Web Appendix for *The Gravity of Knowledge*

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This appendix provindes theoretical and empirical results that take a number of important steps beyond the analysis in the main text. In section 1 we discuss the generality of our model, in particular the assumptions that the costs of disembodied knowledge transfer does not vary with geography and that trade costs do not vary with knowledge intensity. Section 2 lays out an extension of the model to include fixed costs of knowledge transfer, while details on the data are given in section 3. The robustness of our micro-level estimation results is examined along several dimensions in the following section 4. Section 5 provides more details on the steps taken in the quantification of the model. Finally, in section 6 we corroborate the finding on the knowledge intensity of trade as presented in Figure 1 in the paper.

1 Generalizations of the Theory

In this section, we elaborate on generalizations of the simple model presented in the paper lead to qualitatively similar results. First, the assumption that shipping costs were uniform across goods could have been weaken to all these costs to vary across goods according to

$$\tau_{jk}(z) = \tau_{jk} \times g(z)$$

where $g(z) \geq 1$ and $t'(z) > g'(z)$. The key assumption is that trade costs do not rise faster in knowledge intensity than do disembodied knowledge transfer costs. Second, the assumption that knowledge transfer costs did not rise in trade costs can be adjusted so that

$$t(z; \tau) = \delta(\tau)t(z),$$

where $\delta'(\tau) \geq 0$ and $\tau\delta'(\tau)/\delta(\tau) < 1$. The key assumption is that trade costs rise faster in distance than do disembodied knowledge transfer costs. Third, the assumption that the only variation across industries was in the composition of inputs used in the production of the composite intermediate input can be generalized to allow an industry's knowledge intensity to affect intermediate input transfer costs directly according to

$$t^i(z) = t(\phi^i)f(z),$$

where $t'(\phi_i) > 0$. As long as $f(z)$ is not too convex in z it is straightforward to show that this is sufficient to generate our results, and it reinforces the composition effect in the model.

Some of the model assumptions cannot be generalized. For instance, if the elasticity of substitution across goods is relatively low in knowledge intensive industries, as opposed to be identical across industries as we have assumed, this would limit the transmission of higher marginal costs to affiliate sales, thereby confounding Proposition 2 which supports Hypothesis 2. In contrast, if inputs were relatively substitutable in knowledge intensive industries, which seems implausible, this too would have confounding effects on the relationship between trade costs and the import share.

In the following section we consider fixed costs of knowledge transfer.

2 Fixed Costs of Knowledge Transfer

Recent quantitative models of multinational production typically maintain tractability by assuming that knowledge transfer costs take the form of variable, not fixed costs (Burstein and Monge-Naranjo 2009, McGrattan and Prescott 2010, and Ramondo and Rodriguez Clare 2010). This is also the case here, even though it is worth noting that our framework allows already for fixed costs of affiliate production (f_k^a), which are absent in much of the literature. Nevertheless, fixed costs may be particularly relevant in the context of knowledge transfers. While a full treatment is beyond the scope of this paper, the following extension captures what we think would be their central implication in any model: firms with large operations incur fixed costs of knowledge transfers in order to lower their marginal costs, while small firms do not.

Suppose that firms may invest in information and communication technology (ICT) in order to lower the efficiency cost of knowledge transfer, but doing so requires incurring an additional fixed cost F^T. Having installed ICT, the efficiency loss of remote production falls from $t(z)$ to $t(\alpha z)$, $\alpha \in (0, 1)$ for all z and for all foreign locations. In this setting, the following proposition holds.

Proposition 3: *In each industry, there exists a threshold productivity $\widehat{\varphi}^{ICT}$ such that firms with productivity $\varphi > \widehat{\varphi}^{ICT}$ incur the fixed cost F^T. Firms that incur the fixed cost have lower import cost shares in all countries relative to other firms in their industry.*

Proof. We first show that the affiliates of a firm that installs ICT equipment have lower marginal costs and a lower import cost share in all countries relative to a firm that does not We then show that only highly productive firms will install such equipment. The marginal imported input, $\widetilde{z}(\tau)$, of the affiliate of a firm that has incurred F^T that faces trade costs τ is given by $\widetilde{z}(\tau) = \widehat{z}(\tau)/\alpha > \widehat{z}(\tau)$,where $\widehat{z}(\tau)$ is given by equation (4). The marginal cost of the composite intermediate of such a firm, $C^M(\tau, \phi^i, \alpha)$, is

$$C^M(\tau, \phi^i, \alpha) = \left(\int_0^{\widetilde{z}(\tau)} \beta(z|\phi^i) t(\alpha z)^{1-\eta} dz + \tau^{1-\eta} \int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz \right)^{1/(1-\eta)}$$

which is strictly increasing in α. Hence, $C^M(\tau, \phi^i, \alpha) < C^M(\tau, \phi^i, 1)$ for $\alpha < 1$. The import cost share is

$$\theta(\tau, \phi^i, \alpha) = \frac{\tau^{1-\eta} \int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz}{\int_0^{\widetilde{z}(\tau)} \beta(z|\phi^i) t(\alpha z)^{1-\eta} dz + \tau^{1-\eta} \int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz},$$

where $\alpha < 1$ if $F^T(\phi^i)$ is incurred and $\alpha = 1$ otherwise. We now show that $\theta(\tau, \phi^i, \alpha) < \theta(\tau, \phi^i, 1)$. Suppose instead that $\theta(\tau, \phi^i, \alpha) > \theta(\tau, \phi^i, 1)$, then

$$\begin{aligned} \frac{\int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz}{\int_0^{\widetilde{z}(\tau)} \beta(z|\phi^i) t(\alpha z)^{1-\eta} dz + \tau^{1-\eta} \int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz} &> \frac{\int_{\widehat{z}(\tau)}^{\infty} \beta(z|\phi^i) dz}{\int_0^{\widehat{z}(\tau)} \beta(z|\phi^i) t(z)^{1-\eta} dz + \tau^{1-\eta} \int_{\widehat{z}(\tau)}^{\infty} \beta(z|\phi^i) dz} \\ \frac{\int_0^{\widehat{z}(\tau)} \beta(z|\phi^i) t(z)^{1-\eta} dz}{\int_0^{\widetilde{z}(\tau)} \beta(z|\phi^i) t(\alpha z)^{1-\eta} dz} &> \frac{\int_{\widehat{z}(\tau)}^{\infty} \beta(z|\phi^i) dz}{\int_{\widetilde{z}(\tau)}^{\infty} \beta(z|\phi^i) dz} > 1 \end{aligned}$$

where the last step follows from $\widehat{z}(\tau) < \widetilde{z}(\tau)$. Hence,

$$0 > \int_{\widehat{z}(\tau)}^{\widetilde{z}(\tau)} \beta(z|\phi^i) t(\alpha z)^{1-\eta} dz + \int_0^{\widehat{z}(\tau)} \beta(z|\phi^i) \left(t(\alpha z)^{1-\eta} - t(z)^{1-\eta} \right) dz$$

Because $t(\alpha z)^{1-\eta} \geq t(z)^{1-\eta}$ for $\eta \geq 1$ the term on the right hand of this expression must be positive, which contradicts the assertion. We conclude that $\theta(\tau, \phi^i, \alpha) < \theta(\tau, \phi^i, 1)$. The profit on sales to country k of a firm of productivity φ in industry i with an affiliate in country k is given by

$$\Pi_k^{i,ICT}(\varphi) = B_k^i \varphi^{\sigma-1} C^M(\tau, \phi^i, \alpha)^{1-\sigma} - f_k^a, \tag{1}$$

and the profit of this firm were it to not install the ICT would be

$$\Pi_k^{i,N}(\varphi) = \max\left\{B_k^i \varphi^{\sigma-1} C^M(\tau, \phi^i, 1)^{1-\sigma} - f_k^a, 0\right\}. \tag{2}$$

Let K^{ICT} be the set of countries the firm would open an affiliate if it installs ICT and let K^N be the set of countries the firm would open an affiliate if it did not install ICT. It is immediate from the condition in (8) that $K^N \subset K^{ICT}$ because $C^M(\tau, \phi^i, \alpha)^{1-\sigma} > C^M(\tau, \phi^i, 1)^{1-\sigma}$ so the profit associated with local production will be higher relative to exporting from the home country. The profit gain associated with installing ICT is thus given by

$$\sum_{K^{ICT}} \left(\Pi_k^{i,ICT}(\varphi) - \Pi_k^{i,N}(\varphi)\right) - F^T.$$

This expression is strictly increasing, continuous and unbounded from above in φ and negative for sufficiently small φ, hence there exists a cutoff productivity $\widehat{\varphi}^{ICT}$ that satisfies $\sum_{K^{ICT}} \left(\Pi_k^{i,ICT}\left(\widehat{\varphi}^{ICT}\right) - \Pi_k^{i,N}\left(\widehat{\varphi}^{ICT}\right)\right) = F^T$. Further, all firms with $\varphi > \widehat{\varphi}^{ICT}$ will invest in ICT and all others will not. ■

Firms that reduce the efficiency loss of disembodied technology transfer reduce their reliance on imported intermediates and reduce their affiliates' marginal cost of production. It is only profitable to incur this fixed cost when aggregate affiliate sales will be large, which will happen when the scale of a firm's foreign operations is large as will be the case if it is very productive (high φ).

The following section provides additional details on the data that we employ.

3 Data Sources and Summary Statistics

As noted in section 3 of the paper, the empirical analysis employs a number of country- and industry-level variables to see whether our results are due to mechanisms other than emphasized by the model. This section describes the rationale for these additional control variables as well as their sources. According to the model the size of foreign demand determines the scale of foreign operations and so directly affects the volume of local sales and indirectly can affect the import cost share. Therefore, we include GDP and the size of the host country's population, which are taken from the Penn World Tables. Other controls are motivated by determinants of FDI that are outside our model. To allow for comparative advantage to affect the structure of affiliate operations, we control for factor price differences across countries by interacting a country's skill abundance with an industry's skill intensity and capital abundance with capital intensity. Our measure of skill abundance is human capital per worker, and the analogous measure of capital abundance is capital per worker (source: Hall and Jones 1999). We also consider comparative advantage based on institutional quality as proposed by Nunn (2007), which is also the source of our skill and capital intensity variables.

We employ a number of variables that are directly related to international transactions costs: an indicator variable for common language between the host country and the U.S., from Hanson, Mataloni, and Slaughter (2005), and the costs of making a phone call, from the World Competitiveness Yearbook (1999). Moreover, some research suggests that multinationals may engage in transfer pricing by altering the value of within-firm transactions to reduce their global tax burden. We address this by including the host country's maximum marginal corporate tax rate (source: University of Michigan World Tax Database).

A major strand of work views multinational firms as vehicles that internalize (within the firm) relationships where contracting on the transfer of technological knowledge is crucial (Ethier 1986). We expect that countries in which intellectual property regimes are strongly enforced will be those in which relationships between independent firms are more prevalent. In contrast, countries with weak IPRs may require more frequently the in-house, that is, multinational, mode of organization. To make sure that our results are not principally driven by make-versus-buy decisions related to a country's IPR regime, we control for the quality of country's IPR regime using data from Park (2008).

Recent work has also emphasized that the quality of a country's legal institutions will affect the boundary of the firm in the presence of contract incompleteness, especially for knowledge-intensive goods. While our analysis is consistent with both FDI and foreign outsourcing, we want to be certain that our findings are not primarily due to factors that determine the make-versus-buy decision. We include therefore as another variable the quality of the judicial system of a country; this has recently been emphasized by Nunn (2007), which is also the source of our data. Table A gives summary statistics for the firm-level sample that is employed to test Hypothesis 1 and Hypothesis 2.

The following section presents a number of regression results that are an important complement to the micro evidence we have presented in section 4 of the text.

4 Micro-level evidence: further results

4.1 Alternative Measures of Knowledge Intensity

Several of our alternative measures of knowledge intensity are inspired by the recent literature on offshoring (Levy and Murnane 2005, Costinot, Oldenski, and Rauch 2009). According to this literature, offshoring of production activities is relatively more difficult in industries in which production activities are non-routine or that require the exercise of judgment. We use the Occupational Information Network (O*NET) data from the Bureau of Labor Statistics that ranks occupations by the extent to which these occupations require (i) the extensive analysis of data, (ii) the processing of information, or (iii) the exercise of judgement and the need for decision making. Aggregating over occupations using labor requirements by industry for the year 2004, we construct alternative measures capturing the difficulty of offshoring activities by industry. We construct this measure as described in Costinot, Oldenski, and Rauch (2009). We also employ industry-level values of the share of computers in total capital as alternative measures of knowledge intensity (source: Bureau of Labor Statistics).

In Table B, we present results for one of the O*NET measures, the importance of Analyzing Data as determinant of the knowledge intensity of an industry.[1] The second measure is the share of information technology (IT) capital in total capital, specifically, the computer share. In this table, the R&D intensity results are repeated in columns 1 and 4 for convenience. with OLS estimates in Panel A on top and two-step Heckman results in Panel B at the bottom. Generally the differences between Panel A and Panel B are small, and we focus the discussion on the latter. If knowledge intensity is proxied by Analyzing Data, we estimate a positive coefficient on the trade cost-knowledge intensity ($TC \times KI$) variable in the import cost share equation (column 2B, Table B). This is in line with Hypothesis 1. While the size of the coefficient is not comparable to that of the R&D intensity specification in column 1B due to different scales, the Analyzing Data variable performs better in the sense that the $TC \times KI$ coefficient is more precisely estimated than with R&D intensity, and the empirical fit of the equation is somewhat improved.

Turning to the sales results on the right, using the Analyzing Data variable the coefficient on $TC \times KI$ is estimated at 0.029 and not significant at standard levels in the sales specification (column 5B). This suggests that the skill of Analyzing Data is not important in explaining why affiliate sales fall particularly strongly with trade costs in certain industries. In contrast, a high computer share is very powerful in explaining gravity for affiliate sales (column 6B): the linear trade cost coefficient is not significant anymore, while the coefficient on the $TC \times KI$ interaction variable is precisely estimated. At the same time, the computer share in total capital yields a negative coefficient on $TC \times KI$ in the import cost share equation (see column 3B), which is not what is expected if the computer share were a good proxy for knowledge intensity in the light of the model. This may be related to the fact that the linear TC variable is not significant in the import cost share equation in column 3B.

[1] The exact definition is: "Identifying the underlying principles, reasons, or facts of information by breaking down information or data into separate parts."

Given these results with the computer share and Analyzing Data variables, we have broadened our analysis and considered five additional variables that might measure the knowledge intensity of an industry. There is, first of all, a frequently used measure of skills in the labor force, the share of non-production workers in all workers. Second, we present results on three additional occupational measures derived from the O*NET database, namely:

1. Processing information (Mental Processes): Compiling, coding, categorizing, calculating, tabulating, auditing, or verifying information or data.

2. Updating and using relevant information (Work Activities): Keeping up-to-date technically and applying new knowledge to your job.

3. Judgment and decision making (System Skills): Consider the relative costs and benefits of potential actions to choose the most appropriate one.

Third, results are shown for a second information capital variable, namely the share of communication capital in total capital (from the Bureau of Labor Statistics). Table C reports results employing these varying for four different specifications: one the one hand, least squares and two-step Heckman specifications, and on the other hand, for both import cost share and affiliate sales equations. We report only the trade cost-knowledge intensity ($TC \times KI$) coefficient estimate from these regressions for space reasons.

The main findings are as follows. First, the communication capital share does not appear to capture the notion of knowledge intensity as laid out in the model, as the $TC \times KI$ coefficient is estimated imprecisely in all four cases. Second, the three O*NET variables give similar results, which are also similar to the Analyzing Data variable employed in Table B: proxying knowledge intensity by an O*NET variable yields results in the import equation that support the model, and that are in fact stronger than for R&D intensity. At the same time, the O*NET variables do not predict well how the gravity of affiliate sales varies with knowledge intensity according to the model. Finally, the results based on the share of non-production workers are quite similar to those using the occupation-based O*NET variables.

These results can be summarized as follows. We find that the Analyzing Data variable performs very well in the import cost share equation (a result that is confirmed for other O*NET measures, see Table C). Moreover, a particular type of information technology capital, namely computers, performs well as an alternative proxy for knowledge intensity in the sales equation. This constitutes support for the model going beyond identifying knowledge intensity with R&D intensity. At the same time, there is no strong support from either the O*NET measures or the computer share for *both* hypotheses. Specifically, while the O*NET variables determine well the split between imports and local affiliate activity, they do not predict well the level of affiliate sales. And while the computer share predicts well the level of affiliate sales, in line with earlier work on foreign outsourcing (Feenstra and Hanson 1999), it does not predict well the import share of the affiliate.

4.2 Geography, or Other Variation? Further Results on Knowledge Intensity Interactions

One might be concerned that the results on the trade cost-knowledge intensity ($TC \times KI$) variable supporting Hypothesis 1 and Hypothesis 2 is driven by omitted variables, in particular other relevant features in the world that might vary with the trade costs from the United States. While there are potentially numerous channels, among the most salient are (i) institutional quality, (ii) comparative advantage, and (iii) the costs of communication. For example, it is not implausible that knowledge intensive products rely systematically more on strong institutions than less knowledge intensive products, and if the quality of institutions across offshoring destinations is correlated with trade costs from the United States, our results on $TC \times KI$ could be spurious. In the following, we address this concern by including additional interactions with knowledge intensity as regressors, and check whether our results are substantially unchanged. The results are shown in Table D, with Panel A reporting OLS results and Panel B summarizing the corresponding two-step Heckman results.

In column 1 of Table D, Panel A, the IPR interaction with knowledge intensity, $IPR \times KI$, is included in the import cost share equation in addition to all regressors of column 3 in Table 1 (in particular, the linear IPR variable). The $IPR \times KI$ variable does not enter significantly and the trade cost-knowledge intensity variable is virtually unchanged compared to before (see column 3, Table 1). Adding further the skill endowment-knowledge intensity and judicial quality-knowledge intensity interactions capturing comparative advantage effects, we see that this does not qualitatively change the results in support of Hypothesis 1 and Hypothesis 2; if anything it strengthens these results by raising the point estimate on $TC \times KI$ away from zero. In contrast, the IPR-, skill-, and judicial quality- interactions are generally not significant. At the same time it appears that the additional knowledge intensity interactions are correlated with each other, as, for example, the $IPR \times KI$ point estimate changes signs upon the inclusion of the skill- and judicial quality knowledge interaction variables (Table D, Panel A, columns 1 and 2).

In the corresponding Heckman MLE results we also find that the trade cost-knowledge intensity results are not substantially affected by the inclusion of further knowledge intensity interaction variables; the point estimate on $TC \times KI$ is around 22 (columns 1 and 2 of Table D, Panel B), which is quite similar to the value of 22.3 reported earlier (see Table 2, column 3).

Turning to the affiliate sales results on the right side of Table D, the inclusion of additional knowledge intensity interactions seems to matter more than for the affiliate's imports, especially if several of them are present at the same time. In particular, the coefficient on $TC \times KI$ falls for the Heckman two-step case in absolute value from about -18.2 without the three additional interactions (Table 2, column 6) to -12.7 with them (Table D, Panel B, column 5). Similarly, if on top of the three additioinal knowledge intensity interactions country fixed effects are included, the coefficient on $TC \times KI$ is not statistically significant at standard levels anymore (p-value of 0.107, see Table D, Panel A, column 7).[2] However these results should be discounted because there is evidence that the high correlation among the additional knowledge intensity interactions produces poor results; in the Heckman results, for example, as with imports the $IPR \times KI$ point estimate changes from about -0.5 (p-value of 0.122) to +1.4 (p-value of 0.04) upon the inclusion of the skill- and judicial quality-interaction variables.

In the following we consider the impact of the costs of communication. Specifically, it may be that the choice of multinational firms in how much and in what way to offshore is affected by the ease of communication between headquarter and affiliate plant, and that is driven by the bilateral costs of communication *independent of* the geography of countries as captured by the $TC \times KI$ variable. To explore this possibility we construct knowledge intensity interaction variables for both of our measures of communication costs, namely common language and the cost of a phone call; denote these by $CL \times KI$ and $PH \times KI$, respectively. As seen from Table D, the $CL \times KI$ and $PH \times KI$ interaction variables enter with varying significance (Panel A, columns 4 and 8; Panel B, columns 3 and 6). At the same time, we find that in all specifications–import share versus sales, OLS versus MLE– the point estimate of the trade cost-knowledge intensity rises in absolute value upon the inclusion of the communication cost-knowledge intensity interaction variables. Moreover, in the case of the Heckman estimates the p-values of the $TC \times KI$ point estimate are now less than 0.001, for example (see Table D, Panel B, columns 3 and 6). Thus, our results tend to be strengthened here.

In summary, the size of our estimates is somewhat reduced upon the inclusion of institutional quality and comparative advantage interactions with knowledge intensity, mostly for affiliate sales. Even here, statistical significance at standard levels is preserved

[2] The country fixed effects specification is omitted in Panel B because there is not sufficient variation in the exclusion variables (Cost of Starting a Business, Foreign Market Potential) to be able to estimate the selection equation. Note that adding country fixed effects *per se* changes the results very little (Table 1, columns 4 and 8).

except when the joint inclusion of many collinear regressors apparently leads to overall poor results. Moreover, as we have seen the inclusion of communication cost effects tends to strengthen our results. On balance, we conclude that the existence of major biases by factors outside the model is unlikely, and the support in favor of Hypothesis 1 and Hypothesis 2 of the model as presented in the main text is both qualitatively as well as quantitatively confirmed.

4.3 Third-Country Imports and Dynamics of U.S. Multinational Firms: Firm-level Evidence

4.3.1 Imports from Affiliates in Third-Countries

In the model, all imports of the affiliates come from the U.S., both from the parent and from unaffiliated sources located in the United States. One might be concerned, however, that imports from third-country affiliates may be higher whenever more embodied knowledge is imported from the parent country. If this were the case and the effect would 'pass' the control variables, it may produce an important bias for our import share results. Unfortunately in the BEA data (and nowhere else that we know of) there is no information on bilateral trade of affiliates with non-parent countries. To explore this possibility in a more limited way we have pursued two strategies, see Table E for results.

In the first, we add a measure of prevalence of third-country sales on the right hand side of the regression. It is reasonable to assume that third-country affiliate imports will tend to be high whenever third-country sales (which we observe) are high. While third-country imports could come also from unaffiliated parties, and correspondingly third-country sales could be to unaffiliated parties, we expect there to be a strong positive correlation between third-country sales and imports from affiliates in third countries. We have thus computed the ratio of third-country sales of its affiliates relative to its total sales for each multinational firm, and include it on the right hand side of our hypothesis 2-regressions. The results are in Table E, column (2) for OLS and column (4) for the full model including extensive margin, compared to the benchmark results in (1) and (3), which are from Table 1a and Table 2, respectively. In both the OLS and the Heckman specification, the third-country sales variable enters significantly with a negative coefficient, indicating that imports from the U.S. tend to be low whenever third-country sales are high. This is consistent with imports from the parent and imports from third-country affiliates being substitutes for each other. While the third-country sales variable enters significantly, its inclusion has virtually no effect on our estimates of the trade cost x knowledge intensity ($TC \times KI$) variable.

We have also split the sample into two subsamples, the observations with low imports from the U.S. and the observations with high imports from the U.S. If our result is obtained primarily because affiliates that import relatively much from the U.S. import relatively much embodied knowledge in general, one would expect that the results for the sample with generally low imports from the U.S. are quite different than the results for the sample with generally high imports from the U.S. In Table E, columns (5) and (6) we report the results for these two samples. The estimated coefficients on the $TC \times KI$ intensity variable are very similar in both subsamples, even though the coefficient for the low import share sample is less precisely estimated.

Overall we conclude from this that it is unlikely that the results in support of Hypothesis 2 are in imported ways driven by imports from affiliates from third-countries that are not accounted for.

4.3.2 The Nature of International Knowledge Transfer: Dynamics

In our static model, the costs of knowledge transfer are variable in the sense that per unit of intermediate good produced in the affiliate, the resource costs are higher than if it was produced in the multinational home country. In a multi-period setting, it would be possible to distinguish between a number of different knowledge transfer costs. First, it may be that there are ongoing communication frictions that do not diminish over time, perhaps because the number of possible problems is very large relative to the actual number of production steps that are required. Second, it may be that some of the knowledge transfer costs are of the once-and-for-all type. In the latter case, one would expect that over time affiliates produce more locally and import less from home. While making the model fully dynamic is beyond the scope of this paper, given the panel nature of our data where affiliates are (potentially) observed in 1994, 1999, and 2004, Table F provides evidence on this.

The specifications in Table F are identical to those in Table 1 and Table 2 except that we include a variable which is equal to one if the affiliate existed in the previous period (five years earlier). In the intensive-margin specification for the import cost share, Table F, column 1, the affiliate age variable comes in positive, whereas once sample selection is accounted for affiliate age has a negative coefficient (column 2). The latter is consistent with the idea that technology transfer costs are in part fixed, in the sense that over time the affiliate relies more on local input production. Moreover, the largely unchanged coefficient on the trade cost-knowledge intensity variable $TC \times KI$ indicates that these fixed technology transfer costs exist side-by-side with ongoing (variable) technology transfer costs. Note that the coefficient on parent sales changes from about -0.3 to -0.15 with the inclusion of the age variable. One interpretation of that is that firm productivity is to some extent captured by parent sales and to some extent by age.

A similar picture emerges in the affiliate sales specifications, see Table F on the right side. If the affiliate had existed five years earlier already, it tends to have higher sales, and the coefficient on parent sales in the Heckman specification falls from 0.66 to 0.60 (Table 2, column 6, and Table F, column 4). Again it appears that age is an alternative proxy for firm productivity, and moreover, as before the coefficient on the trade cost-knowledge intensity variable is largely unchanged.

The analyses discussed in this section has generally confirmed the results reported in the text. First, multinationals have greater difficulty in knowledge intensive industries to substitute local production for trade, which is in line with the costs of knowledge transfer in specific industries making it hard for these firms to switch from embodied to disembodied knowledge transfer as trade costs rise. Second, our result that gravity is particularly strong in knowledge intensive industries is robust to a broad range of robustness checks. Overall, this is strong evidence that the support in favor of Hypothesis 1 and Hypothesis 2 of the model is due to the mechanism that the model emphasizes and not other factors.

In the following section, we provide results that are employed in the quantification of the model (section 5).

5 A Decomposition of Multinational Sales

An expression for affiliate sales can be derived in our model as follows. From equation (8) in the text, we find that all firms with productivity exceeding a cutoff ($\varphi \geq \widehat{\varphi}_k$) will open an affiliate in country k. This cutoff is the solution to

$$B_k(\widehat{\varphi}_k)^{\sigma-1}\left(C^M(\tau,\phi)^{1-\sigma}-\tau^{1-\sigma}\right)=\sigma f_k^a. \tag{3}$$

The total sales of affiliates to country k and industry i is obtained by aggregating over the individual firms that own an affiliate:

$$\begin{aligned}
R_k &= N\int_{\widehat{\varphi}_k}^{\infty} R_k^i(\varphi,\tau_k,\phi)dG(\varphi) \\
&= NB_kC^M(\tau_k,\phi)^{1-\sigma}\int_{\widehat{\varphi}_k}^{\infty}\varphi^{\sigma-1}dG(\varphi) \\
&= NB_kC^M(\tau_k,\phi)^{1-\sigma}\frac{\upsilon}{\upsilon-\sigma+1}\widehat{\varphi}_k^{-\upsilon+\sigma-1}
\end{aligned}$$

substituting for the cutoff using (3), we obtain (11). We now derive an expression for the fixed cost of opening an affiliate in country k. First, note that the number of home firms that own an affiliate in country k is given by $N_k = N\widehat{\varphi}_k^{-\upsilon}$ Combining this expression with (11) and (3), we arrive at the following expression:

$$\frac{R_k}{N_k} = f_k^a \left(\frac{\upsilon\sigma}{\upsilon - \sigma + 1} \frac{C^M(\tau_k, \phi)^{1-\sigma}}{C^M(\tau_k, \phi)^{1-\sigma} - \tau_k^{1-\sigma}} \right). \tag{4}$$

This equation shows that the fixed cost parameters for each country can be recovered given estimate of τ_k and $C^M(\tau_k, \phi)$, average affiliate size R_k/N_k, and parameters σ and υ. Trade costs τ_k and average affiliate size R_k/N_k are directly coming from our data, while the marginal costs $C^M(\tau_k, \phi)$ are estimated as discussed in the first part of the quantitative section 5.

This leaves the parameters σ and υ to be determined. First, the parameter σ is set at $\sigma = 6$ to be consistent with a twenty percent mark-up over cost. Second, given σ we can estimate the parameter υ analogous to the procedure employed in Helpman, Melitz, and Yeaple (2004), which our model generalizes. In this procedure the dispersion parameter of the Pareto distribution $\upsilon/(\sigma - 1)$ is estimated from a log rank-log sales regression. We employ COMPUSTAT data for 1999 and calculate the domestic sales as the difference between total firm revenues and the value of exports. As the Pareto approximation of the size distribution is only appropriate in the upper tail, we restrict attention to the top 10% of firms. Using the bias correction method in Gabaix and Ibragimov (2011), the regression of the logarithm of a firm's rank in the distribution on the logarithm of a firm's sales yields a coefficient of 1.09 with a T-statistic of over 104 and an R-squared in excess of 0.98. With $\upsilon/(\sigma - 1) = 1.09$ and $\sigma = 6$, it follows that υ is equal to 5.45.

With the parameters σ and υ and information on trade costs, marginal costs, and average affiliate size in hand, we employ equation (4) to back out the country specific fixed costs, f_k^a. Finally, given this same information and the derived f_k^a, we can then use (11) to isolate the mark-up adjusted demand level B_k. This allows us to construct the three individual components of affiliate sales, for both our model and the more restricted model of Helpman, Melitz, and Yeaple (2004), which are employed in the gravity decomposition of Table 5b in the text.

6 The Knowledge Intensity of Multinational Trade: Regression Results

In section 6 of the paper we have discussed the relationship between trade costs from the United States and the knowledge intensity of multinational trade that is implied by the model. In this section we examine the robustness of the positive relationship shown in Figure 1 by moving to a multiple regression framework. Summary statistics for this country-level data are provided in Table G, while the regression results are given in Table H. The first column reports the simple bivariate relationship that is plotted in Figure 1.[3] An increase in trade costs is associated with an increase in the average knowledge intensity of U.S. multinational trade. Indeed, this single regressor accounts for 44 percent of the variation as indicated by the R-squared. In column 2, we add a number of country control variables to the regression. The knowledge intensity of multinational trade is lower in large, developed countries where English is spoken. None of the other coefficients are statistically significant. The coefficient on trade costs is still significantly positive but moderately smaller than in the bi-variate case.

One concern is that the relationship reflects trade costs rising more slowly in distance for highly knowledge-intensive goods because these goods, to some extent intangibles, have lower weight-to-value ratios. To see if this is the case, we have calculated the average weight-to-value ratio of goods traded between the U.S. and each host country and include that measure in the regression; see column 3.[4] The weight-to-value variable turns out to be not statistically significant, while the coefficient on trade costs retains its approximate magnitude and level of statistical significance. The model's prediction that multinational firms change the knowledge content of their international trade in relation to geographic distance (and trade costs) thus finds strong support in the data.

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[3] These are weighted least squares results, with GDP as the weight; the results are qualitatively similar when not weighted.

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Table A: Summary Statistics

	Mean	Standard Deviation
Firm-level data		
Affiliate Sales, total	10.900	1.696
To local unaffiliated customers	10.388	1.771
To U.S. customers	7.932	2.850
To 3rd country customers	9.236	2.509
Parent Sales	13.705	1.544
Import Cost Share	-3.005	1.961
Industry Characteristics		
R&D Intensity	0.045	0.039
Analyzing Data	51.974	8.677
Computer Share	0.024	0.011
Skill Intensity	0.426	0.124
Capital Intensity	0.804	0.395
Contract Intensity	0.538	0.202
Other Variables		
Trade Cost	0.133	0.108
Phone Call	0.621	0.605
IPR protection index	3.701	1.080
GDP	19.521	1.244
Population	10.205	0.984
Tax Rate	3.524	0.241
Common Language	0.231	0.422
Skill Endowment	0.772	0.216
Physical Capital Endowment	10.250	0.983
Judicial Quality	0.669	0.212
Cost of Starting a Business	1.074	0.662
Foreign Market Potential	14.487	1.198

Note: All variables, except Industry Characteristics and Common Language, are in natural logarithms.

Table B: Alternative Measures for Knowledge Intensity

	Import Share			Sales		
Panel A: Intensive Margin						
Knowledge Intensity variable	**R&D Intensity**	**Analyzing Data**	**Computer Share**	**R&D Intensity**	**Analyzing Data**	**Computer Share**
	(1A)	(2A)	(3A)	(4A)	(5A)	(6A)
Trade costs	-3.786 [<.001]	-12.267 [<.001]	-0.547 [0.600]	-0.770 [0.085]	-2.484 [0.066]	0.047 [0.924]
Trade costs x knowledge intensity	24.906 [0.039]	0.169 [<.001]	-131.109 [0.042]	-17.149 [0.055]	0.020 [0.376]	-80.025 [0.002]
Population	-0.628 [0.150]	-0.618 [0.143]	-0.511 [0.238]	-0.207 [0.296]	-0.249 [0.209]	-0.207 [0.291]
GDP	0.410 [0.324]	0.405 [0.315]	0.297 [0.471]	0.753 [<.001]	0.795 [<.001]	0.754 [<.001]
R-squared	0.447	0.450	0.448	0.557	0.556	0.557
# of obs	5,644	5,644	5,644	7,581	7,581	7,581
Panel B: Ext. & Int. Margin						
	(1B)	(2B)	(3B)	(4B)	(5B)	(6B)
Trade costs	-2.037 [<.001]	-9.190 [<.001]	-0.109 [0.875]	-0.772 [0.027]	-3.013 [0.007]	0.253 [0.595]
Trade costs x knowledge intensity	22.349 [0.029]	0.140 [<.001]	-71.218 [0.044]	-18.223 [0.003]	0.029 [0.135]	-97.429 [<.001]
Population	-0.375 [0.049]	-0.355 [0.061]	-0.298 [0.117]	-0.233 [0.071]	-0.279 [0.030]	-0.229 [0.076]
GDP	-0.259 [0.192]	-0.250 [0.205]	-0.311 [0.114]	0.922 [<.001]	0.970 [<.001]	0.936 [<.001]
Mills ratio: λ	-1.572 [<.001]	-1.486 [<.001]	-1.496 [<.001]	0.541 [<.001]	0.551 [<.001]	0.593 [<.001]
Wald χ^2 (57 d.o.f.)	883.34 [<.001]	923.64 [<.001]	894.72 [<.001]	1,853.08 [<.001]	1,838.26 [<.001]	1,839.96 [<.001]
# of obs	45,121	45,121	45,121	45,121	45,121	45,121

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), and (3); local affiliate sales to unaffiliated customers in columns (4), (5), and (6). Panel A: Specifications by least squares, firm-year fixed effects included. Robust p-values allow for clustering by country-year and are shown in brackets. Panel B: Specifications by two-step Heckman, industry and year fixed effects included. Second-stage coefficients reported. Exclusion variables: Cost of Starting Business, Foreign Market Potential. P-values are shown in brackets. Other variables included: Tax rate, Skill Endowment, Capital Endowment, Intellectual Property Rights index, Judicial Quality, Cost of Phone Call, and Common Language.

Table C: Additional Knowledge Intensity Results

	Knowledge Intensity variable				
	Share of Non-Production Workers	ProcInfo	Upknow	JudgInfo	Communication Capital Share
Panel A: Least Squares					
Import Share	10.000	0.185	0.171	0.207	-44.474
	[0.003]	[<.001]	[<.001]	[<.001]	[0.684]
Sales	1.283	0.033	0.024	0.042	15.506
	[0.531]	[0.194]	[0.348]	[0.172]	[0.876]
Panel B: Two-step Heckman					
Import Share	8.335	0.163	0.161	0.180	-13.649
	[0.002)	[<.001]	[<.001]	[<.001]	[0.905]
Sales	1.107	0.044	0.030	0.053	38.365
	[0.537]	[0.039]	[0.138]	[0.031]	[0.625]

Note: Reported is the coefficient for the Trade Cost x Knowledge Intensity variable. Each entry corresponds to a separate estimation. In the Import Share results, the dependent variable is imports for further processing from the U.S. relative to total affiliate sales. In the Sales results, the dependent variable is local sales to non-affiliated parties. Second-step results are shown in the Heckman specifications, where the exclusion variables are Cost of Starting a Business and Foreign Market Potential. OLS specifications include firm-year fixed effects, and two-step Heckman specifications have industry and year fixed effects. All specifications include Trade Costs, Population, GDP, Tax rate, Skill endowment, Capital endowment, Intellectual Property Rights protection, Judicial quality, Common Language, and Cost of Phone Call. P-values in brackets; they are robust and clustered on country-year for OLS, and following Heckman (1976) in the two-step specifications.

Table D: Additional Interactions with Knowledge Intensity

Panel A: Ordinary Least Squares

	Import Share				Affiliate Sales			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Trade costs	-3.670 [<.001]	-3.729 [<.001]	-0.939 [0.113]	-4.041 [<.001]	-0.208 [0.622]	-0.346 [0.396]	0.270 [0.462]	-0.540 [0.311]
Trade costs x knowledge intensity	23.629 [0.023]	25.499 [0.015]	25.123 [0.005]	30.215 [0.021]	-19.661 [0.017]	-14.998 [0.091]	-13.289 [0.107]	-21.635 [0.081]
Intellectual property rights prot'n index x knowledge intensity	-0.234 [0.688]	1.545 [0.190]	1.369 [0.263]		-0.387 [0.400]	1.532 [0.036]	1.519 [0.044]	
Skill endowment x Knowledge intensity		-14.605 [0.070]	-9.225 [0.296]			-21.180 [<.001]	-20.455 [<.001]	
Judicial quality x knowledge intensity		5.430 [0.523]	0.247 [0.977]			11.482 [0.005]	10.973 [0.008]	
Common language x knowledge intensity				-2.110 [0.280]				-4.516 [<.001]
Cost of phone call x knowledge intensity				-2.828 [<.001]				0.517 [0.589]
Industry & Year Fixed Effects	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Country Fixed Effects	No	No	Yes	No	No	No	Yes	No
Firm-year Fixed Effects	No	No	No	Yes	No	No	No	Yes

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), (3), and (4); local affiliate sales to unaffiliated customers in columns (5), (6), (7), and (8). Specifications with industry and year effects include parent sales as a regressor. Also included are GDP, population, skill endowment, capital endowment, tax rate, intellectual property rights protection, judicial quality, common language, and cost of phone call in columns (1), (2), (3), (5), (6), and (7); also included in columns (4) and (8) are GDP per capita, skill endowment, capital endowment, tax rate, intellectual property rights protection, judicial quality, common language, and cost of phone call. Robust p-values allow for clustering by country-year and are shown in brackets.

Table D, continued

Panel B: Two-step Heckman estimation

	Import Share			Affiliate Sales		
	(1)	(2)	(3)	(4)	(5)	(6)
Trade costs	-2.058 [<.001]	-2.008 [<.001]	-2.786 [<.001]	-0.763 [0.031]	-0.965 [0.007]	-0.383 [0.290]
Trade costs x knowledge intensity	22.818 [0.022]	21.013 [0.037]	40.347 [<.001]	-18.570 [0.004]	-12.710 [0.055]	-25.875 [<.001]
Intellectual property rights prot'n index x knowledge intensity	0.386 [0.390]	1.740 [0.107]		-0.464 [0.122]	1.435 [0.040]	
Skill endowment x Knowledge intensity		-3.226 [0.545]			-23.756 [<.001]	
Judicial quality x knowledge intensity		-4.432 [0.435]			14.236 [<.001]	
Common language x knowledge intensity			-0.954 [0.486]			-5.373 [<.001]
Cost of phone call x knowledge intensity			-5.337 [<.001]			1.676 [0.022]

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), and (3); local affiliate sales to unaffiliated customers in columns (4), (5), and (6). Shown are results from the second step. Exclusion variables in the first step: Cost of starting a business, foreign market potential. All specifications include industry and year fixed effects. Also included are parent sales, GDP, population, skill endowment, capital endowment, tax rate, intellectual property rights protection, judicial quality, common language, and cost of phone call in columns (1), (2), (4), and (5); also included in columns (3) and (6) are parent sales, GDP per capita, skill endowment, capital endowment, tax rate, intellectual property rights protection, judicial quality, common language, and cost of phone call. P-values are shown in brackets.

Table E: The Nature of Technology Transfer Costs and Dynamics

	Import Share		Sales	
	(1)	(2)	(3)	(4)
Trade costs	-3.691 [<.001]	-2.746 [<.001]	-0.722 [0.087]	-0.634 [0.061]
Trade costs x knowledge intensity	22.404 [0.053]	23.409 [0.017]	-17.199 [0.040]	-18.300 [0.004]
Affiliate existed in (t-1)	0.329 [0.001]	-1.678 [<.001]	0.578 [<.001]	1.476 [<.001]
Population	-0.446 [0.274]	-0.378 [0.047]	-0.234 [0.201]	-0.242 [0.057]
GDP	0.246 [0.531]	-0.058 [0.764]	0.755 [<.001]	0.914 [<.001]
Tax rate	0.950 [0.017]	1.081 [<.001]	-0.291 [0.039]	-0.475 [<.001]
Skill Endowment	0.969 [0.211]	1.122 [<.001]	-0.353 [0.074]	0.462 [0.003]
Capital Endowment	-0.030 [0.875]	-0.075 [0.439]	0.423 [<.001]	0.539 [<.001]
Judicial Quality	-2.559 [0.022]	-2.093 [<.001]	-0.687 [0.087]	-0.854 [0.004]
Intell. Property Rights Index	-0.422 [0.002]	-0.526 [<.001]	0.175 [0.024]	0.187 [0.001]
Cost of Phone Call	0.515 [<.001]	0.538 [<.001]	0.071 [0.209]	0.061 [0.116]
Common Language	0.370 [0.003]	0.017 [0.852]	0.355 [<.001]	0.504 [<.001]
Parent Sales		-0.146 [<.001]		0.596 [<.001]
Mills ratio: λ		-1.581 [<.001]		0.830 [<.001]
R-squared	0.447		0.572	
Wald χ^2 (60 d.o.f.)		876.98 [<.001]		2,647.04 [<.001]
# of observations	5,961	45,121	7,726	45,121

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1) and (2); local affiliate sales to unaffiliated customers in columns (3) and (4). Specifications (1) and (3) are least squares, and (2) and (4) are two-step Heckman with Cost of Starting Business and Foreign Market Potential as exclusion variables; second step results shown. (1) and (3) have firm-year fixed effects and robust p-values based on clustered s.e.s at the country-year level are shown in brackets; (2) and (4) have industry and year fixed effects, with p-values in brackets.

Table F: Imports from affiliates in third-countries

	Ordinary Least Squares		Heckman Second Stage		Low Import Share	High Import Share
	(1)	(2)	(3)	(4)	(5)	(6)
Trade costs	-3.672 [<.001]	-3.601 [<.001]	-2.037 [<.001]	-2.008 [<.001]	-1.029 [0.042]	-1.197 [0.001]
Trade costs x knowledge intensity	23.761 [0.022]	23.424 [0.023]	22.349 [0.024]	22.385 [0.024]	11.987 [0.191]	11.494 [0.055]
Parent Sales	-0.050 [0.012]	-0.036 [0.052]	-0.297 [<.001]	-0.268 [<.001]	0.031 [0.180]	-0.033 [0.013]
Third-Country Sales		-0.787 [0.010]		-1.429 [<.001]		
Mills Ration: λ			-1.572 [<.001]	-1.532 [<.001]		
Industry & Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.139	0.141			0.071	0.091
Wald χ^2			883.34 [<.001]	896.03 [<.001]		
# of observations	5,961	5,961	45,121	45,121	3,003	2,958

Note: Dependent variable: imports for further processing from the US parent relative to total affiliate sales. Other independent variables included are Population, GDP, Tax rate, Skill Endowment, Capital Endowment, Intellectual property rights protection index, Judicial quality, Common language, and Cost of phone call. Exclusion variables in the Heckman specifications are Cost of Starting Business and Foreign Market Potential. P-values are shown in brackets, robust to clustering by country-year in the OLS specifications.

Table G: Summary Statistics for Country-level Sample

	Mean	Standard Deviation
Knowledge Intensity	-3.471	0.128
Trade Costs	0.065	0.019
Cost of Phone Call	0.582	0.619
IPR Protection Index	1.393	0.150
GDP per Capita	9.429	0.756
Population	16.138	1.424
Maximal Tax Rate	-1.093	0.516
Common Language	0.085	0.252
Skill Endowment	0.801	0.207
Judicial Quality	0.694	0.202
Value-to-Weight	0.385	1.383

Note: All variables except Common Language are in natural logarithms. There are a maximum N = 39 countries.

Table H: The Knowledge Intensity of Multinational Trade

	(1)	(2)	(3)
Trade Costs	5.111 [<.001]	3.700 [<.001]	3.231 [0.014]
Phone Call		0.008 [0.755]	0.015 [0.539]
IPR Protection Index		0.076 [0.603]	0.131 [0.378]
GDP per capita		-0.099 [0.058]	-0.095 [0.083]
Population		-0.064 [<.001]	-0.070 [<.001]
Tax Rate		0.071 [0.166]	0.093 [0.055]
Common Language		-0.067 [0.086]	-0.021 [0.669]
Skill Endowment		-0.154 [0.240]	-0.221 [0.120]
Judicial Quality		0.245 [0.192]	0.152 [0.417]
Weight-to-Value			0.013 [0.417]
R-squared	0.440	0.793	0.802
N	39	36	35

Note: The dependent variable is the average knowledge intensity of U.S. related-party exports. All regressions have a constant (coefficient not reported). All variables except Common Language are in natural logarithms. Robust t-statistics are shown in brackets.