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ABSTRACT

This paper offers a new perspective on technology diffusion, a topic crucial to many fields in economics. We develop a theory of technology transfer by multinationals to their foreign affiliates in which gravity for technology arises because direct communication substitutes for the transfer of technology embodied in traded intermediates. The greater an industry's knowledge intensity, the harder communication becomes. The model predicts that in knowledge-intensive industries trade costs dampen affiliate intermediate imports the least while affiliate sales are deterred the most. Further, the average knowledge content of affiliate imports is increasing in trade costs. We con.rm these predictions using a rich firm-level dataset for U.S. multinationals, and show that the cost of shipping technology is substantial, especially in knowledge-intensive industries.

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1 Introduction

The development and geographical diffusion of technology is center stage in many fields of economics. For instance, modern theories of growth and international trade place little emphasis on the accumulation of tangible factors such as capital and labor, focusing almost entirely on access to technology. Given the recent advances in communication technology, this emphasis on internationally variable access to technology may seem misplaced. After all, in the world of the Internet, technology would seem to be weightless in the sense that physical distance plays no role in the transfer of technology.[1]

The assumption that technology is easily transferred while goods are expensive to move is at the heart of theories of the multinational enterprise (see Markusen 2002). Multinational enterprises account for the bulk of global research and development (R&D) spending and are generally thought to be free to move their operations around the globe in order to maximize the value of their knowledge assets. And yet, the foreign operations of U.S. multinational firms show that technology is subject to the laws of gravity.[2] As we document in this paper, individual multinational affiliates sell less the further away they are from their home country, and gravity has its strongest bite for knowledge-intensive goods. We examine the structure of multinationals' international operations to show that this can be explained by the nature and size of international technology transfer costs.

To account for the apparently very strong force of gravity for knowledge-intensive goods, we focus on the interaction between the difficulties of communicating technological knowledge

[1] An earlier characterization of the weightless economy is given by Quah (1999).

[2] The tendency of foreign direct investment (FDI) to decline in distance has been noted both at the aggregate and firm level (Markusen and Maskus 2002 and Yeaple 2009, respectively); see also Kleinert and Toubal (2010).

from one person to another and the costs of moving goods internationally. The tacit nature of technology means that it is best demonstrated and explained in person. Eighty percent of business executives, for example, hold that face-to-face meetings with co-workers are crucial for effective teamwork (Forbes 2009). In the absence of face-to-face meetings, technology transfer is imperfect, and the efficiency consequences of imperfect transfer are greater the more knowledge-intensive production is. If technology transfer costs are high, firms will concentrate the production of knowledge-intensive goods near the experts and rely instead on trade in finished products that are subject to shipping costs.

We propose a model that builds on this basic insight. In this framework, the multinational's production process can be fragmented into individual intermediate inputs that vary in their knowledge intensity, defined as the number of tasks that require non-codifiable information. Enabling the affiliate to produce individual inputs requires communication between home country and affiliate managers. We assume that the potential for communication failure is rising as goods become more knowledge-intensive but is invariant to physical distance once regular face-to-face interaction becomes infeasible.[3] After all, communication over the Internet should be just as effective at small distances as it is at large distances. The alternative to international communication is to ship intermediates that embody the technology to affiliates in offshore locations. Exporting a given intermediate input to an affiliate avoids communication failure but requires the firm to incur shipping costs that do rise in geographic distance.[4] It

[3] This is most closely related to Arrow (1969), who argues that technology transfer costs are mainly communication costs between teacher and student. Hayek (1945), Polanyi (1958), and Hippel (1994) note that codifiability of information affect its transfer cost. Our approach contrasts with the commonly made no-cost transfer assumption within the multinational firm of Helpman (1984), Markusen (1984), and others. The latter emerges as a special case of our analysis.

[4] Production within the home country allows relatively easy face-to-face interaction between top managers

is the interaction between the costs of imperfect communication for disembodied technology transfer and shipping costs for embodied technology transfer that explains why there is gravity for seemingly weightless technology.

Two sharp, firm-level predictions emerge from this framework. First, the knowledge intensity of production affects the level of affiliate sales around the world. We show that the sales of multinational affiliates to customers in their host country fall as trade costs rise, and the effect of trade costs is *strongest* for knowledge-intensive goods, precisely because it is in these industries that the scope for offshoring is most limited by imperfect technology transfer. Second, the knowledge intensity of production is a determinant of the degree of international vertical specialization. As shipping costs increase, multinational affiliates substitute away from importing intermediate inputs from their home country (where their parent is located), but their ability to do so is constrained by how high the technology transfer costs for the tasks are.[5] Therefore, trade costs have the *weakest* influence on intermediate inputs imported by the affiliate from the country of the parent in relatively knowledge-intensive industries. An additional prediction of the model is that firms change systematically the composition of their international trade in terms of its knowledge intensity as trade costs change relative to technology transfer costs. Confronting the theory with empirical evidence based on detailed information on individual U.S. multinationals and the composition of their trade, we find striking support for these predictions.

and line workers, and face-to-face communication is the most effective form of communication for non-codified information (see Koskinen and Vanharanta 2002).

[5] Rising marginal costs of affiliates may be due to a fixed share of intermediate imports from the parent that are subject to trade costs (Markusen and Zhang 1999, Irrazabal, Moxnes, and Opromolla 2008). In contrast, here the choice of exports versus FDI is endogenous and determined by the transferability of the firm's technology.

Our analysis contributes to several branches of the literature. First, we develop the work on vertical production sharing, which addresses the question of which part of multinational production is locally produced by the affiliate versus imported from home. Our empirical results extend Hanson, Mataloni, and Slaughter's (2005) analysis on trade and factor costs by demonstrating that knowledge intensity is another critical factor that affects vertical production sharing within the multinational firm. Further, in our model the vertical production sharing decision is determined jointly with the multinational's overall activity, which highlights the forces generating complementarity between trade and FDI when there is substitution at the task level (Blonigen 2001).[6] Our work formalizes the way that communication of noncodifiable information imposes limits to offshoring, and we confirm empirically that this affects the offshorability of jobs.[7] In addition to providing a test of the theory, our empirics inform the rapidly growing body of trade theory that highlights the importance of international communication costs determining the feasibility of offshoring (see Antras, Garicano, and Rossi-Hansberg 2008, for instance).[8]

Second, we contribute to the literature on the size of international technology transfer costs and their implications for the gains from openness. A small group of papers studies quantitatively the gains from openness in multi-country general equilibrium models (Eaton and Kortum 2002, Ramondo and Rodriguez-Clare 2008, Burstein and Monge-Naranjo 2008,

[6] In line with our model, Norbaeck (2001) explains his finding of relatively high affiliate import shares in R&D intensive industries for a sample of Swedish multinationals with higher technology transfer costs. Evidence that parent exports rise faster with R&D intensity than affiliate sales do is also provided in Brainard (1997).

[7] Levy and Murnane (2004) hold that routine tasks are the ones that are easy to offshore, while Leamer and Storper (2001) consider codifiability of information to be key; also see Blinder (2009) who defines offshorability as the ability to perform tasks from abroad with little loss of quality.

[8] Grossman and Rossi-Hansberg's trade in tasks framework (2008a, 2008b) also features imperfect task transferability between countries but abstracts from trade costs and the additional empirical implications.

and Garetto 2008). While these studies rely largely on aggregate evidence, here the focus is on testing key model elements with a unique array of micro information on the trade and investment behavior of individual multinational firms. Our emphasis on micro evidence should be very useful to better understand the gains from openness and so inform the design of aggregative models.

Finally, even though the mobility of technological knowledge is crucial for the extent of convergence between firms, regions, or countries, there is little theory that puts the question at the center of the analysis.[9] Our analysis of multinational-led technology transfer leading to gravity provides a new framework for thinking about, for example, the empirical finding of geographically localized international technology diffusion (Keller 2002). It may also help to explain why economic activity is declining with distance *within* countries, even when the actual transport costs are only a small fraction of the value of shipments.[10]

One literature to which we do not contribute directly is the recent work on the boundaries of internationally operating firms (McLaren 2000, Grossman and Helpman 2002, Antras 2003, Antras and Helpman 2004, and Costinot, Oldenski, and Rauch 2009).[11] This literature emphasizes the factors defining the boundaries of the firm within and across borders, rather than the extent and commodity composition of international activity that is our focus. While we abstract from the boundaries of the firm, both our model and our evidence are complementary to this literature in that we shed new light on the level and the composition of offshoring

[9]Exceptions include Aghion and Howitt (1998), Chapter 12, and Howitt (2000).

[10]Glaeser and Kohlhase (2004) report strong distance effects in U.S. shipments even though 80% of all shipments occur in industries where transport costs are less than 4% of total value.

[11]While much of the recent literature, as well as Horstmann and Markusen (1987), emphasizes incentive problems arising from asset specificity when contracts are incomplete, it might also be that lack of intellectual property rights protection means more asset dissipation for arm's length than for integrated production. Recent evidence includes Feenstra and Hanson (2005) and Nunn and Trefler (2008).

irrespective of what organizational form it takes.

The remainder of the paper is as follows. The following section 2 introduces the model and shows that knowledge intensity affects both the level of offshoring as well as the breakdown between tasks of the firm that are completed at home versus abroad. Moreover, section 2 derives the estimating equations implied by the model. Our data on individual U.S. multinational firms is described in section 3. Section 4 provides the evidence, first introducing our baseline empirical results and then covering the major alternative arguments. A number of concluding observations are presented in section 5.

2 Theoretical Framework and Estimating Equations

We begin by introducing the two main elements of the model. Any country has a large number of firms that can each produce a unique variety of a differentiated final good. A given firm in the home country can sell its good to consumers abroad in one of two ways. First, the good can be produced at home and exported. Second, the firm can turn multinational, which means setting up an affiliate in the foreign country, producing there and selling locally. By exporting, the firm incurs trade costs that depend on the distance to the foreign country, while if the firm serves the foreign market through affiliate sales it faces the costs of transferring its technology: productivity abroad is lower than at home. This is the first element of the model.

The second element lies in the production of differentiated goods. Each final good is produced from a range of intermediate goods and services. The intermediate activities may include: market research, R&D towards product design, creation of prototypes, testing, organization of shop-floor production, final assembly, marketing and advertising, packing and shipping to the consumer, and legal services. The ease of technology transfer varies by activity. It is relatively difficult, for example, to transfer R&D towards product design abroad, because this technological know-how is highly non-codified.

These two elements lead to an exports-versus-FDI trade-off for the firm at the level of the intermediate input. For a given foreign market, intermediates with high technology transfer costs will be produced at home and exported, while inputs with low transfer costs will be produced abroad. As distance to the foreign market increases, the shipping costs of exporting increase. Firms equate shipping and technology transfer costs at the margin, and affiliates located far from Home have relatively high costs. Because higher costs reduces sales, affiliates in relatively distant countries from home sell less than affiliates in more nearby countries (gravity).

We now turn to describing the model more formally.

Production A firm (the parent) has developed in its home country j the technology for a variety of a final differentiated good i. The firm wants to produce its variety at a plant (the affiliate) located in host country k with the intent of selling it there. The firm's variety is produced from a continuum of intermediate inputs, index by z, according to:

$$Q^i = \exp\left(\int_0^\infty \beta^i(z) \ln\left(\frac{m(z)}{\beta^i(z)}\right) dz\right), \tag{1}$$

where $m(z)$ is the quantity of firm-specific intermediate z and $\beta^i(z)$ is the cost share of z in industry i. Equation (1) captures the idea that individual pieces of the firm's technology are embodied in each input z. The marginal cost of production for a cost-minimizing affiliate will be

$$C^i_{jk} = \exp\left(\int_0^\infty \beta^i(z) \ln c_{jk}(z) dz\right), \tag{2}$$

where $c_{jk}(z)$ is the minimum unit cost for the affiliate of obtaining input z.

Knowledge intensity in intermediate production To produce one unit of input z, a number of tasks, given by z, must be completed successfully. Because higher z inputs are associated with a greater number of tasks, we call these relatively knowledge-intensive inputs.[12] As in Antras, Garicano, and Rossi-Hansberg (2008), we assume that in the application of each task problems arise that will, if unsolved, result in the destruction of that unit. If all problems that arise are successfully solved, then one unit of the input is produced for each unit of labor employed. If not, then that input is useless, and the labor is wasted. The multinational's parent has expert managers that know the solution to every type of problem that might arise.

Trade vs FDI The affiliate can obtain each input either by importing it from home or through production in the affiliate host country.[13] If input z is imported, then the technology is transferred *embodied* (in the imported input). We assume that when the plant and the headquarters are located in the same country problem-solving communication is perfect and all tasks are completed. However, when an input is shipped from the home country (where the multinational parent is located) to the host country (where the affiliate is located) iceberg-type

[12] Costinot (2009) applies a similar idea in a study of institutional quality and comparative advantage.

[13] If the input is imported, it can come from the multinational parent or from an independent supplier that produces the input for the multinational. Our analysis is consistent with contract frictions determining the boundaries of the firm as in Antras (2003); however, the role of knowledge intensity for offshoring that is our focus is independent of that.

trade costs, $\tau^i_{jk} > 1$, are incurred. This captures the idea that physical transport costs are largely independent of how knowledge-intensive a particular input is (for example, the LCD screen versus the case of a laptop). We abstract from factor cost motivations in the choice between exporting and local affiliate production by considering a world in which the wage is the same and normalized to unity in both countries.[14]

To obtain input z locally, the parent firm must transfer the technology for producing it to the host country. In this case the technology is transferred in *disembodied* form. By doing so, the firm avoids shipping costs, but imperfect communication between managers leads to a loss of productivity. In particular, when the firm's headquarters and the producer are in different countries, the solutions to only a fraction $\widetilde{\lambda} \in (0,1)$ of potential problems is successfully transmitted to the offshore producer of the input. Assuming that the success rate of communication is independent across tasks, the probability of successful communication is declining in the number of tasks.[15] Consequently the expected number of labor units needed to produce a unit of the input is increasing in the number of tasks; it equals

$$\exp(\lambda z), \tag{3}$$

where the $\lambda \equiv -\ln \widetilde{\lambda} > 0$ captures the costs of international technology transfer. Because a greater number of tasks implies that communication problems have more severe consequences,

[14] Lower wages in the host country will generally favor affiliate production, and it may lead to the affiliate shipping further processed inputs to the multinational parent for home country sales. While it is straightforward to extend the model along these lines, it does not yield new major insights on the role of knowledge intensity for technology transfer and offshoring. We allow for wage differences in the empirical analysis however.

[15] A success rate of communication that is independent across tasks for a given firm is consistent with there being different languages and codes across firms, as emphasized in Cremer, Garicano, and Prat (2007).

the cost of offshoring is increasing in the knowledge intensity of the input.[16]

The cost to the affiliate of obtaining a unit of intermediate input z is therefore

$$c_{jk}(z) = \min\left\{\tau^i_{jk}, \exp(\lambda z)\right\}. \tag{4}$$

Equation (4) implies that a cost-minimizing affiliate will produce less knowledge-intensive inputs $z < \widehat{z}^i_{jk}$ locally and import from the home country all relatively knowledge-intensive inputs $z > \widehat{z}^i_{jk}$, where

$$\widehat{z}^i_{jk} = \frac{1}{\lambda} \ln\left(\tau^i_{jk}\right). \tag{5}$$

We see that the average knowledge intensity of an affiliate's imports from the home country is increasing in the size of trade costs ($d\widehat{z}^i_{jk}/d\tau^i_{jk} > 0$). This prediction on the knowledge intensity of the multinational's international trade will be tested in section 4 below.

Knowledge intensity at the industry level The link between the knowledge intensity of intermediate inputs and the corresponding final goods industry is established through the cost shares, $\beta^i(z)$ in equation (2). Industries that use predominantly knowledge-intensive (high-z) inputs have high cost shares $\beta^i(z)$ for such inputs, and we refer to such industries as knowledge-intensive. For simplicity, we choose a functional form that summarizes an industry's knowledge intensity using a single parameter:

$$\beta^i(z) = \phi^i \exp(-\phi^i z). \tag{6}$$

[16] Note that knowledge intensity might not only affect marginal but also fixed costs of production. As long as higher knowledge intensity leads to higher fixed costs, this will strengthen our results while making the model much less tractable.

This implies that the average knowledge intensity of inputs in industry i is $1/\phi^i$.[17]

Geography of marginal costs Using (2), (4), and the definition of $\beta^i(z)$, the marginal cost of an affiliate producing a variety of good i in country k is given by

$$C^i_{jk} = \exp\left(\frac{\lambda}{\phi^i}\left(1 - \left(\tau^i_{jk}\right)^{-\frac{\phi^i}{\lambda}}\right)\right). \tag{7}$$

How do affiliate costs depend on technology transfer costs and geography? Differentiating (7) with respect to trade costs we obtain

$$\varepsilon^{C^i_{jk}}_{\tau_{ik}} \equiv \frac{\tau^i_{jk}}{C^i_{jk}} \frac{\partial C^i_{jk}}{\partial \tau^i_{jk}} = (\tau^i_{jk})^{-\frac{\phi^i}{\lambda}} > 0. \tag{8}$$

An increase in trade costs between host and home countries results in an increase in the marginal cost of the affiliate, and the size of this increase is increasing in the knowledge intensity of the industry, $1/\phi^i$. In the special case of zero knowledge intensity ($1/\phi^i \to 0$), our model features no-cost transfer of the firm's technology, as in Helpman (1984), Markusen (1984). In that case, the marginal cost of the multinational does not depend on trade costs, as in Brainard's (1997) proximity-concentration framework once FDI is the optimal firm strategy.

The impact of knowledge-intensive production on the affiliate's marginal cost affects both the affiliate's level of sales and the extent to which the affiliate imports inputs from the home country. Before we turn to these predictions, we close the model by specifying preferences and deriving the resulting demand for a multinational firm's product. In each country, the repre-

[17] There are other formulations that yield the same results as this exponential functional form. Their common feature is that a single parameter governs the size of the inverse Mills ratio for all possible truncations.

sentative consumer has identical, homothetic preferences over I differentiated goods, indexed by i, and a single, freely-traded homogenous good Y, given by

$$U = \sum_{i=1}^{I} \Phi^i \ln \left(\int_{\omega \in \Omega^i} Q^i(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}} + \left(1 - \sum_{i=1}^{I} \Phi^i \right) \ln Y, \tag{9}$$

where Ω^i is the set of varieties available in industry i, $Q^i(\omega)$ is the quantity of output of variety ω consumed, $\sigma > 1$ is the elasticity of demand, and Y is the quantity consumed of the homogenous good. Each country produces good Y using a single unit of labor, which yields identical wages across countries.

Assuming that firms are too small to affect industry-level demands, the preferences (9) imply the following iso-elastic demand for variety ω in country k:

$$Q_k^i(\omega) = B_k^i (p_k(\omega))^{-\sigma}, \tag{10}$$

where B_k^i is the endogenous demand level in country k and industry i, and $p_k(\omega)$ is the price of the variety ω in country k.

Now we show the impact of knowledge intensity on the multinational's sales as well as it's degree of vertical specialization. We turn to the latter first.

Vertical specialization The affiliate's total costs, TC_{jk}^i, are the sum of its import costs from the home country, IM_{jk}^i, plus the costs of the locally produced inputs. A good measure of vertical specialization of the multinational is the cost share of inputs imported from home, IM_{jk}^i / TC_{jk}^i, which is observed in our dataset. By Shephard's Lemma, this is equal to the elasticity of marginal costs with respect to τ^i_{jk} (equation (8)). Thus the degree of vertical specialization is given by a simple expression consisting of trade costs (τ^i_{jk}), technology transfer costs (λ), and the industry's knowledge intensity (ϕ^i):

$$\ln\left[\frac{IM^i_{jk}}{TC^i_{jk}}\right] = -\frac{\phi^i}{\lambda}\ln(\tau^i_{jk}). \tag{11}$$

Intuitively, the degree of vertical specialization depends on knowledge intensity because knowledge-intensive industries are those where input production requires a lot of problem-solving communication, which can fail, thereby making them harder to move offshore. Specifically, for a given increase in trade costs the cost share of inputs imported from the home country is decreasing more slowly in knowledge-intensive industries:

Hypothesis 1: the share of intermediate inputs imported from the home country in total costs (IM^i_{jk}/TC^i_{jk}) is strictly decreasing in transport costs (τ^i_{jk}) between affiliate host and home countries, and the percentage rate of decline is slower in knowledge-intensive (low ϕ^i) industries.

Gravity in Affiliate Sales Given a demand for its variety according to equation (10), the affiliate's revenues obtained on sales to customers in country k are

$$R^i_{jk} \equiv p^i_{jk}Q^i_{jk} = \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} B^i_k\left(C^i_{jk}\right)^{1-\sigma_i}. \tag{12}$$

Totally differentiating this expression with respect to trade cost, we find

$$\varepsilon_{\tau_{ik}}^{R_{jk}^i} \equiv \frac{\tau_{jk}^i}{R_{jk}^i}\frac{\partial R_{jk}^i}{\partial \tau_{jk}^i} = -(\sigma-1)\varepsilon_{\tau_{jk}^i}^{C_{jk}^i}. \tag{13}$$

The influence of knowledge intensity on revenues is inversely proportional to its effect on costs. Given that our dataset has detailed information on sales, we can bring to bear micro evidence on this model. Equation (13) yields the following hypothesis for the effect of knowledge intensity on gravity:

Hypothesis 2: Holding fixed the demand level, B_k^i, the value of affiliate revenues generated on sales to local customers, R_{jk}^i, is decreasing in trade cost τ_{jk}^i, and the percentage rate of this decrease is highest in the most knowledge-intensive industries (low ϕ^i).

It is the interaction between trade costs and knowledge intensity that generates gravity in affiliate sales. When technology is perfectly transferable internationally, as in the limiting case when $1/\phi^i \to 0$, affiliate sales display no gravity effect. As technology becomes more knowledge-intensive ($1/\phi^i$ rises), the pull of gravity increases. Note that higher costs in more distant markets could also be due simply to technology transfer costs going up with distance (e.g., cultural differences). This model shows that it is not necessary to assume this, and empirically we find that country-specific factors alone fall well short of explaining the patterns in the data.[18]

Before turning to the empirical analysis, note that knowledge intensity in production *lowers* the impact of trade costs on vertical specialization (Hypothesis 1) while it *raises* the effect of

[18] Moreover, the empirical analysis of section 4 will also account for fixed costs in multinational activity.

trade costs on affiliate sales (Hypothesis 2). These contrasting predictions offer a strong test of our framework.

Estimating Equations We now derive estimation equations for Hypotheses 1 and 2, turning first to intermediate input imports by the affiliate from the home country. The key relationship is given by equation (11), which we amend by adding an error, $\epsilon^i_{\omega jkt}$, to obtain

$$\ln\left[\frac{IM^i_{\omega jkt}}{TC^i_{\omega jkt}}\right] = -\frac{\phi^i_t}{\lambda}\ln(\tau^i_{jkt}) + \epsilon^i_{\omega jkt},$$

where ω indexes firm (and variety) and t time; ϕ^i_t is the inverse measure of knowledge intensity, λ is the measure of technology transfer costs, and $\epsilon^i_{\omega jkt}$ captures unobserved differences in the cost of importing. We parameterize ϕ^i_t as $\phi^i_t = -(\delta_0 + \delta_1 KI^i_t)$, where KI^i_t is knowledge intensity, measured as R&D over sales. R&D-intensive products typically require many tasks to be completed, and R&D is also associated with frequent changes in production techniques and product design that require the problem-solving communication captured by the model.[19] We assume that $\epsilon^i_{\omega jkt}$ is given by

$$\epsilon^i_{\omega jkt} = \eta_{\omega t} + \rho X_{kt} + \varepsilon^i_{\omega jkt},$$

where $\eta_{\omega t}$ is a firm-year fixed effect to control for idiosyncratic, firm-level variation in the ability to transfer technology, X_{kt} is a set of country determinants of FDI, and $\varepsilon^i_{\omega jkt}$ is measurement error. Our estimating equation is

[19] An alternative measure of knowledge intensity, based on worker data on skills and occupation (the Bureau of Labor Statistics' O*NET data), gives qualitatively similar results to what we obtain below.

$$\ln\left[\frac{IM^i_{\omega jkt}}{TC^i_{\omega jkt}}\right] = \eta_{\omega t} + \rho X_{kt} + \frac{\delta_0}{\lambda}\ln(\tau^i_{jkt}) + \frac{\delta_1}{\lambda}\left[\ln(\tau^i_{jkt}) \times KI^i_t\right] + \varepsilon^i_{\omega jkt}. \tag{14}$$

The model predicts that $\delta_0/\lambda < 0$ and $\delta_1/\lambda > 0$. As trade costs increase, firms substitute local production for imports of intermediate goods from the home country, but this substitution is more costly in knowledge-intensive industries with hard-to-transfer technologies.[20]

Hypothesis 2 on gravity in affiliate sales is tested by estimating an equation similar to (14) for the sales of the affiliate, $R^i_{\omega jkt}$. This estimating equation is given by

$$\ln R^i_{\omega jkt} = \gamma_{\omega t} + \kappa X_{kt} + \varsigma_0 \ln(\tau^i_{jkt}) + \varsigma_1\left[\ln(\tau^i_{jkt}) \times KI^i_t\right] + \upsilon^i_{\omega jkt}, \tag{15}$$

where the demand term B^i_k in the sales equation (12) above indicates that we need to control for market size effects. Hypothesis 2 is that the trade cost complementarity effect is negative, $\varsigma_1 < 0$; also, ς_0 is non-positive.

There are a number of generic issues in estimating equations (14) and (15), of which endogeneity is the most important. In order to address endogeneity concerns, we first include firm-year fixed effects, $\eta_{\omega t}$, and country variables, X_{kt}, which reduces omitted variable problems. Second, the affiliate's import share and sales are *not* related to firm-level variables according to equations (14) and (15). Instead, the key measure of knowledge intensity is an industry-wide measure, R&D over sales, for the industry to which firm ω belongs. This will reduce the extent that dependent and independent variables are simultaneously determined in our estimating equations.

[20] We do not include a linear term for KI^i_t because it is subsumed into the firm-year fixed effect.

We now turn to describing the data set.

3 Data

Our firm-level data of the international structure of U.S. multinationals' operations come from the Bureau of Economic Analysis (BEA) surveys of *U.S. Direct Investment Abroad*.[21] A U.S. multinational entity is the combination of a single U.S. legal entity that has made the direct investment, called the U.S. parent, and at least one foreign business enterprise, called the foreign affiliate. As a result of confidentiality assurances and penalties for non-compliance, BEA believes that coverage in this survey is close to complete and levels of accuracy are high.

In building the dataset we first link the BEA data for each U.S. parent whose main-line-of-business is a manufacturing industry to each of its majority-owned foreign affiliates for each of the benchmark years 1994, 1999, and 2004. For each parent, we extract information on its industry, its total expenditure on research and development, and its total sales.[22] Aggregating over parents by industry and year, we calculate the R&D intensity of each industry as R&D expenditures over sales. This is the variable KI_t^i, the measure of the knowledge intensity of each industry's technology. Next, we obtain from the BEA all of the relevant information concerning affiliate operations. Our main measure of affiliate sales is the affiliate's sales to customers in the host country.[23]

[21] U.S. direct investment abroad is defined as the direct or indirect ownership or control of a single U.S. legal entity of at least ten percent of the voting securities of an incorporated foreign business enterprise or the equivalent interest in an unincorporated foreign business enterprise.

[22] BEA industry definitions changed from SIC-based categories in 1994 to NAICS-based categories in 1999. To match tariff and freight cost data to our firm-level data, we concorded the later year NAICS-based categories into 1994 SIC-based categories.

[23] In the Appendix, also results for affiliate sales to customers located in the United States and to customers

Our main imports measure is the affiliate's imports of intermediate inputs from the United States.[24] We then aggregate over all the affiliates of each parent firm by country and year to form a single country-year-parent observation. We avoid including purely wholesaling affiliates by discarding all affiliates that lack operations in a manufacturing industry. Each country-year-parent observation has then assigned the parent firm's industry, and therefore the firm fixed effect controls for all pure industry effects.[25]

Our *ad-valorem* measure of trade costs is defined as

$$\tau_{kt}^{i} = 1 + fc_{kt}^{i} + tariff_{kt}^{i},$$

where fc_{kt}^{i} is an *ad-valorem* measure of freight costs, and $tariff_{kt}^{i}$ is an ad-valorem measure of tariffs, both at the industry-country-year level. Freight costs, fc_{kt}^{i}, are constructed from trade values including cost, insurance, freight (c.i.f.) to values that do not include this (free on board, or f.o.b. values) in the Feenstra, Romalis, and Schott (2002) dataset following the methodology of Hanson, Mataloni, and Slaughter (2005).[26] The tariff measure, $tariff_{kt}^{i}$, is calculated from figures in the United Nations' TRAINS dataset and extracted with the WITS software of the World Bank, where we use the same method of computing industry-level values

located in other foreign countries are shown. We find strong evidence that the factors emphasized by the model are not only related to local market conditions.

[24]We identify intermediate input imports in the BEA data as imports "for further processing". In the Appendix, we also employ the broader measure of all affiliate imports from the United States, which gives similar results.

[25]In three food processing industries and one fabricated metal industry, there is virtually no trade between parent and affiliate. These industries with import shares less than 3 percent were dropped from the sample, leaving us with 48 SIC-based BEA industries.

[26]From U.S. import data disaggregated by country-industry-year, the freight cost is computed as the ratio of freight and insurance charges to the customs value of imports. The resulting figures are then aggregated to BEA industry classifications using U.S. exports to that country as weights.

as employed to construct the freight cost measure.

We also assemble variables on other factors known to affect multinational activity (the $\mathbf{X}$ in equations 14 and 15 above). First, there is information on GDP per capita and population from the Penn World Tables. These variables capture market size effects that we expect to play a role especially for affiliate sales (see the market size term B_k^i in equation 12 above). The size of the population in a host market may also pick up fixed costs of affiliate operations, which might give rise to increasing returns to scale.

We also control for factor price differences across countries. Skill abundance of the host country may affect FDI because it can lead to a low factor price for skilled labor, thereby making local affiliate production of skill-intensive tasks relatively attractive. Our measure of skill abundance is human capital per worker, and the analogous measure of capital abundance is capital per worker, both from Hall and Jones (1999). General factor price differences between the FDI host country and the U.S. are also picked up by GDP per capita. Note that while including a number of variables is conservative in terms of testing the predictions, the variables may partly capture the same variation in the data, and collinearity problems might arise.

We also 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).[27] Moreover, work on the international tax system emphasizes that multinationals may engage in transfer pricing by altering the value of within-

[27] Cross-country variation in the cost of making a phone call to the United States will also be indicative of differences in within-country communication costs, one of the key factors in Antras, Garicano, and Rossi-Hansberg (2008).

firm transactions to reduce their global tax burden. In order to be able to pick up these effects, we include the host country's maximum marginal corporate tax rate (source: Michigan 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. We expect that countries in which intellectual property rights (IPRs) 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 outsourced offshoring, we want to be certain that our findings are not primarily due to factors that determine firm organization. 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.

The summary statistics of the data, shown in Table 1, reveal several interesting features. The first four rows show the average sales (in natural logarithms) by location of the final customer. These data reveal that the average affiliate sells much more to customers in its host country than to customers located elsewhere. For instance, the average affiliate revenue in its host country market is more than ten times its revenue on sales to customers in the United States ($e^{10.397}$= \$33 million compared to $e^{7.713}$ = \$2.2 million). At the same time, there is much more variation across affiliates in export sales than in local sales, as indicated by the larger standard deviations in rows three and four relative to row two. The next two rows in Table 1 report (in natural logarithms) the average import shares from the United States for U.S.-owned affiliates located abroad, indicating that the bulk of these imports are intermediate inputs, as emphasized in our model.

The following section presents the empirical results.

4 Estimation results

In this section we present our empirical results. We will see that the coefficient estimates for the trade costs-knowledge intensity variable ($TC \times KI$ for short) are consistent with Hypotheses 1 and 2 and are remarkably robust across specifications that incorporate a wide range of other determinants. In particular, we account for variation across countries and goods that is due to (1) comparative advantage, (2) market size and fixed costs, (3) communication costs and knowledge intensity, and (4) institutional quality and knowledge intensity. We begin with a set of specifications that feature trade costs (TC) and $TC \times KI$ plus a set of country variables in Table 2. Subsequent tables show specifications that allow for interactions between country and industry variables that plausibly could be correlated with $TC \times KI$. None of the specifications shown below report coefficients for variables that vary only by industry because the specifications are all estimated on data that has been demeaned by firm-year, and each firm observation is associated with a particular industry. The coefficient estimates associated with additional robustness checks can be found in the Appendix.

Table 2 shows results for the affiliate's import share (Hypothesis 1) on the left-hand panel and the parallel results for the affiliate's sales (Hypothesis 2) on the right-hand panel. We first discuss the import share results. The import share is decreasing in trade costs as shown in column 1, but the coefficient is only significant once the $TC \times KI$ variable is included as well (column 2).[28] The latter has a positive coefficient, indicating that the import share in industries using more knowledge intensive technologies tends to be less sensitive to changes in trade costs than the import share in industries featuring less knowledge-intensive technologies. This provides initial support for Hypothesis 1 of our model.

In column 3 we control for a country's population and GDP per capita to capture variation in market size and level of development, and we include the host country's corporate tax rate. The coefficients are each statistically significant and indicate that the import share is decreasing in a country's population and its GDP per capita and increasing in its corporate tax rate. The fact that the import share is declining in population and GDP per capita is consistent with the existence of fixed costs associated with local production: when sales are large, firms substitute local production of inputs for imports. The negative coefficient on GDP per capita may also reflect variation across countries in the quality of policies and institutions that make local production relatively more attractive. The positive coefficient on the tax rate is consistent with a role for transfer pricing, where multinationals overcharge the value of shipments to

[28] We do not include KI independently because the data has been demeaned by firm-year and KI varies only by a firm's industry.

affiliates if these are located in high-tax countries. Conditional on total sales, this would yield a high import share. Note that after controlling for these fundamental country characteristics, the absolute effect of trade costs on the import share is larger than in column 2.

Next, we find that high-quality institutions tend to favor local economic activity, or low import shares: both IPR protection and Judicial Quality have a negative coefficient (the former significant, see column 4). As long as affiliate production leads to stronger technological learning for firms in the host economy than exporting from home (see Keller and Yeaple 2009), high levels of IPR protection will make multinational firms less reluctant to move sensitive production processes abroad because it is associated with less leakage of technological knowledge. The inclusion of institutional variables seems to reduce the impact of GDP per capita, suggesting that they also pick up variation in the level of development. In contrast, the coefficient on $TC \times KI$, of key interest in terms of Hypothesis 1, changes little. Among the two factor endowment variables that we also add in column 4, human capital has a positive coefficient while that of physical capital is essentially zero. This may be because they pick up primarily a country's level of development which is already covered by other covariates.

Communication problems are central to our analysis of international technology transfer, so we include two direct measures of communication costs in the specification shown in column 5. Interestingly, imports are relatively high both in English-speaking host countries and in countries that are expensive-to-call. To the extent that offshore production requires advice via frequent telephone conversations, the latter is consistent with our emphasis on technology transfer costs. One would also expect that better communication through a common language leads to lower imports, but our results indicate the opposite, in part perhaps because what matters is technical as opposed to everyday language similarity.[29] Importantly, the communication variables do not affect the finding that affiliates' imports are less sensitive to trade costs in knowledge-intensive industries (Hypothesis 1), as evidenced by the largely unchanged coefficient on the $TC \times KI$ variable in column 5.

We now turn to the results associated with local affiliate sales on the right side of Table 2. Our discussion proceeds along the same sequence of specifications. We see from column 6 that local affiliate sales are declining in trade costs (gravity), and this result is particularly strong for firms that specialize in knowledge-intensive products, as the coefficient on $TC \times KI$ in column 7 shows. This is in line with Hypothesis 2: stronger gravity in relatively knowledge-intensive industries. Controlling for population, GDP per capita, and corporate tax rate, we find as one would expect that affiliate sales are higher in larger and richer countries (column 8). While the coefficient on $TC \times KI$ is somewhat reduced in absolute size it is still significant. In column 9, we find that among the factor endowment variables, the role of physical capital in determining affiliate sales is larger than that of human capital, and the former also appears to shrink the GDP per capita coefficient to about one half. In contrast, the impact of institutions on affiliate sales appears to be smaller than on imports versus local activity (comparing column 9 with column 4).

The final column of Table 2 shows how affiliate sales are affected by adding the communication variables. Common language raises affiliate sales, in line with standard gravity results, while the price of phone calls does not matter. We also see that human capital, the tax rate,

[29] It could also be that the common language variable picks up to some extent the difference between Canada and Mexico, two major U.S. FDI locations.

and IPR protection are now significant while before they were not. High IPR protection favors affiliate sales, while high tax rates and high human capital endowments reduce sales of US affiliates. Moreover, with the language variable included, the coefficient on $TC \times KI$ is again quite similar to column 7, where no variables other than TC and $TC \times KI$ are included. In the following discussion, we will refer to columns (5) and (10) of Table 2 as our baseline results.

To summarize, we find evidence for both Hypothesis 1 and Hypothesis 2 that is robust to controlling for a variety of country-level variables. In the following section, we extend the analysis by allowing for comparative advantage.

Comparative Advantage The model of Helpman (1985) suggests that imports of intermediate inputs should be high when countries are very different in terms of their endowment so that comparative advantage plays a role. In his model, high human capital countries develop technologies and intermediates of relatively high skill intensity. In the following we consider three specific sources of comparative advantage, arising from skill abundance, capital abundance, and institutional factors (on the latter, see e.g. Nunn 2007). Our first approach, following Romalis (2004) and Nunn (2007), is based on multiplying a country characteristic (such as skill abundance) by the corresponding industry characteristic (skill intensity). If strong comparative advantage effects are present, this country-industry interaction will enter the regression with a significant positive sign.

The results from including all three sources of comparative advantage in the import share regression are shown in column 1 of Table 3. It turns out that none of the three comparative advantage interaction variables has a significant impact on the import share of U.S. multinational affiliates, and consequently, the impact on the trade cost-knowledge intensity ($TC \times KI$) variable is small. However, one might wonder whether the trade cost variable itself acts as a proxy for certain kinds of factor abundance, because the countries that have accumulated factors tend to have relatively low trade costs *vis-a-vis* the United States. To address this concern, our second approach multiplies the country characteristic (such as skill abundance, SA) with knowledge intensity and includes this $SA \times KI$ variable in the regression in addition to the $TC \times KI$ variable.

Including the skill-knowledge intensity variable $SA \times KI$ leads to a negative but imprecise estimate, and the $TC \times KI$ variable is hardly affected (column 2). Also the judicial quality-knowledge intensity point estimate is negative and insignificant, while capital-knowledge intensity comes in positive and insignificant (columns 4 and 3, respectively). High levels of skill and capital abundance typically mean that a country is relatively rich, so a more crude but at the same time more parsimonious way of checking whether the trade cost-knowledge intensity variable picks up factors that are negatively related to TC is to include the interaction of GDP per capita with knowledge intensity in addition to $TC \times KI$. The results of this are shown in column 5; the GDP per capita times knowledge intensity variable is not significant at standard levels, while the $TC \times KI$ coefficient is similar to before. This suggests that our import share results are not strongly driven by comparative advantage effects.

On the right side of Table 3 the corresponding results for affiliate sales are shown. Generally, comparative advantage has a stronger impact on affiliate sales than on the vertical specialization of the multinational. While skill- and capital-based comparative advantage do not play a significant role, we find that the institutional quality-contract intensity variable has a positive effect on sales (column 6). This is in line with Nunn's (2007) result for international trade. Including institutions-based comparative advantage also reduces the (absolute) size of the $TC \times KI$ variable somewhat.

The next three columns of Table 3 include the skill-, capital-, and institutions-knowledge intensity variables in addition to $TC \times KI$, respectively. The strongest finding is that U.S. affiliates sell less in skill abundant countries if the good is knowledge-intensive instead of basic (column 7). This finding is distinct from a simple comparative advantage argument where knowledge intensity proxies for skill intensity, as the results of column 6 have shown where the skill intensity variable is not significant. Rather, it points to some correlation between trade costs and human capital, as discussed above. It is therefore important that the $TC \times KI$ estimate is still highly significant and negative, which provides support for the model's prediction that gravity in affiliate sales is strongest for knowledge intensive products. Similar to the skill-knowledge intensity variable, we find that judicial quality reduces affiliate sales most for knowledge intensive products (column 9), while the $TC \times KI$ estimate is hardly changed. The parsimonious interaction of GDP per capita with knowledge intensity is not significant (last column of Table 3).

Overall, we have found that comparative advantage matters. It affects especially affiliate sales, while the influence of comparative advantage on the import share of multinational affiliates is smaller. Moreover, the results are consistent with some correlation between factor abundance (or level of development) and trade costs, which underlines the importance of this robustness check. At the same time, the empirical support for Hypothesis 1 and 2 of the model remains very strong, from which we conclude that at least the most important comparative advantage channels are not driving these results.

We now explore the role of market size in our results on the affiliates' offshoring activity.

Fixed costs of FDI For simplicity, the model dispenses with fixed costs of production and technology transfer by assuming that all costs are proportional to sales. Substantial plant-level fixed costs, however, may result in scale economies that give the multinational an incentive to concentrate production at home and serve the foreign market through exports. In our analysis this would show up as relatively high affiliate imports where fixed costs are high. If fixed costs are higher in knowledge-intensive industries, as seems plausible, this would lead to high imports in knowledge intensive industries. As long as this is a simple mean-shift in imports it will be picked up by the firm fixed effects.[30] However, the key slope coefficients may be affected if fixed costs interact with trade costs or something that is correlated to trade costs, such as the level of development.

Our first approach to examining the role of fixed costs in this context is to add GDP per capita, multiplied by knowledge intensity, to the regression and see what impact that has on the $TC \times KI$ variable. In fact, this was one of the Table 3 specifications (see columns 5 and 10), and the impact on the trade cost-knowledge intensity variable was small. The second approach is more direct by employing measures of scale economies in interactions with trade costs. We use Antweiler and Trefler's (2004) measures, which are skill intensity and capital intensity. Table 4 shows the results.

We begin on the left-hand side of Table 4 by examining the import share prediction. The

[30] Recall that each firm is allocated to a single industry, so that our specification encompasses the case of industry-specific fixed effects.

specification in the first column is one in which the $TC \times KI$ variable is dropped and skill intensity is interacted with trade costs instead. The estimate is positive, consistent with the idea that imports fall less with trade costs for high fixed cost-industries, but the coefficient is not precisely estimated. Employing capital intensity instead of skill intensity also yields a positive coefficient, but in this case the variable is highly significant (column 2). These results are consistent with substantial fixed costs in offshoring. An important question is whether these relationships are behind our findings on the trade cost-knowledge intensity variable.

To find out, we have repeated the previous two specifications with $TC \times KI$ included as well, see columns 3 and 4 of Table 4. The results for the skill- and capital-intensity variables are similar to before, with a stronger TC times capital intensity than TC times skill intensity effect. The linear trade cost coefficient changes from about -4 to -9 with the inclusion of the TC times capital intensity variable. Together with the positive coefficient on TC times capital intensity, this is highly consistent with important fixed costs of offshoring. At the same time, the estimates for the trade cost-knowledge intensity variable are positive, highly significant, and quantitatively similar to the baseline estimation (Table 2, column 5). We conclude that while fixed costs might help to explain the vertical specialization of multinational firms, the evidence for variable technology transfer costs in support of Hypothesis 1 is not affected by it.[31]

We take the same steps in the analysis of affiliate sales on the right side of Table 4. If included by themselves (columns 5 and 6), both $TC\times$ skill intensity and $TC\times$ capital intensity

[31] Fixed costs might also be related to the contract intensity of a good; we have included TC times contract intensity in the regression, finding that the $TC \times KI$ coefficient is largely unchanged.

have a negative coefficient, consistent with the idea that fixed costs help to explain the relatively strong gravity for certain industries; at the same time, neither coefficient is significant at standard levels, and in addition, the capital intensity-based coefficient is close to zero. Not surprisingly, the results are very similar to the baseline result of Table 2, column 10 when we add the $TC \times KI$ variable again in the regressions (see columns 7 and 8).

Overall this analysis suggests that the evidence in support of Hypothesis 1 and 2 reported above is not primarily due to fixed costs of offshoring that are not associated with multinational's technology transfer.[32] The following examines the robustness of the findings with respect to our communication cost assumptions.

Communication Costs The model assumes that communication costs are symmetric across countries so that only trade costs vary across locations, but this may not be the case in the data. Moreover, it is plausible that trade costs are high when communication costs are high as well, and in that case trade costs will pick up the communication cost differences that is omitted from the regression. A straightforward way of assessing the importance of such effects is to include the communications variables, common language and the costs of phone calls, multiplied by knowledge intensity in the analysis. Table 5 shows these results.

The first column on the left shows for comparison the baseline import share result (of Table 2, column 5). In columns 2 and 3 we include the common language-knowledge intensity and phone call-knowledge intensity variables, respectively. The estimates for both are negative but

[32] Another way of looking at the results in Table 4 is to ask whether skill- or capital intensity might be good alternative measures of knowledge intensity. We see that neither skill- nor capital intensity yields consistently significant coefficients in the light of the theory; this is consistent with R&D intensity being a better measure for knowledge intensity.

insignificant at standard levels, and the results for the $TC \times KI$ variable do not change much.

For the affiliate sales results on the right-hand side of Table 5, the two additional communication variables turn out to be more important (see columns 5 and 6; baseline again in column 4). Common language has a lower effect of raising sales when the products are knowledge intensive (column 5), may be because simply speaking the same language does not help to communicate complex technological knowledge. The second finding is that expensive phone calls raise affiliate sales especially for complex products (column 6; marginally significant). The latter result is somewhat surprising. It may be related to the fact that the $TC \times KI$ estimate moves from -21 to -25 as the phone-knowledge intensity variable is included.

Generally the results, especially for sales, are consistent with the idea that variation in communication costs plays some role in explaining affiliate activity. At the same time the omitted variable problems resulting from that are small and do not affect the evidence in favor of Hypothesis 1 and Hypothesis 2.

We now turn to a more thorough examination of the impact of institutional quality on the structure of affiliate operations.

Institutions, Complexity, and Contracts An interesting possibility is that firms are forced to import intermediates from their home country because they have difficulty writing or enforcing contracts with local suppliers. If so, this might also raise the cost of serving particular markets from local affiliates and so affect affiliate sales. Moreover, the effects of such contract issues might behave in a fashion similar to technology transfer costs in that they are most serious for knowledge-intensive goods.[33] To allow for this possibility we consider several specifications that incorporate various dimensions of this potential problem into our analysis. First, the importance of judicial quality might vary with the knowledge intensity of the input. To the extent that judicial quality and trade costs are correlated (negatively, one would presume), the trade cost-knowledge-intensity variable $TC \times KI$ will pick this up. We will thus include the product of judicial quality and knowledge intensity directly in the regression. Second, IPR protection is likely more important for relatively knowledge-intensive products. This motivates the inclusion of an IPR times knowledge intensity variable. And third, it is possible that contract intensity is correlated with knowledge intensity, in which case the $TC \times KI$ variable may primarily pick up firm-boundary effects that are not central to our analysis. To alleviate this concern we include a TC times contract intensity variable in the regression. Table 6 shows the results for import share specifications in columns 1-3 and local affiliate sale specifications in columns 4-6.

In column 1, we see that the impact of judicial quality on the affiliate's import share does not depend on knowledge intensity.[34] In contrast, the imports-reducing effect of high IPR protection is lower in the case of knowledge-intensive goods (column 2, marginally significant). This suggests, as expected, that the local protection of intellectual property rights is relatively more important for knowledge-intensive goods. At the same time, the $TC \times KI$ variable remains positive and significant, in fact it increases from 27 (Table 2, column 5) to 34, so the

[33] Contracting difficulties can give an incentive to obtain knowledge intensive goods through in-house production rather than from independent suppliers (Constinot, Oldenski, and Rauch 2009). In our framework, knowledge intensity affects the ability of firms to use their technology abroad in the first place, irrespective of which organizational form is chosen.

[34] We repeat this result from Table 3, (4) here for convenience.

support for Hypothesis 1 remains strong. Including the trade cost-contract intensity (column 3) variable yields a negative and statistically significant coefficient. Interestingly, the coefficient on $TC \times KI$ is largely unaffected, suggesting that the collinearity between the interaction terms is small. At the same time, the linear coefficient on TC is now statistically insignificant, which suggests that a combination of contracting issues and knowledge-intensive production are the key industry features that make affiliate import shares sensitive to variation in trade costs.

The analogous results for affiliate sales are on the right-hand side of Table 6. There is some support for the idea that high judicial quality particularly lowers affiliate sales for knowledge-intensive goods (column 4). This result is somewhat surprising, but it could be indicative of competition effects in the host country market. At the same time, the results for the $TC \times KI$ variable are not much affected. Further, the IPR times knowledge intensity variable confirms the analysis of affiliate imports, namely, local IPR protection is particularly important for knowledge-intensive goods; although the effect is imprecisely estimated. Finally, the impact of gravity on affiliate sales is greater not only for knowledge-intensive but also for contract-intensive goods (marginally). Nevertheless, the largely unchanged estimate for the $TC \times KI$ variable suggests that any omitted variable problem must be small.

Summary of additional robustness checks on Hypotheses 1 and 2 The coefficient estimates reported above show that the support for Hypotheses 1 and 2 are highly robust to a wide range of specifications that allow for a variety of alternative channels through which trade costs affect import shares and affiliate sales. Additional robustness checks, presented in the Appendix, show that the results are also robust to various assumptions regarding alternative controls and functional form. We briefly list these specifications here. First, including a quadratic term for trade costs allows for a non-linearity of the impact on affiliate sales and import shares. Such a non-linearity does exist, but it turns out not to have a large impact on the coefficient estimates for $TC \times KI$ (Table A). Second, variation across industries in terms of the degree of product market competition and substitutability of products could be correlated with the knowledge intensity of a product. Interactions of industry measures motivated by Nunn (2007) with country characteristics suggest that there may be other interesting determinants of multinational activity, but their effect on the coefficients of the trade cost-knowledge intensity variable is small (Table B). Finally, going beyond local affiliate sales, we have examined also third-country sales as well as sales back to the home country. We find that the same mechanism that affects horizontal FDI also affects both vertical and export-platform FDI (Table C).

The Knowledge Intensity of Affiliate Imports The previous results demonstrate that trade costs interact with knowledge intensity in a clear and consistent way in determining the choice of imports versus local affiliate production, with import shares decreasing less rapidly if products are more knowledge intensive. We now ask whether another prediction of the model is borne out by the data. The theory predicts that as trade costs increase, the composition of an affiliate's imports from its home country shifts toward relatively more knowledge-intensive intermediates (see equation 5). To examine this composition prediction, we employ detailed industry trade data from the U.S Census Bureau to compute the average knowledge intensity of U.S. exports to affiliates in other countries.[35]

[35] The Census data provides information on 500 different industries, whereas the BEA data distinguishes only about 50; see the Appendix for more details on the data sources and construction of this variable.

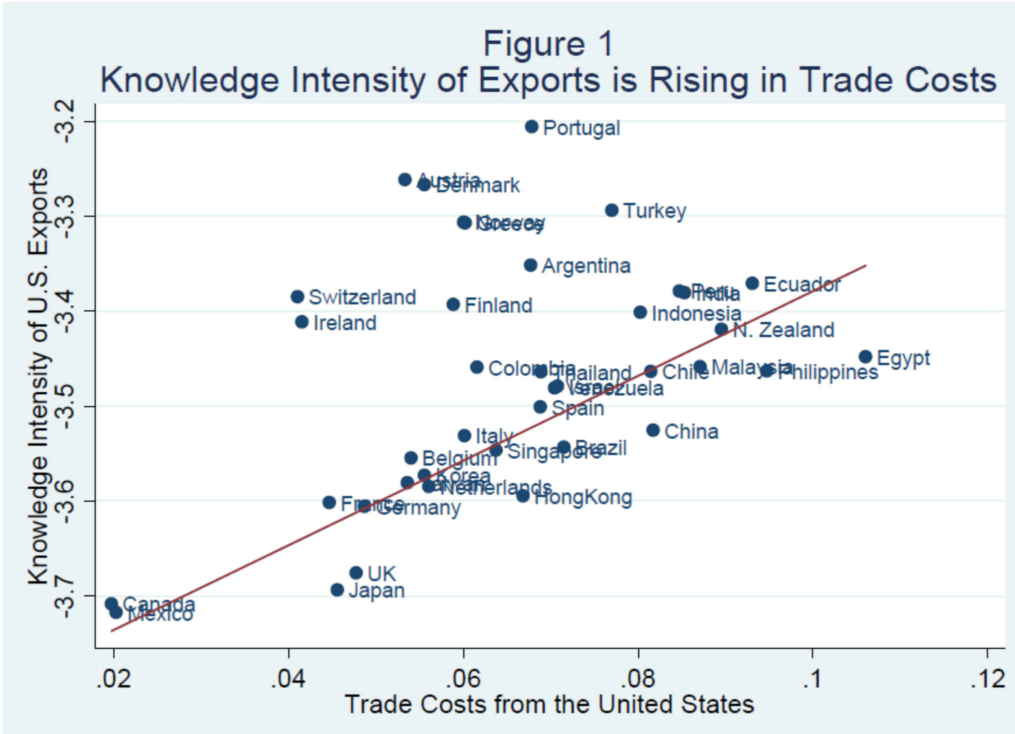

Figure 1 plots the knowledge intensity of U.S. exports against trade costs by country.[36]

The figure shows a strong positive relationship between knowledge intensity and the size of trade costs. This relationship provides support for our model: as trade costs rise, multinationals offshore the production of increasingly knowledge-intensive activities, and at the same time the affiliates' imports become increasingly concentrated in goods that are knowledge intensive as well. In the Appendix, we show that this relationship holds up to including a large set of other variables. This constitutes an important confirmation of the model's prediction regarding multinational trade using detailed information on the technological content of trade.

The following section presents a number of concluding remarks.

[36] The best-fit line corresponds to a weighted regression, with GDP as weights.

5 Concluding Remarks

How well does technology transfer between production sites? The answer to this question is important to many fields of economics, and yet it has proven to be a hard question to address. We tackle it by developing a framework in which technology can be transferred either embodied in traded intermediates or in disembodied form through direct communication. Disembodied technology transfer costs vary with the knowledge intensity of production but not in the distance of the transfer, while embodied technology transfer costs vary in the distance of the transfer but not with the knowledge intensity of production.

We show that it is the interaction between a product's knowledge intensity, on the one hand, and the distance between the buyer and the seller, on the other hand, that determines the costs of selling in international markets. In the context of a multinational enterprise, we derived three important implications. First, more distant markets will be served less than proximate markets, and the size of this effect is stronger for knowledge-intensive products. Second, if products are knowledge-intensive, firms are constrained in their ability to shift production towards their affiliates; instead, a large part of the final good is produced in the multinational's home country. Finally, the model predicts that firms change systematically the composition of their international trade in terms of its knowledge intensity as trade costs change relative to technology transfer costs.

Employing extensive information on U.S. multinational firms, we find evidence for all three of these predictions. Moreover, the results are robust to incorporating a wide range of other determinants of multinational activity. This gives not only support to the idea that international technology transfer costs matter, but we are also able to address a major puzzle, namely the fact that there is gravity for weightless goods.

Economists know little about the impact of relative cost changes for disembodied versus embodied technology transfer, even though both appear to be changing at a rapid pace. Communicating knowledge-intensive technology may become cheaper through video-conferencing compared to telephone calls, while at the same time the technology embodied in intermediate goods becomes more movable because trade barriers and transportation costs are falling. The present paper should be useful for future research on the diffusion of technological knowledge.

We have presented our view of certain key influences of international commerce in terms of a theory of multinational firms because arguably this is the perfect lens to do so. Multinational firms are central to the spread of technological knowledge across borders as the technology developed by the parent can be employed by its affiliates in other countries. The parent's development costs are fixed while technology is non-rival, leading to international increasing returns to scale. Further, in the context of the multinational firm, none of the well-known obstacles to international technology transfer emphasized in the existing literature are present.[37] And yet, we see that technology transfer costs strongly limit the benefits of these scale economies.

If such technology transfer frictions are even present within the multinational firm, this suggests that they also affect the way in which domestic firms are organized. How do technology transfer costs affect multi-plant operation, and the structure of hierarchies? What additional issues arise when transactions are carried out at arm's length? This last question

[37] There are, for example, no policy-induced costs of technology adoption (Parente and Prescott 2000), no costs of imitation (Barro and Sala-i-Martin 1997), or appropriate technology issues (Basu and Weil 1998).

is important because to the extent that the technology developed by one firm becomes available to unaffiliated firms, there are externalities, or technology spillovers, and the potential efficiency consequences arising from fixed costs and non-rivalness are increased. While there is evidence that both international trade and foreign direct investment may be major channels for spillovers, the literature still lacks a suitable framework for thinking about these issues.[38] We believe that our framework can be used to make progress on this, not least because it determines which affiliates will produce relatively knowledge-intensive goods and which will not.

[38] Keller (2010) discusses technology spillovers, putting them in the context of other factors that may affect a firm's productivity, such as changes in competition and pecuniary externalities.

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Table 1. Summary Statistics		
	Mean	**Standard Deviation**
Affiliate Sales		
Total	10.886	1.665
To local unaffiliated customers	10.397	1.747
To U.S. customers	7.713	2.183
To 3rd Countries	9.076	2.505
Import shares		
From all US, all imports	-2.889	1.927
From all US, further processing	-2.985	1.973
Other Variables		
Knowledge Intensity	0.050	0.041
Trade Costs	0.099	0.091
Phone Call	0.472	0.615
IPR Protection	0.617	0.652
GDP per capita	9.734	0.633
Population	10.514	1.267
Tax Rate	3.612	0.269
Common Language	0.389	0.488
Human Capital	0.855	0.192
Judicial Quality	0.757	0.185

Note: All variables, except Knowledge Intensity and Common Language, are in natural logarithms

Table 2: Technology transfer and multinational activity

	Import Share					Sales				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Trade costs	-1.26	-2.73	-3.54	-3.75	-3.90	-3.83	-2.69	-1.14	-0.93	-0.53
	[0.17]	[0.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[0.03]	[0.03]	[0.18]
Trade costs x knowledge intensity		32.02	25.18	27.12	26.83		-24.80	-15.87	-17.45	-20.73
		[<.01]	[0.01]	[0.01]	[0.01]		[0.01]	[0.07]	[0.03]	[0.01]
Population			-0.20	-0.16	-0.16			0.46	0.51	0.52
			[<.01]	[0.01]	[0.01]			[<.01]	[<.01]	[<.01]
GDP per capita			-0.76	-0.14	0.05			1.02	0.41	0.53
			[<.01]	[0.65]	[0.86]			[<.01]	[0.01]	[<.01]
Tax rate			0.80	0.84	0.82			-0.01	-0.28	-0.34
			[0.03]	[<.01]	[0.01]			[0.95]	[0.10]	[0.02]
Skill endowment				1.38	0.62				0.15	-0.47
				[0.04]	[0.32]				[0.45]	[0.03]
Capital endowment				-0.02	0.08				0.47	0.53
				[0.88]	[0.59]				[<.01]	[<.01]
Intellectual property rights prot'n index				-0.57	-0.43				0.08	0.17
				[<.01]	[<.01]				[0.27]	[0.01]
Judicial quality				-1.40	-1.74				0.23	-0.41
				[0.12]	[0.07]				[0.57]	[0.30]
Common language					0.35					0.44
					[<.01]					[<.01]
Cost of phone call					0.42					0.037
					[<.01]					[0.46]
R-squared	0.004	0.007	0.052	0.076	0.092	0.046	0.049	0.194	0.207	0.209
# of observations	5,412	5,412	5,298	5,298	5,204	6,691	6,691	6,527	6,527	6,419

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), (3), (4), and (5); local affiliate sales to unaffiliated customers in columns (6), (7), (8), (9), and (10). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table 3: Multinational firms, technology transfer, and comparative advantage

	Import Share					Sales				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Trade costs	-3.91	-3.84	-4.04	-3.85	-3.98	-0.51	-0.22	-0.44	-0.36	-0.49
	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[0.20]	[0.61]	[0.29]	[0.36]	[0.22]
Trade costs x knowledge Intensity	26.53	25.64	29.87	25.59	28.63	-20.43	-27.24	-22.87	-24.66	-21.76
	[0.01]	[0.03]	[0.02]	[0.02]	[0.02]	[0.01]	[<.01]	[0.01]	[<.01]	[0.01]
GDP per capita	0.05	0.05	0.05	0.05	0.03	0.54	0.53	0.53	0.53	0.54
	[0.88]	[0.86]	[0.86]	[0.86]	[0.94]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
GDP per capita x knowledge Intensity					0.48					-0.25
					[0.75]					[0.71]
Skill endowment	0.70	0.72	0.63	0.61	0.62	-0.42	0.08	-0.47	-0.48	-0.47
	[0.39]	[0.29]	[0.32]	[0.33]	[0.32]	[0.43]	[0.72]	[0.03]	[0.02]	[0.03]
Skill endowment x skill intensity	-1.43					-0.02				
	[0.89]					[0.93]				
Skill endowment x knowledge Intensity		-2.04					-10.67			
		[0.59]					[<.01]			
Capital endowment	0.06	0.08	0.05	0.08	0.08	0.64	0.54	0.56	0.54	0.54
	[0.71]	[0.59]	[0.76]	[0.59]	[0.59]	[<.01]	[<.01]	[<0.01]	[<.01]	[<.01]
Capital endowment x capital intensity	0.10					-0.04				
	[0.74]					[0.38]				
Capital endowment x knowledge intensity			0.58					-0.39		
			[0.65]					[0.48]		
Judicial quality	-1.32	-1.75	-1.74	-1.66	-1.74	-1.06	-0.45	-0.41	-0.20	-0.41
	[0.21]	[0.07]	[0.07]	[0.11]	[0.07]	[0.01]	[0.23]	[0.30]	[0.60]	[0.30]
Judicial quality x contract intensity	-0.78					1.22				
	[0.26]					[0.02]				
Judicial quality x knowledge intensity				-1.46					-4.05	
				[0.74]					[0.08]	
R-squared	0.092	0.092	0.092	0.092	0.092	0.211	0.212	0.209	0.210	0.209
# of observations	5,204	5,204	5,204	5,204	5,204	6,419	6,419	6,419	6,419	6,419

Note: Dependent variables: imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), (3), (4), and (5); local affiliate sales to unaffiliated customers in columns (6), (7), (8), (9), and (10). Always included are the additional variables Population, Tax rate, Cost of phone call, Common language, and Intellectual property rights protection index (results not shown). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table 4: The role of fixed costs for multinational production and offshoring

	Import Share				Sales			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Trade costs	-3.84	-7.44	-4.61	-9.07	-0.19	-1.37	0.39	-0.19
	[0.04]	[<.01]	[0.02]	[<.01]	[0.87]	[0.29]	[0.75]	[0.89]
Trade costs x knowledge intensity			26.19	28.37			-19.81	-20.83
			[0.02]	[0.01]			[0.01]	[0.01]
Trade costs x skill intensity	0.66		0.43		-0.75		-0.57	
	[0.57]		[0.71]		[0.27]		[0.41]	
Trade costs x capital intensity		1.48		1.59		-0.02		-0.11
		[0.01]		[<.01]		[0.96]		[0.79]
GDP per capita	0.04	0.03	0.06	0.07	0.55	0.56	0.52	0.53
	[0.90]	[0.90]	[0.84]	[0.81]	[<.01]	[<.01]	[<.01]	[<.01]
Population	-0.17	-0.16	-0.16	-0.16	0.52	0.52	0.52	0.52
	[0.01]	[0.01]	[0.01]	[0.01]	[<.01]	[<.01]	[<.01]	[<.01]
Tax rate	0.83	0.82	0.82	0.82	-0.35	-0.34	-0.34	-0.34
	[0.01]	[0.01]	[0.01]	[0.01]	[0.02]	[0.02]	[0.02]	[0.02]
Skill endowment	0.64	0.63	0.62	0.62	-0.48	-0.47	-0.47	-0.47
	[0.31]	[0.31]	[0.32]	[0.32]	[0.02]	[0.03]	[0.03]	[0.03]
Capital endowment	0.07	0.07	0.08	0.07	0.54	0.53	0.54	0.54
	[0.62]	[0.65]	[0.60]	[0.65]	[<.01]	[<.01]	[<.01]	[<.01]
Judicial quality	-1.76	-1.73	-1.76	-1.75	-0.38	-0.43	-0.38	-0.41
	[0.06]	[0.07]	[0.06]	[0.06]	[0.35]	[0.28]	[0.35]	[0.30]
Intellectual property rights prot'n index	-0.42	-0.43	-0.43	-0.43	0.15	0.16	0.16	0.17
	[<.01]	[<.01]	[<.01]	[<.01]	[0.03]	[0.01]	[0.02]	[0.01]
Common language	0.36	0.35	0.35	0.35	0.43	0.43	0.44	0.44
	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
Cost of phone call	0.41	0.41	0.42	0.42	0.04	0.04	0.03	0.04
	[<.01]	[<.01]	[<.01]	[<.01]	[0.49]	[0.46]	[0.49]	[0.46]
R-squared	0.090	0.091	0.092	0.093	0.208	0.208	0.210	0.209
# of observations	5,204	5,204	5,204	5,204	6,419	6,419	6,419	6,419

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). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table 5: Communication costs and the trade cost-knowledge intensity effect

	Import Share			Sales		
	(1)	(2)	(3)	(4)	(5)	(6)
Trade costs	-3.90	-3.87	-4.05	-0.53	-0.35	-0.33
	[<.01]	[<.01]	[<.01]	[0.18]	[0.41]	[0.45]
Trade costs x knowledge intensity	26.83	26.39	29.3	-20.73	-22.90	-25.23
	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[<.01]
GDP per capita	0.05	0.05	0.05	0.53	0.52	0.53
	[0.86]	[0.87]	[0.88]	[<.01]	[<.01]	[<.01]
Skill endowment	0.62	0.62	0.63	-0.47	-0.48	-0.47
	[0.32]	[0.32]	[0.32]	[0.03]	[0.02]	[0.03]
Capital endowment	0.08	0.08	0.08	0.53	0.53	0.54
	[0.59]	[0.59]	[0.59]	[<.01]	[<.01]	[<.01]
Judicial quality	-1.74	-1.74	-1.73	-0.41	-0.45	-0.42
	[0.07]	[0.07]	[0.07]	[0.30]	[0.23]	[0.28]
Intellectual property rights protection index	-0.43	-0.43	-0.43	0.17	0.19	0.16
	[<.01]	[<.01]	[<.01]	[0.01]	[<.01]	[0.01]
Common language	0.35	0.39	0.35	0.44	0.66	0.44
	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
Common language x knowledge intensity		-0.72			-4.38	
		[0.67]			[<.01]	
Cost of phone call	0.42	0.41	0.47	0.04	0.04	-0.04
	[<.01]	[<.01]	[<.01]	[0.46]	[0.47]	[0.61]
Cost of phone call x Knowledge intensity			-1.09			1.40
			[0.47]			[0.12]
Population	-0.16	-0.16	-0.16	0.52	0.51	0.52
	[0.01]	[<.01]	[0.01]	[<.01]	[<.01]	[<.01]
Tax Rate	0.82	0.82	0.82	-0.34	-0.34	-0.34
	[0.01]	[0.01]	[0.01]	[0.02]	[0.01]	[0.02]
R- squared	0.092	0.092	0.092	0.209	0.213	0.210
# of observations	5,204	5,204	5,204	6,419	6,419	6,419

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). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table 6: Institutions, knowledge intensity, and contracts

	Import Share			Sales		
	(1)	(2)	(3)	(4)	(5)	(6)
Trade costs	-3.85	-4.24	-1.03	-0.36	-0.57	0.13
	[<.01]	[<.01]	[0.22]	[0.36]	[0.16]	[0.81]
Trade costs x knowledge intensity	25.59	33.67	28.12	-24.66	-19.82	-20.16
	[0.02]	[<.01]	[0.01]	[<.01]	[0.01]	[0.01]
Trade costs x contract intensity			-6.88			-1.58
			[<.01]			[0.15]
GDP per capita	0.05	0.06	0.00	0.53	0.53	0.53
	[0.86]	[0.85]	[0.99]	[<.01]	[<.01]	[<.01]
Skill endowment	0.61	0.63	0.63	-0.48	-0.46	-0.46
	[0.33]	[0.31]	[0.30]	[0.02]	[0.03]	[0.03]
Capital endowment	0.08	0.08	0.08	0.54	0.53	0.53
	[0.59]	[0.61]	[0.59]	[<.01]	[<.01]	[<.01]
Judicial quality	-1.66	-1.74	-1.65	-0.20	-0.41	-0.39
	[0.11]	[0.07]	[0.07]	[0.60]	[0.30]	[0.31]
Judicial quality x knowledge intensity	-1.46			-4.05		
	[0.74]			[0.08]		
Intellectual property rights prot'n index	-0.43	-0.56	-0.43	0.17	0.15	0.17
	[<.01]	[<.01]	[<.01]	[0.01]	[0.04]	[0.01]
IPR protection index x knowledge intensity		2.32			0.32	
		[0.11]			[0.72]	
Common language	0.35	0.35	0.34	0.44	0.44	0.44
	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
Cost of phone call	0.42	0.41	0.42	0.04	0.04	0.04
	[<.01]	[<.01]	[<.01]	[0.44]	[0.48]	[0.45]
Population	-0.16	-0.16	-0.15	0.52	0.52	0.52
	[0.01]	[0.01]	[0.01]	[<.01]	[<.01]	[<.01]
Tax rate	0.82	0.82	0.79	-0.34	-0.34	-0.35
	[0.01]	[0.01]	[0.01]	[0.02]	[0.02]	[0.02]
R-squared	0.092	0.093	0.096	0.210	0.209	0.210
# of observations	5,204	5,204	5,204	6,419	6,419	6,419

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). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

6 Appendix - Not for publication

6.1 Discussion of additional results on Hypotheses 1 and 2

The results for additional trade cost specifications are shown in Table A. As before, on the left side the import share and on the right side affiliate sales are the dependent variables. The affiliate's import share is falling non-linearly in trade costs, as the highly significant (and positive) coefficient on the quadratic trade cost variable in column (1) indicates. The linear trade cost coefficient changes from around -4 to around -8 while the trade cost-knowledge intensity ($TC \times KI$) variable changes relatively little. Underlying the following four columns are additional trade cost-interaction variables, based on GDP per capita, skill endowment, IPR protection index, and the cost of phone calls. It turns out that none of these four variables is significant, and in line with that the estimates for the $TC \times KI$ variable are largely unchanged.

Turning to the affiliate sales results on the right, there is evidence that the force of gravity is declining with trade costs: the coefficient on the quadratic trade cost term in column (6) is positive. Including the same set of variables interacted with trade costs as before, we find that none of them enter the regression significantly, and the coefficient on $TC \times KI$ remains similar to the baseline results obtained in Table 2. We conclude that accounting for additional effects related to the variation of trade costs in the sample does not change our main findings.

Extending our analysis of the influence of comparative advantage on our results in Table 3 above, we also have included additional measures recently employed in Nunn (2007). If U.S. affiliates were to specialize in certain industries unrelated to knowledge intensity and the choice between embodied and disembodied technology transfer, our findings might be spurious.

We thus include three variables multiplied with GDP per capita, namely the share of value added in shipments across industries, the amount of intra-industry trade in each industry, and the TFP growth in the past 20 years across industries. Further, we divide GDP per capita by the Herfindahl index of input concentration of that industry, a measure of how self contained an industry is. As noted in Nunn (2007), it might be that countries with relatively poorly developed transportation, communication, and distribution infrastructure specialize in relatively self-contained industries, or one might also believe that input concentration is (inversely) related to the knowledge intensity of an industry. In addition, we add the variable Credit (defined as private bank credit to GDP ratio) as a proxy for a country's financial development, also interacted with the capital intensity of each industry.

In Table B on the left, we show the import share results. Column 1 reports the baseline results from Table 2 for comparison. Among the additional variables, the credit-capital intensity enters significantly, indicating that imports of relatively capital-intensive products tend to be low for affiliates located in countries with good credit. The other five additional variables are not significant at standard levels. In column 3 we include also skill-, capital-, and contract intensity multiplied with the corresponding country characteristic (skill endowment, capital endowment, and judicial quality, respectively). The latter variables are estimated similar to Table 3 above, while the $TC \times KI$ coefficient remains significantly positive and also quantitatively similar.

Turning to the affiliate sales results on the right side of Table B, the inclusion of the six additional variables controlling for industry specialization yields significant coefficients on Credit and for the GDP per capita $\times$ Herfindahl index variable: U.S. affiliate sales are lower in host countries with good credit, and they are lower in industries that are complex in the sense that the Herfindahl index is small (the industry has diversified input sources; column 5). This effect goes in the same direction as the $TC \times KI$ variable, whose coefficient is now closer to zero, which is consistent with the Herfindahl measure being an alternative measure of knowledge intensity. Adding the skill-, capital-, and contract intensity comparative advantage variables in column 6, we see that affiliate sales are relatively high for goods that are contract intensive, mirroring the results from Table 3 in the text. The $TC \times KI$ coefficient is now estimated at -13, compared to -21 in the baseline regression, and marginally significant (p-value of 11%). Taken together, our results turn out to be robust to the inclusion of additional industry specialization measures that vary with the level of development. The single case where the $TC \times KI$ coefficient is only marginally significant at standard levels occurs when an alternative measure of knowledge intensity is included, so that the variation is effectively divided between the two variables.

Finally, we broaden the analysis by considering alternative dependent variables in our tests of Hypothesis 1 and Hypothesis 2, see Table C. On the left side, we compare the baseline results in column 1 (see Table 2, column 5) with those obtained when the import share is computed using all affiliate imports, as opposed to only imports for further processing. While the R-squared for the all imports regression is smaller and the $TC \times KI$ coefficient falls somewhat (from around 27 to 22), overall the results are similar, which reflects the fact that most of the imports are intermediate goods for further processing.

The differences are greater when we examine alternative sales directions (Table C, right side). In column 3 we present the local affiliate sales results from before. When the final destination of the affiliate sales is the United States, a number of interesting findings emerge (column 6). First of all, the coefficient on the trade cost-knowledge intensity variable is larger (in absolute value), which is plausible because for these sales there is typically two-way shipping, intermediate goods from the U.S. to the FDI host country, and back to the United States. Second, neither skill abundance nor capital endowment of the host country play a role anymore. This is consistent with U.S. operations that are primarily assembly activities, perhaps employing local unskilled labor. In line with this argument, a high GDP per capita, a proxy for host country factor prices, is not positively affecting affiliate sales anymore. It is also plausible that the strength of IPR protection does not matter as much for these export sales as it does for local sales. Despite these differences we find support for the idea that technology transfer to the affiliate raises its marginal costs as firms choose optimally between the embodied and the disembodied form also for affiliate sales that are destined back to the home market: the coefficient on the trade cost-knowledge intensity variable is negative and highly significant, in line with our Hypothesis 2.

We now consider affiliate sales that are to countries other than the local host country and the United States (column 5). We find that these sales are increasing in trade costs, consistent with a tariff- or transportation cost-jumping idea typical for the horizontal mode of FDI (e.g., Brainard 1997). At the same time, the coefficient on the trade cost-knowledge intensity variable is negative, consistent with the idea that technology transfer costs raising the costs of offshoring especially for knowledge-intensive goods. A high GDP per capita is not associated with higher third-market sales, in contrast to local sales. This may be because high GDP per capita is indicative of high local factor prices, so these host countries may not be good locations if substantial value is added in these countries (which would have to be low-skilled tasks, given that the coefficient on human capital is negative). Also noteworthy, a strong local judicial system is associated with higher third-market sales from this country, consistent with the idea that at least some of the value added in this country comes from independent suppliers.

Finally, the results for all affiliate sales are shown in column 6 of Table C. By and large, they resemble the local sales results of column 3. In particular, the coefficient on the trade cost-knowledge intensity variable is negative, which supports Hypothesis 2 of our model. To sum up our analysis employing additional dependent variables, there is evidence that the mechanism that we have identified is important not only for multinational activity towards the host country market but also for assembly operations in the relatively low-wage countries as well as for sales to third countries. We conclude that the argument developed in this paper is relevant not only for horizontal- but also for vertical- and export-platform FDI.

6.2 The knowledge intensity of trade in relation to trade costs

In this model, firms offshore the production of the least knowledge-intensive tasks and export to their affiliates the intermediates embodying the most knowledge. As shipping costs increase, the cutoff intermediate input rises so that the remaining exports become more knowledge-intensive (see equation 5). This variation in the extensive margin implies that the average knowledge intensity of exports from the U.S. to U.S.-owned multinational affiliates should be systematically increasing in the size of trade costs. It is this relationship that we analyze in Figure 1 and in this section of the Appendix.

Our measure of the knowledge intensity of U.S. exports are constructed from data from the U.S. Census Bureau and the *Compustat* database. The Census Bureau reports all related party trade between U.S. entities and foreign entities, where a related party is one in which there exists at least a 6 percent ownership share. Our model does not take a stand on whether an affiliate's imports come from the parent in the U.S., or an independent supplier located in the United States. In the data, affiliate imports from the U.S. are often from their parents, which makes the Census Bureau related-party trade data base suitable for our purposes.[39] This data set contains all related party exports by six-digit industrial classification for all countries in our BEA dataset. There are 500 NAICS six-digit manufacturing industries. This Census trade data are for the year 2002.

Let EX_k^i be the value of related party exports in commodity i from the U.S. to country k. The total number of traded commodities between the U.S. and country k is

$$N_k = \sum_{i=1}^{500} \{1|EX_k^i > 0\},$$

where $\{1|EX_k^i > 0\}$ is an indicator variable that takes the value of one when there are positive exports between the U.S. and country k in good i and zero otherwise. Let RD^i be the R&D intensity, R&D expenditures divided by sales, for all firms in the *Compustat* dataset for industry i. The average knowledge intensity of exports between the U.S. and country k is then

$$AC_k = \frac{1}{N_k} \sum_{i=1}^{500} RD^i \cdot \{1|EX_k^i > 0\}.$$

[39] Moreover, while some of the related-party exports are from foreign-owned affiliates located in the U.S. to their foreign parents, most of these exports are from U.S. parents to their foreign affiliates. For example, in 1997, the aggregate shipments of U.S. parents to their foreign majority owned affiliates was $193 billion while the aggregate shipments of U.S. affiliates to their foreign parents was only $28 billion.

Variation in AC_k then reflects variation in the extensive margin of the knowledge intensity of traded intermediates. It is the logarithm of this measure that is plotted against trade costs from the U.S. in Figure 1.

We show the results of regressing the logarithm of AC_k on a number of other variables in Table D.[40] The first column reports the simple bivariate relationship that is plotted in Figure 1. 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 the other country variables employed in the text to the regression. We find that the coefficient on trade costs is still very large and statistically significant but is moderately smaller than in the bivariate case. We also find that the knowledge intensity of multinational trade is lower in large, developed countries in which English is spoken, as indicated by the negative coefficients on GDP per capita, population, and Common Language. These results could be consistent with an incentive to offshore the production of relatively knowledge-intensive intermediates when communications costs are relatively low or market size is relatively high (as would be the case if there were fixed costs to offshoring each individual task). None of the other coefficients are statistically significant.

One concern is that the relationship reflects trade costs that rise 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 calculate the average weight-to-value

[40] These are weighted least squares results, with GDP as the weight; the results are qualitatively similar when not weighted. Summary statistics of the variables are shown in Table E.

ratio of goods traded between the U.S. and each host country and include that measure in the specification shown in column 3.[41] As the results indicate, the weight-to-value indicator is not statistically significant, while the coefficient on trade costs is only marginally affected, retaining its approximate magnitude and level of statistical significance. Thus using detailed information on the nature of U.S. multinational trade and controlling for other factors, we find supportive evidence of the model's prediction of how multinational firms change the technological content of their international trade.

[41] The country level value-to-weight measure is computed from detailed U.S. imports data of the U.S. Census Bureau. We add the values of air and vessel shipments by country, and divide by the sum of their weight.

Table A: Trade cost non-linearities and other country variation in trade costs

	Import Share					Sales				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Trade costs	-8.44	-6.94	-6.04	-4.67	-4.69	-1.45	-0.03	-0.83	0.27	-0.73
	[<.01]	[0.08]	[<.01]	[0.07]	[<.01]	[0.03]	[0.98]	[0.37]	[0.84]	[0.18]
Trade costs x Complexity	30.71	27.25	26.80	26.68	26.47	-19.82	-20.83	-20.74	-20.60	-20.90
	[<.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[<.01]
Trade costs squared	7.86					1.67				
	[<.01]					[0.05]				
GDP per capita	-0.01	0.04	0.05	0.04	0.11	0.53	0.53	0.53	0.54	0.54
	[0.99]	[0.90]	[0.87]	[0.89]	[0.72]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
Trade costs x GDP per capita		0.33					-0.05			
		[0.43]					[0.75]			
Skill endowment	0.67	0.60	0.33	0.62	0.61	-0.46	-0.46	-0.51	-0.47	-0.47
	[0.25]	[0.34]	[0.61]	[0.32]	[0.33]	[0.03]	[0.03]	[0.06]	[0.03]	[0.03]
Trade costs x skill endowment			2.55					0.37		
			[0.23]					[0.72]		
Capital endowment	0.05	0.06	0.07	0.08	0.07	0.53	0.54	0.53	0.53	0.53
	[0.69]	[0.66]	[0.65]	[0.57]	[0.63]	[<.01]	[<.01]	[<.01]	[<.01]	[<.01]
Intellectual property rights protection index	-0.41	-0.45	-0.47	-0.48	-0.41	0.17	0.17	0.16	0.21	0.17
	[<.01]	[<.01]	[<.01]	[0.01]	[<.01]	[0.01]	[0.01]	[0.01]	[0.02]	[0.01]
Trade costs x IPR protection index				0.21					-0.22	
				[0.73]					[0.50]	
Cost of phone call	0.44	0.41	0.40	0.41	0.32	0.04	0.04	0.03	0.04	0.02
	[<.01]	[<.01]	[<.01]	[<.01]	[0.01]	[0.40]	[0.46]	[0.50]	[0.40]	[0.81]
Trade costs x cost of phone call					0.97					0.23
					[0.12]					[0.58]
R-squared	0.102	0.092	0.092	0.092	0.093	0.210	0.209	0.209	0.209	0.209
# of observations	5,204	5,204	5,204	5,204	5,204	6,419	6,419	6,419	6,419	6,419

Note: Dependent variables are imports for further processing from the US parent relative to total affiliate sales in columns (1), (2), (3), (4), and (5); local affiliate sales to unaffiliated customers in columns (6), (7), (8), (9), and (10). Also included in all specifications are Population, Tax rate, Judicial quality, and Common language (results not shown). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table B: Knowledge intensity, competition, and product substitutability

	Import Share			Sales		
Trade costs	-3.90 [<.01]	-3.84 [<.01]	-3.79 [<.01]	-0.53 [0.18]	-0.83 [0.05]	-0.83 [0.05]
Trade costs x knowledge intensity	26.83 [0.01]	27.44 [0.02]	25.79 [0.03]	-20.73 [0.01]	-17.47 [0.04]	-12.97 [0.11]
Population	-0.16 [0.01]	-0.12 [0.04]	-0.12 [0.04]	0.52 [<.01]	0.54 [<.01]	0.54 [<.01]
GDP per capita	0.05 [0.86]	0.19 [0.64]	0.20 [0.61]	0.53 [<.01]	0.50 [0.15]	0.54 [0.12]
Tax rate	0.82 [0.01]	0.82 [0.01]	0.81 [0.01]	-0.34 [0.02]	-0.35 [0.01]	-0.35 [0.01]
Skill endowment	0.62 [0.32]	0.54 [0.39]	0.64 [0.45]	-0.47 [0.03]	-0.47 [0.03]	-0.52 [0.33]
Skill endowment x skill intensity			-1.76 [0.86]			0.03 [0.92]
Capital endowment	0.08 [0.59]	-0.11 [0.49]	-0.15 [0.37]	0.53 [<.01]	0.45 [<.01]	0.68 [<.01]
Capital endowment x capital intensity			0.14 [0.62]			-0.08 [0.08]
Judicial quality	-1.74 [0.07]	-0.82 [0.47]	-0.20 [0.88]	-0.41 [0.30]	-0.42 [0.30]	-0.82 [0.07]
Judicial quality x contract intensity			-1.10 [0.14]			1.60 [<.01]
Intellectual property rights prot'n index	-0.43 [<.01]	-0.42 [<.01]	-0.42 [<.01]	0.17 [0.01]	0.16 [0.02]	0.16 [0.02]
Common language	0.35 [<.01]	0.34 [<.01]	0.34 [<.01]	0.44 [<.01]	0.42 [<.01]	0.43 [<.01]
Cost of phone call	0.42 [<.01]	0.40 [<.01]	0.40 [<.01]	0.037 [0.46]	0.03 [0.54]	0.03 [0.52]
GDP per capita x value added		0.13 [0.81]	0.13 [0.82]		-0.16 [0.72]	-0.29 [0.55]
GDP per capita x Intra-industry index		-0.02 [0.96]	-0.08 [0.84]		0.59 [0.11]	0.64 [0.09]
GDP per capita x TFP growth		-1.12 [0.62]	-0.79 [0.74]		1.41 [0.42]	0.91 [0.60]
GDP per capita over Herfindahl index		-0.00 [0.94]	0.00 [0.82]		-0.02 [0.01]	-0.02 [0.01]
Credit		-0.12 [0.21]	-0.11 [0.25]		-0.14 [0.01]	-0.14 [0.01]
Credit x capital intensity		-0.60 [0.05]	-0.69 [0.03]		0.07 [0.69]	0.06 [0.75]
R-squared	0.092	0.096	0.096	0.209	0.213	0.216
# of observations	5,204	5,204	5,204	6,419	6,419	6,419

Note: Dependent variables are 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). All variables are defined as deviations from firm-year means. Robust p-values allow for clustering by country-year and are shown in brackets.

Table C: Technology transfer costs in horizontal, vertical, and third-country FDI activity

	Import Share		Sales			
	Pro-cessing	All	Local	U.S.	Third-c'try	All
	(1)	(2)	(3)	(4)	(5)	(6)
Trade costs	-3.90	-3.88	-0.53	-3.40	3.18	0.13
	[<.01]	[<.01]	[0.18]	[0.02]	[<.01]	[0.78]
Trade costs x knowledge intensity	26.83	21.88	-20.73	-58.06	-37.55	-30.53
	[0.01]	[0.02]	[0.01]	[0.03]	[0.03]	[<.01]
GDP per capita	0.05	0.28	0.53	-0.24	0.21	0.34
	[0.86]	[0.41]	[<.01]	[0.52]	[0.57]	[0.06]
Population	-0.16	-0.14	0.52	-0.11	0.27	0.34
	[0.01]	[0.02]	[<.01]	[0.08]	[<.01]	[<.01]
Tax rate	0.82	0.74	-0.34	1.33	-1.53	-0.19
	[0.01]	[0.01]	[0.02]	[<.01]	[<.01]	[0.12]
Skill endowment	0.62	0.74	-0.47	-0.76	-2.17	-1.00
	[0.32]	[0.21]	[0.03]	[0.21]	[<.01]	[<.01]
Capital endowment	0.08	-0.01	0.53	-0.38	-0.08	0.34
	[0.59]	[0.95]	[<.01]	[0.14]	[0.71]	[<.01]
Intellectual property rights prot'n index	-0.43	-0.44	0.17	0.11	0.82	0.35
	[<.01]	[<.01]	[0.01]	[0.67]	[<.01]	[<.01]
Judicial quality	-1.74	-1.67	-0.41	-0.08	2.89	0.38
	[0.07]	[0.09]	[0.30]	[0.93]	[<.01]	[0.35]
Common language	0.35	0.34	0.44	0.69	0.09	0.41
	[<.01]	[<.01]	[<.01]	[<.01]	[0.63]	[<.01]
Cost of phone call	0.42	0.42	0.037	-0.63	-0.72	-0.18
	[<.01]	[<.01]	[0.46]	[<.01]	[<.01]	[<.01]
R-squared	0.092	0.081	0.209	0.105	0.205	0.229
# of observations	5,204	5,191	6,419	3,487	3,994	6,419

Note: Dependent variables are processing imports to sales in column 1, all imports to sales in column 2; local affiliate sales to unaffiliated customers in column 3, affiliate sales to the U.S. in column 4, affiliate sales to third countries in column 5, and all sales in column 6. All variables are defined as deviations from firm-year means. Robust p-values allow for clustering bycc country-year and are shown in brackets.

Table D. **The Knowledge Intensity Multinational Trade**

	(1)	(2)	(3)
Trade Costs	5.111	3.700	3.231
	[0.000]	[0.000]	[0.014]
Phone Call		0.008	0.015
		[0.755]	[0.539]
IPR Protection		0.076	0.131
		[0.603]	[0.378]
GDP per capita		-0.099	-0.095
		[0.058]	[0.083]
Population		-0.064	-0.070
		[0.000]	[0.000]
Tax Rate		0.071	0.093
		[0.166]	[0.055]
Common Language		-0.067	-0.021
		[0.086]	[0.669]
Human Capital		-0.154	-0.221
		[0.240]	[0.120]
Judicial Quality		0.245	0.152
		[0.192]	[0.417]
Weight-to-value			0.013
			[0.417]
R-squared	0.440	0.793	0.802
N	39	36	35

Notes: 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 logarithms. Robust t-statistics shown in brackets.

Table E. Summary Statistics - Appendix		
	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	1.393	0.150
GDP per Capita	9.429	0.756
Population	16.138	1.424
Tax Rate	-1.093	0.516
Common Language	0.085	0.252
Human Capital	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.