis of Gerschenkron (1962). A backward country can use the technologies adopted at the frontier to gain a growth advantage until it has caught up to the frontier. Financial development, age distribution, and openness are excluded from Equation (4) because their coefficients are statistically insignificant, regardless of whether they are measured in levels or in first differences.

R&D is divided by income to allow for product proliferation and increasing complexity of new innovations as TFP increases, following the Schumpeterian growth theory (Ang and Madsen 2011; Ha and Howitt 2007). Growth can be sustained in the Schumpeterian framework if R&D is kept to a fixed proportion of the number of product lines, which is in turn proportional to the size of population in steady state. As such, to ensure sustained TFP growth, R&D has to increase over time to counteract the increasing range and complexity of products, which lowers the productivity effects of R&D activity. Similarly, the Schumpeterian model of Vandenbussche, Aghion, and Meghir (2006) predicts that TFP growth is proportional to per capita human capital, which implies that the growth rate will remain positive as long as the labor force has some education and that the growth is proportional to educational attainment. Semi-endogenous growth theory, by contrast, assumes that human capital has only temporary growth effects (see, e.g., Madsen 2010).

TABLE 6
Growth Estimates of Equation (4)

	(1)	(2)	(3)	(4)
Intercept	0.082 (0.409)	−0.022 (0.799)	0.001 (0.998)	−0.039 (0.454)
$\Delta \ln DS_{it}$	−0.050 (0.334)	−0.037 (0.344)		
$\ln(R\&D/Y)_{it}$	0.046*** (0.002)	0.031** (0.012)	0.029*** (0.000)	0.029*** (0.001)
$\ln DTF_{it}$	0.059** (0.048)	0.035 (0.195)		
$\ln h_{it}$	0.016 (0.213)	0.003 (0.773)		
$\Delta \ln h_{it}$	−0.093** (0.032)	−0.111** (0.012)	−0.119*** (0.004)	−0.129*** (0.001)
$\Delta \ln IKS_{it}^{im}$	0.044** (0.016)	0.050*** (0.004)	0.041** (0.013)	0.043** (0.011)
$\Delta \ln IKS_{it}^{ex}$	0.011* (0.068)	0.010* (0.065)	0.007 (0.159)	
$\Delta \ln IKS_{it}^{FDI}$	0.042 (0.301)			
$\Delta \ln IKS_{it}^{pat}$	−0.120 (0.342)			
$\Delta \ln IKS_{it}^{prox}$	−1.569 (0.139)			
$\Delta \ln IKS_{it}^{nw}$	3.179** (0.019)	1.695** (0.018)	1.729*** (0.004)	2.125*** (0.000)
Time dummies	Yes	Yes	Yes	Yes
Country dummies	Yes	Yes	Yes	Yes
R^2	0.967	0.973	0.779	0.726
Number of observations	60	60	60	60

Notes: The sample period is 1955–2005. Data for $\Delta \ln(IKS_{it}^{FDI})$ prior to 1985 are assumed to be zero. The equations are estimated using the SUR estimator. Figures in parentheses are p values.
***, **, and *indicate 1%, 5%, and 10% levels of significance, respectively.

The results of estimating Equation (4) are presented in Table 6. The model is estimated in first 5-year differences and the seemingly unrelated regression (SUR) estimator is used to gain efficiency. Consider first the estimates in the first column in which all variables are included. The coefficient of domestic knowledge stock is insignificant at the conventional level whereas the coefficient of domestic research intensity is significant at the 1% level. This result has an important implication, that is, R&D has permanent growth effects. The DTF term is positive and significant, suggesting that the Asian economies have been gravitating toward the technology frontier by using the technology adapted at the frontier countries. The coefficient of growth in human capital has the sign opposite to the cointegration estimates in Table 4 and those of Engelbrecht (1997), del Barrio-Castro, Lopez-Bazo, and Serrano-Domingo (2002), and Coe, Helpman, and Hoffmaister (2009). A possible explanation for this discrepancy is that the short-run growth effects of human capital may be too small or blurred because of erratic movements in the data on human capital.

Turning to the knowledge spillover variables, the coefficients of IKS^{im} and IKS^{nw} are highly significant and the coefficient of IKS^{ex} is only marginally significant. The coefficients of other spillover variables are insignificant. The qualitative aspect of the results remains unaltered if the insignificant spillover variables are deleted (column 2). Deleting, additionally, all variables that are insignificant in the second column yields the regression in the third column. Finally, deleting IKS^{ex}, which is insignificant in the third column, yields results that give a very clear picture of the most important spillover variables. Spillovers through the channel of imports and through no particular channel remain significant determinants of TFP growth in all the regressions, while IKS^{ex} is either insignificant or only marginally significant.

VII. SOURCES OF GROWTH IN THE ASIAN MIRACLE ECONOMIES

The discussion has thus far focused on TFP. However, because labor productivity or per capita output is the ultimate source of welfare improvements it is necessary to estimate how much TFP and, therefore, innovative activity have contributed to labor productivity. Decomposition of labor productivity to its sources of growth, through growth accounting methods, is of particular importance for the Asian miracle economies as a large body of the literature has argued that their high labor productivity and per capita income growth rates have predominantly been driven by factor accumulation and not by innovations (see, for discussion, Easterly and Levine 2001). The biggest problem with the growth accounting method is that it treats factors of production as being exogenous and, therefore, fails to allow for the feedback effects from TFP growth on capital deepening (see, for discussion, Madsen and Ang 2009).

Furthermore, because all growth along the balanced growth path is technological progress in standard growth models, growth accounting exercises must have been built on an implicit assumption that growth in the Asian miracle economies has been driven by transitional dynamics where capital deepening played a leading role. However, King and Rebelo (1993) have demonstrated that for growth to have been driven predominantly by transitional dynamics, interest rates must be implausibly high, and often in excess of 100% in the early stages of development. This suggests that R&D must have played a more prominent role in the Asian growth miracles than has been indicated in standard growth accounting exercises. Finally, the transformation from a low-income agricultural society to a modern growth regime reflects the joint forces of a demographic transition, increased female labor force participation, increased thriftiness, and, particularly, the adaptation and development of new technologies. Thus, a large part of the factor-accumulation-induced productivity growth has been endogenous to the growth process in which innovative activity has been playing a leading role.

Allowing for an endogenous response of the capital stock to technological progress the sources of productivity growth can be obtained as follows (see Madsen and Ang 2009 for details). Consider the following constant returns to scale Cobb-Douglas production function:

$$Y = AK^{\alpha}T^{\beta}H^{1-\alpha-\beta}, \tag{5}$$

where A is the technology, K the capital, T the land, and H the quality-adjusted labor.

Quality-adjusted labor input consists of human capital per worker (h), annual hours worked (X), and raw labor (L), as follows:

$$H = hXL, \tag{6}$$

where h is computed following the Mincerian approach:

$$h = \exp(\theta s), \tag{7}$$

where s is educational attainment, defined as the average years of schooling among the population of working age, and θ is the returns to schooling, which is set at 0.07 following the standard practice in the literature.

Using Equation (6), Equation (5) can be written in terms of per worker employed:

$$\begin{aligned} Y/L = {} & A^{1/(1-\alpha)}(K/Y)^{\alpha/(1-\alpha)}T^{\beta/(1-\alpha)} \\ & \times h^{(1-\alpha-\beta)/(1-\alpha)}X^{(1-\alpha-\beta)/(1-\alpha)}L^{-\beta/(1-\alpha)}. \end{aligned} \tag{8}$$

Taking logs and differentiating Equation (7) in combination with Equation (8) yields the labor productivity growth rate ($g_{Y/L}$):

$$\begin{aligned} g_{Y/L} = {} & (1/1-\alpha)g_A + (\alpha/1-\alpha)g_{K/Y} \\ & + (\beta/1-\alpha)g_T + (1-\alpha-\beta)/(1-\alpha)\Delta(\theta s) \\ & + (1-\alpha-\beta)/(1-\alpha)g_X - \beta/(1-\alpha)n, \end{aligned} \tag{9}$$

where g_A is the knowledge growth rate, $g_{K/Y}$ the growth rate in the capital-output ratio, g_T the growth rate in land area, g_X the growth rate in annual hours worked, and n the employment growth rate. The last term in Equation (9) is the population growth drag, in which population growth acts as a drag on the economy because of diminishing returns introduced by land as a fixed factor of production. This drag only exists if agriculture is a nonnegligible part of the economy, that is, $\beta > 0$, and if land under cultivation is not growing at the same rate as population.

Equation (9) decomposes labor productivity growth into its sources while, at the same time, allowing for the endogenous response of capital deepening to technological progress. If this endogenous response was not allowed for

TABLE 7
Sources of Growth in Miracle Economies (Equation (9))

		Contribution by Component					
	Growth in Labor Productivity Y/L	TFP A	Capital Deepening K/Y	Land Area T	Educational attainment θs	Hours Worked X	Employment L
China	5.180	4.285	0.751	0.039	0.425	−0.204	−0.117
India	2.710	1.467	1.083	0.005	0.281	0.004	−0.130
Japan	4.089	3.225	0.803	−0.005	0.373	−0.299	−0.007
Korea	4.071	2.102	1.520	−0.004	0.544	−0.052	−0.040
Singapore	3.802	2.404	1.154	−0.002	0.402	−0.154	−0.001
Taiwan	5.074	4.444	0.679	−0.010	0.449	−0.470	−0.018

Notes: The data are average annualized geometric growth rates over the period from 1956 to 2006. The following parameters are used: $\alpha = 0.7$, β = share of agriculture in total GDP, and $\theta = 0.07$.

the coefficient of $g_{K/Y}$ would have been α instead of $\alpha/(1-\alpha)$, or approximately three times bigger than if the endogenous response was not allowed for. Technological progress results in capital deepening because it increases the expected marginal productivity of capital. This initiates a capital deepening process that terminates when the marginal productivity of capital equals the user cost of capital.

The results of decomposing labor productivity growth to its sources following Equation (9) are shown in Table 7. It is evident from the table that most of the labor productivity growth is due to technological progress. Capital deepening has only accounted for approximately 1% point growth in labor productivity or about 25% of growth, which suggests that increasing savings rates have influenced growth; however, it has not been a major force behind growth. Note, however, it is likely that the increasing savings rates, to a large extent, have been induced by the high productivity growth rates because of the force of habit. Using data for developing countries Radelet, Sachs, and Lee (2001) find that growth is influential for savings rates. Ang (2009, 2011b) obtains similar results for China, India, and Malaysia. Thus, it is likely that the contribution of capital stock to productivity growth, to a large extent, is a result of TFP growth in the first place. Increasing educational attainment has also been influential for growth by accounting for almost half a percentage point of growth for most countries. Finally, the population growth drag has not been influential for growth, which is predominantly because of the fact that most of the Asian miracle economies experienced a demographic transition shortly after WWII, which resulted in low population growth.

Overall, the growth accounting results show that the largest part of the labor productivity rates have been driven by the direct and indirect effects of TFP growth. As most of the TFP growth, according to the estimates above, has been driven by domestic and international innovations, the results do suggest that the high growth rates in these countries are miraculous in the sense that they are not driven predominantly by simple factor accumulation.

VIII. CONCLUSIONS

Using data over the period 1955–2006, this paper has examined the role of international knowledge diffusion on TFP for six Asian miracle economies. Several potential channels through which knowledge can be transmitted internationally were examined, including knowledge spillovers through imports, exports, patent flows, geographical proximity, FDI, and a transmission mechanism that is independent of any particular channel.

The results showed that TFP, domestic R&D stock, and IKS are cointegrated and, therefore, that growth rates of both domestic and international knowledge stock are potential important determinants of productivity growth. The estimates are robust to whether foreign stock of knowledge is measured by R&D expenditure or patent data, different channels of transmission, alternative measures of TFP, knowledge stock depreciations rates, estimation periods, country sample, inclusion of control variables such as human capital, financial development, trade openness, and age structure, and the interaction between knowledge spillovers and openness in estimates where international knowledge is transmitted through the channel of trade. However, only IKS from OECD countries were found to be important for TFP; the estimates fail to identify any significant knowledge spillovers from the Asian miracle economies.

Finally, growth regressions were undertaken to discriminate between the various channels of knowledge transmission. These regressions revealed that knowledge spillovers independent of any particular channel of transmission and knowledge spillovers through imports are the most significant knowledge spillover variables for TFP growth in the Asian miracle economies. Overall, the cointegration as well as the growth equations showed that the domestic innovative activity and IKS were the key drivers of TFP growth. Given that, as shown in the previous section, the TFP growth has been the major force behind the high labor productivity rates in the Asian miracle economies, the results in this paper suggest that investment in R&D and interaction with economies at the technology frontier are important ingredients for a successful development strategy.

APPENDIX

Total Factor Productivity (TFP)

TFP is computed as $Y/(K^{\alpha}L^{1-\alpha})$, where Y is the real GDP, K the nonresidential capital stock, and L the employment multiplied by annual hours worked. Capital income share (α) is set to 0.3, following Aghion and Howitt (2007). The following sources are used to obtain GDP and employment: *China:* Wang and Yao (2003), China Statistical Yearbook (various issues) and "Comprehensive Statistical Data and Materials on 50 Years of New China," Beijing: China Statistics Press. *India:* National Account Statistics (various issues) and Penn World Table 6.2. *Japan:* Japan Statistical Yearbook (various issues). *Korea*: Korea Statistical Yearbook (various issues). *Singapore*: Yearbook of Statistics Singapore (various issues). *Taiwan*: Taiwan Statistical Data Book (various issues). Data for annual hours worked are gathered from Groningen Growth and Development Centre (http://www.ggdc.net/). Data for China (1991–1998) and India (1969–2006) are obtained from the "Yearbook of Labour Statistics," Geneva: International Labour Office. Data for missing years are assumed to be constant.

The construction of K involves: (1) nonresidential buildings and structures and (2) machinery and equipment. A depreciation rate of 3% is assumed for the former and 17% for the latter. Investment data from the earliest available years have been used to generate the initial stock for the year 1955 (China: 1953, India: 1950, Japan: 1870, Korea: 1913, Singapore: 1956, and Taiwan: 1912). The initial capital stock is obtained by using the Solow model steady-state value of $I_0/(\delta + g)$, where I_0 is the initial real investment, δ the rate of depreciation, and g the growth rate in real investment over the period for which investment data are first available to 2006. The breakdown of investment series for China is available only from 1981. They have been backdated using the total investment series. The following sources have been used to obtain investment: *China:* China Statistical Yearbook (various issues) and "Comprehensive Statistical Data and Materials on 50 Years of New China," Beijing: China Statistics Press. *India:* National Account Statistics (various issues). *Japan*: Madsen (2008). 25.7% war damage has been applied to the 1945 capital stock. *Korea*: Timmer and Ark (2000) and Korea Statistical Yearbook (various issues). All pre-1953 investment data have been discounted by 40% to account for war damage. *Singapore*: Yearbook of Statistics Singapore (various issues). *Taiwan*: Timmer and Ark (2000) and Taiwan Statistical Data Book (various issues). All data are expressed in constant 1995 dollars valued at purchasing power parity.

The alternative measures of TFP described in the main text involve land and/or human capital. Land area includes arable land, permanent cropland, and permanent pasture. Data from 1960 onwards are obtained from the World Development Indicator CD Rom (2007). For China, Japan, and Taiwan, the data are gathered from the national sources described earlier for the years 1955–1959. Prior year data are, however, not available for other countries. We therefore extend the series backward by assuming a constant growth rate for India and Korea. For Singapore, we assume that the land area was constant before 1960. Educational attainment is measured by the average years of schooling. The estimates of Barro and Lee (2001) are used for India, Korea, Singapore, and Taiwan. The data, which are available only for every 5 years to 2000, are interpolated to get annual series and extrapolated to 2006. Data for China up to 1999 are obtained from Wang and Yao (2003). Following their methodology, the series is extended to 2006 using data from the China Statistical Yearbook (various issues). Data for Japan are obtained from Madsen (2009a).

R&D Expenditure

Real total R&D expenditures are used in the estimation. The data are obtained from the following sources: *China*: China Statistical Yearbook (various issues), "Comprehensive Statistical Data and Materials on 50 Years of New China," Beijing: China Statistics Press, "Statistics on Science and Technology of China: 1949–1989," Peking: *Zhongguo Tong Ji Chu Ban She* and the various issues of "S&T Statistics Data Book" published by the Ministry of Science and Technology. *India*: various issues of "R&D Statistics" published by the Department of Science and Technology and "Macro-Aggregates" published by the Planning Commission, Government of India. These data are complemented with various issues of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Statistical Yearbook published by the United Nations Educational, Scientific, and Cultural Organization. Data are available at 5-year intervals between 1950 and 1970, and continuously thereafter. Missing data are interpolated using the geometric growth rate. *Japan:* Japan Statistical Yearbook (various issues). *Korea*: Korea Statistical Yearbook (various issues) and UNESCO Statistical Yearbook (various issues). Data before 1967 are predicted using the first principal component of the data for China, India, Japan, and Taiwan. *Singapore:* Yearbook of Statistics Singapore (various issues). UNESCO Statistical Yearbook (various issues). Data before 1970 are predicted using the first principal component of the data for China, India, Japan, and Taiwan. *Taiwan*: Taiwan Statistical Data Book (various issues) and Statistical Yearbook of the Republic of China (various issues). Data before 1970 are estimated using the first principal component of the number of patent applications (obtained from various issues of "Annual Report" and "Yearbook of Intellectual Property" published by the Taiwan Intellectual Property Office [TIPO]), enrollment numbers in science and engineering courses and R&D data for China and India. *OECD*: Data for 1965–2004 are obtained from OECD Main Science and Technology Indicators, OECD Archive (OECD/DSTI/EAS), National Science Foundation and Statistics Netherlands. The data are extrapolated to 2006. Earlier year data are obtained from various sources documented in Madsen (2008b). The following 20 OECD countries are included: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK, and the United States.

Nominal R&D expenditure is deflated using an unweighted average of the economy-wide value-added price deflator and hourly earnings, following Coe and Helpman (1995), to express in real terms. Price deflator is obtained from the same domestic sources as GDP (see above). Except for Japan where the data are available from Japan Statistical Yearbook (various issues), hourly earnings data for all other countries are compiled from the "Yearbook of Labour Statistics," Geneva: International Labour Office and other domestic sources described above. For China, data before 1979 are estimated by assuming that the growth rate of wages equals the sum of labor productivity growth and the inflation rate. Real R&D capital stock is calculated using the perpetual inventory method. The initial R&D capital stock is obtained using the same procedure as the physical capital stock (K) with a depreciation rate of 20%.

Imports, Exports, and Bilateral Trade Flows

For the Asian countries, the same sources that are used to obtain GDP are used to obtain import data. Except for Taiwan where the data are collected from various issues of the Taiwan Statistical Data Book and Statistical Yearbook of the Republic of China, bilateral trade weights for all countries are constructed using data from the International Monetary Fund Direction of International Trade Statistics.

Patent Statistics

Patent data are obtained from the World Intellectual Property Organization. Total patent applications by residents are obtained from http://www.wipo.int/ipstats/en/statistics/patents/. Data for patent applications by country of origin since 1995 are obtained from the same source. For data before 1995, see Madsen (2007).

Distance

Data for geographical distance between cities are gathered from the following source: http://www.macalester.edu/research/economics/page/haveman/trade.resources/Data/Gravity/dist.txt

FDI

Data on FDI flows are obtained from the UNCTADstat online database.

Control Variables

Human capital, financial development, trade openness, and age structure are used as control variables. Measures of human capital and trade openness are obtained using the sources described above. The depth of financial systems is measured by the ratio of private credit to GDP. Data for private credit are obtained from the same domestic sources as GDP described above. Data for different age groups are also from the same domestic sources as GDP described above, but are supplemented by B.R. Mitchell's "International Historical Statistics, Africa, Asia & Oceania 1750–2005," fifth edition.

Growth Accounting

Except for the number of hours worked, all data used in the growth accounting exercise are described above. Data for annual hours worked are gathered from Groningen Growth and Development Centre (http://www.ggdc.net/). Data for China (1991–1998) and India (1969–2006) are obtained from the "Yearbook of Labour Statistics", Geneva: International Labour Office. Data for missing years are assumed to be constant.

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