Technology, Geography, and Trade

Jonathan Eaton and Samuel Kortum[1]
Boston University and NBER

September 1998

[1]Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215, USA; jeaton@bu.edu, kortum@bu.edu. A previous version circulated under the title "Technology and Bilateral Trade," *NBER Working Paper No. 6253*. We thank Daniel Ackerberg, Georgio Basevi, Zvi Eckstein, Gene Grossman, Elhanan Helpman, Kaivan Munshi, Diego Puga, Marie Thursby, and Daniel Trefler for comments. Deepak Agrawal and Xiaokang Zhu provided excellent research assistance. We gratefully acknowledge the support of the National Science Foundation.

Abstract

We develop a Ricardian model in which technology and geography govern trade patterns. The theory delivers simple equations for bilateral trade which we estimate with OECD data. The parameter estimates allow us to simulate the model: (i) to assess the gains from trade, (ii) to quantify the role of trade in spreading the benefits of innovation, (iii) to investigate how the forces of technology and geography compete in determining comparative advantage, and (iv) to identify the winners and losers from tariff reductions. Key findings are: (i) the extent to which trade barriers leave the gains from trade largely unrealized, (ii) the geographic concentration of the gains to country-specific technological advance, (iii) the likelihood that reductions in trade barriers will shift manufacturing to smaller countries, and (iv) the potential for regional trade agreements to create losers.

Key words: trade, gravity, technology, geography, research, integration

JEL classification: F11; F17; O33

1 Introduction

In Ricardian trade theory technological differences shape patterns of international specialization. A country's location is irrelevant and its size matters only for its terms of trade. A key result of the empirical literature is that trade diminishes dramatically with distance, suggesting that transporting goods is costly. Combining trade frictions with a second basic fact, the prevalence of trade in intermediates, size and location do influence comparative advantage: Largeness or a central location favors activities that use intermediates intensively. This insight is at the heart of the more recent literature on economic geography.[1]

We develop and quantify a Ricardian model of international trade that incorporates a role for geography. Our point of departure is the Dornbusch, Fischer, and Samuelson (1977) version of the two-country Ricardian model with a continuum of goods. In that model a distribution of relative productivities summarizes technology. We describe each country's technology in terms of an extreme value distribution.[2] Under this assumption the model extends naturally to a world of many countries which are separated by trade impediments and which exchange both intermediate and final goods.

The analysis clarifies how technology and geography shape the world's trade patterns. Simple expressions relate bilateral trade volumes, first, to deviations from purchasing power parity and, second, to wages and national levels of technology.[3] Trade impediments play an explanatory role in each. We estimate these relationships using data on trade in manufactures among 19 OECD countries.[4] The key parameters correspond to: (i) each country's techno-

[1] Grossman and Helpman (1995) survey the literature on technology and trade while Krugman (1991) provides an introduction to geography and trade.

[2] In Kortum (1997) and Eaton and Kortum (1998a) we show how a process of innovation and diffusion can give rise to such distributions.

[3] Engel and Rogers (1996) and Crucini, Telmer, and Zachariadis (1998) explore the geographic determinants of deviations from the law of one price. Our model relates such deviations to bilateral trade volumes in general equilibrium.

[4] We think that our model best describes trade in manufactures among industrial countries. For most of these countries trade in manufactures represents 75-90 per cent of total merchandise trade. (The exceptions are Australian exports and Japanese imports.) Moreover, these countries trade mostly with themselves. (The exception is Japanese imports.)

logical sophistication, (ii) the determinants of trade impediments, and (iii) the heterogeneity of comparative advantage. More telling than the estimates themselves, however, is what the they mean for general equilibrium outcomes under various scenarios.

The simulations attack four issues: (i) the magnitude of gains from trade, (ii) the importance of trade in spreading the benefits of technology, (iii) the relative contributions of technology and location in determining patterns of specialization, and (iv) the effects of worldwide, unilateral, and regional tariff reductions.

Our first set of simulations ask how welfare evolves as trade barriers fall. Not surprisingly, all countries benefit from freer world trade, with small countries gaining more than big ones. Quite shocking, however, is how much existing trade impediments keep the world from realizing the full benefits of unhindered trade: Welfare is much closer to its autarky level than to what it would be in a world liberated from any frictions whatsoever.

Our second set of simulations show how much trade spreads the benefits of technology across national boundaries. An improvement in a country's technology raises welfare almost everywhere. But the magnitude of the gains abroad approach those at home only in countries enjoying proximity to the source and the flexibility to downsize their manufacturing labor forces. For example, Canada's benefit from an improvement in U.S. technology can approach 90 per cent of the U.S. gain.

Our third set of simulations ask how patterns of specialization evolve as trade impediments shrink. As barriers fall from their autarky level, manufacturing shifts toward larger countries. But as they continue to fall beyond their current level this pattern gets reversed; larger countries lose their edge, and technology takes over as the major determining factor. From their current levels, declining trade barriers will favor manufacturing in smaller countries. The results imply an elasticity of world trade with respect to trade impediments of about 2 to 3.

Our fourth set of simulations shows that nearly every country benefits from a multilateral move to freer trade, but that the United States suffers if it drops its tariffs unilaterally. These simulations also illustrate the potential harm from European regional integration either to participants (through trade diversion) or to nonparticipants nearby (through worsened terms of trade).

How does our work relate to the existing empirical modeling of international trade? The Ricardian model itself has generated relatively little empirical work, probably because it glosses over so many first-order features of the data.[5] More active empirical fronts have been: (i) the gravity modeling of bilateral trade flows, (ii) computable general equilibrium (CGE) models of the international economy, and (iii) factor endowments or Heckscher-Ohlin-Vanek (HOV) explanations of trade.

Our theory does imply that bilateral trade volumes adhere to a structure resembling a gravity equation, which relates trade flows to distance and to the product of the source and destination countries' GDPs. Given the success of the gravity model in explaining the data, this feature of our model is an empirical plus.[6] But in our model GDP is endogenous, so we must scratch beneath the surface of the gravity equation to uncover the key structural parameters governing the roles of technology and geography in trade.[7]

In common with CGE models we analyze trade flows within a general equilibrium framework, so we can conduct policy simulations. Our specification is more Spartan than a typical CGE model, however. For one thing, CGE models typically treat each country's goods as unique, entering preferences separately as in Armington (1969).[8] In contrast, we take the Ricardian approach of defining the set of commodities independent of country, with specialization

[5] What has been done focuses on bilateral comparisons of export shares. MacDougall (1951, 1952) is the classic reference. Deardorff (1984) and Leamer and Levinsohn (1995) discuss it and subsequent contributions in this tradition.

[6] Deardorff (1984) reviews the earlier gravity literature. For recent applications See Wei (1996), Jensen (1996), and Rauch (1996) (in cross-section) and Helpman (1987), Hummels and Levinsohn (1995), and Evenett and Keller (1996) (in time-series).

[7] We are certainly not the first to give the gravity equation a structural interpretation. Previous theoretical justifications posit that every country specializes in a unique set of goods, either using Armington (1969) preferences, as in Anderson (1979), or by assuming monopolistic competition, as in Helpman (1987) and Bergstrand (1989). Either justification implies that each source should export a specific good everywhere. Haveman and Hummels (1997) report evidence to the contrary. In our model more than one country may produce the same good, with individual countries supplying different parts of the world.

[8] Hertel (1997) is a recent state-of-the-art example.

governed by comparative advantage.

Our approach has less in common with the empirical work emanating from the HOV model, which has focussed on the relationship between factor endowments and patterns of specialization.[9] This work has tended to ignore locational questions (by treating trade as costless), technology (by assuming that it is common to the world), and bilateral trade volumes (since the model makes no prediction about them).[10] While we make the Ricardian assumption that labor is the only internationally immobile factor, in principle our approach could incorporate additional immobile factors.

Section 2, which follows, sets out the foundation of the model, deriving the two bilateral trade relationships that underlie our empirical analysis. Section 3 explores one of them, the relationship between bilateral trade and prices. Section 4 puts further detail into the model, placing it into a general equilibrium context. Using this additional structure, Section 5 estimates the second relationship, explaining bilateral trade in terms of technology, wages, and geography. Having obtained estimates of the necessary parameters from Sections 3 and 5, in Section 6 we simulate. Section 7 concludes. The appendix discusses our data and the robustness of our estimates to the particular data series we use.

2 The Basic Model

We build on the Dornbusch, Fischer, Samuelson (1977) model of Ricardian trade with a continuum of goods and N countries. In recognition of the importance of trade in intermediates, we deviate from the pure Ricardian framework by introducing material inputs in addition to labor. We assume constant returns to scale and identical factor and materials intensities across commodities. Under these assumptions the cost of hiring the cost-minimizing bundle of inputs is the same across commodities in each country. We define the cost of a bundle of these inputs

[9] Leamer (1984) epitomizes this approach.

[10] This literature has begun to incorporate roles for technology and location, introducing technological differences, as in Trefler (1993, 1995) and Harrigan (1997), and home-bias in preferences, as in Trefler (1995).

in country i as c_i. Later on we show how c_i relates to underlying wages and materials prices, but for now it suffices to treat c_i as a parameter.

As in Ricardo, countries have differential access to technology, so that productivity varies across commodities and countries. We denote by $z_i(j)$ the amount of good j that a bundle of inputs can produce in country i. Hence the cost of producing a unit of good j in that country is $c_i/z_i(j)$.

To take into account the preponderance of domestic to international transactions, we introduce trade impediments. In particular, we make Samuelson's standard and convenient "iceberg" assumption, that a fraction $1/d_{ni}$ of what country i exports arrives in country n.[11] We normalize $d_{ii} = 1$ for all i. The c.i.f. cost of obtaining good j from country i in country n is

$$p_{ni}(j) = c_i d_{ni}/z_i(j).$$

We assume perfect competition, so that the minimum of this cost across potential sources i is also the price of good j in country n.[12]

While the Dornbusch-Fischer-Samuelson framework is an elegant construct that has yielded a number of important theoretical results, it does not readily generalize to a multicountry world. We now introduce an assumption about the distribution of productivity across countries under which this extension is straightforward. While we think that this extension is of interest from the perspective of pure theory, our motivation is to provide a model that can confront data.

2.1 The Technological Frontier

In deciding where to buy good j, country n looks across all potential suppliers $i = 1, ..., N$ to find the lowest price. Treating z as arising from a probability distribution, the likelihood

[11] See Krugman (1995) for a discussion of this assumption.

[12] The analysis can be extented to allow for potential producers of each good in each country who engage in Bertrand competition in each destination. Each destination would still be served by the low-cost provider, but the price would be the c.i.f. price of the *second*-cheapest potential provider.

that some country s is the cheapest source for country n is the probability that $z_s(j) \geq z_i(j) c_s d_{ns} / c_i d_{ni}$ for each $i = 1, ..., N$.[13] For almost any joint distribution of the $z(j)$ across sources, evaluating this probability is intractable.

However, the theory of extrema identifies a family of joint distributions for which this problem is straightforward. To exploit this simplicity, we assume that for each good j the distribution for country i's productivity is Fréchet (also called the Type II extreme value distribution):

$$F_i(z) = e^{-T_i z^{-\theta}}. \tag{1}$$

Here $T_i > 0$ is a measure of country i's technological sophistication: An increase in T_i constitutes an upward shift in the distribution of its productivities. The parameter $\theta > 1$ reflects the amount of variation within that distribution, with a rise in θ implying less variability. We treat the distributions as independent across countries, although the model could be restated to incorporate correlation.[14] We can think of T_i as reflecting absolute advantage while θ generates comparative advantage.

[13] This condition delivers the Ricardian result that country n will tend to buy what each source country i is best at making. Associating individual goods with individual firms, a country's most productive firms are most likely to export. This implication jives with Bernard and Jensen's (1996) finding that exporting firms have higher productivity than other firms in the United States, largely due to selection: We explore the implications of our model for productivity in Eaton and Kortum (1998b).

[14] The technological frontier in any country represents the best techniques for producing each good culled from a long history of invention and imitation. Therefore it makes sense to represent this frontier as an extreme value distribution. The distribution of the maximum of a set of draws can converge to one of only three distributions, the Weibull, the Gumbell, or the Fréchet. See Billingsley (1986). (Only the third generates a simple distribution of prices.) Kortum (1997) provides a model of innovation, which, if countries do not share their ideas, generates this distribution with independence across countries and with T_i representing each country's accumulated research effort. For our analysis here, however, an observationally equivalent joint distribution that embeds correlation across countries is:

$$F(z_1, ..., z_N) = \exp\left\{ - \left[\sum_{i=1}^{N} \left(T_i z_i^{-\theta} \right)^{1/\rho} \right]^{\rho} \right\},$$

where $1 \geq \rho > 0$. Correlation decreases as ρ rises, with $\rho = 1$ implying independence. See, e.g., Small (1987). All that we do in this paper stands, with T_i reinterpreted as $T_i^{1/\rho}$ and θ as θ/ρ. Correlation could arise if ideas generated in each country applied globally, but with country-specific effectiveness; T_i would then represent how effectively, on average, a country makes use of innovations.

2.2 The Distribution of Prices

Under our assumptions about technology and trade impediments, country i presents country n with a distribution of prices $G_{ni}(p) = 1 - e^{-d_{ni}^{-\theta}\phi_i p^\theta}$. Here

$$\phi_i \equiv T_i c_i^{-\theta}$$

measures country i's technological sophistication tempered by its production costs. A very convenient feature of our assumptions is that the distribution of the *minimum* drawn from such price distributions has exactly the same form. Hence, shopping around the world for the best deal, country n faces the price distribution:

$$G_n(p) = 1 - e^{-\widetilde{\phi}_n p^\theta} \tag{2}$$

for what it actually buys. Here

$$\widetilde{\phi}_n \equiv \sum_{i=1}^{N} \phi_i d_{ni}^{-\theta} = \sum_{i=1}^{N} T_i (c_i d_{ni})^{-\theta} \tag{3}$$

measures the technology that a country can tap both through its own production and through imports from other countries.

The possibility of international trade enlarges the stock of technologies available domestically with those available from other countries, discounted by the appropriate production and transport costs. At one extreme, with no trade barriers $\widetilde{\phi}$ is the same everywhere and the law of one price holds worldwide for each good. At the other extreme, if international barriers are prohibitive then $\widetilde{\phi}_n$ reduces to ϕ_n.

We exploit three key features of the price distribution (2):

1. The probability that country i provides a good at the lowest price in country n is simply:

$$\pi_{ni} = \phi_i d_{ni}^{-\theta} / \widetilde{\phi}_n, \tag{4}$$

its share in country n's trade-augmented technology. Since there are a continuum of goods having the same distribution of technology across countries, this probability is also the fraction of goods that country n buys from country i.[15]

2. The price of a good that country n *actually buys* from any country i also has the distribution $G_n(p)$. Thus, for goods that are actually bought, conditioning on the source has no bearing on the good's price.

3. The exact price index P for a constant elasticity of substitution (CES) aggregator is of the form $P_n = A\widetilde{\phi}_n^{-1/\theta}$, where A is a constant which depends on θ and the elasticity of substitution, but not on $\widetilde{\phi}_n$ itself.[16] This last property shows how trade impediments generate deviations from purchasing power parity in our framework. In the next section we show how these deviations relate systematically to bilateral trade patterns.

2.3 Two Trade Relationships

These three properties of the price distribution yield the two trade relationships that form the basis of our empirical work: The first relates bilateral trade patterns to technology and factor costs, the second to price levels.

On the demand side, we assume that a CES aggregator combines goods, with the same elasticity in each country. Since the distribution of prices that country n pays for goods from any country i is the same for all i, the fraction of country n's spending devoted to country i equals the measure of goods imported from there:

$$\frac{X_{ni}}{X_n} = \pi_{ni} = \frac{\phi_i d_{ni}^{-\theta}}{\widetilde{\phi}_n} = \frac{T_i(c_i d_{ni})^{-\theta}}{\sum_{k=1}^{N} T_k\left(c_k d_{nk}\right)^{-\theta}}, \tag{5}$$

[15]Our results translate nicely into the two-country world considered by Dornbusch, Fischer, and Samuelson (1977). They represent technologies by a function $A = A(x)$ such that the ratio of home-country to foreign-country productivity exceeds A for a fraction x of all goods. In our model, x is the fraction of goods that country 1 (home) provides at the lowest price to country 2 (foreign) given that the ratio of home-country to foreign-country input and transport costs, $c_1 d_{21}/c_2$, equals A. Thus, $\pi_{21} = x = (1 + A^{\theta}T_2/T_1)^{-1}$, which yields, $A = A(x) = (T_1/T_2)^{1/\theta}((1-x)/x)^{1/\theta}$. The function has the shape of an ogee, as determined by θ. It is shifted up if the level of technology in the home country increases relative to the foreign country's level.

[16]The moment generating function for $x = -\ln P$ is $E(e^{tx}) = \widetilde{\phi}^{t/\theta}\Gamma(1 - t/\theta)$. (See, e.g., Johnson and Kotz (1970).) Hence $E[P^{-t}]^{-1/t} = \Gamma(1-t/\theta)^{-1/t}\widetilde{\phi}^{-1/\theta}$.

where X_n is country $n's$ total spending, of which X_{ni} is spent (c.i.f.) on goods from i.

Equation (5) links technology and export share: Given factor costs and trade impediments, countries with larger T's have larger market shares while, given technology, countries with higher input costs have lower shares. These effects on trade shares work via the range of goods supplied to different countries: As country i's cost of serving market n rises, the range of goods it can sell there shrinks.[17]

This relationship forms the basis of our simulation analysis described in Section 6. A key parameter in this analysis is θ, which governs the substitutability of resources and technologies from different countries. Empirical models of bilateral trade typically make the Armington assumption that goods produced by different sources are imperfect substitutes. Our parameter θ, while having nothing to do with preferences, has similar implications for the price sensitivity of imports from competing sources.

We discuss below how we estimate θ, along with the other parameters of the model, using equation (5). But our model also delivers a simpler relationship, between trade share and prices, that also provides evidence on the value of θ.

Substituting our result on the exact price index into equation (5) gives:

$$\frac{X_{ni}/X_n}{X_{ii}/X_i} = \frac{\widetilde{\phi}_i}{\widetilde{\phi}_n} d_{ni}^{-\theta} = \left(\frac{P_i d_{ni}}{P_n}\right)^{-\theta}. \tag{6}$$

Exports from country i to country n relative to i's sales to itself, each normalized by the buyer's total purchases, depend, with an elasticity of θ, on price levels in the two countries and on the cost of transporting goods from country i to n. Recall that θ reflects the degree of heterogeneity

[17] We can draw a close analogy between our model of trade share and discrete-choice models of market share, popular in industrial organization (e.g., McFadden (1974), Berry (1994)): (i) Our trade model has a discrete number of countries whereas their consumer demand model has a discrete number of differentiated goods; (ii) In our model a good's efficiency of production in different countries is distributed multivariate extreme value whereas in their's a consumer's preferences for different goods is distributed multivariate extreme value; (iii) In our model each good is purchased (by a given importing country) from only one exporting country whereas in their model each consumer purchases only one good; (iv) We assume a continuum of goods whereas they assume a continuum of consumers. A key distinction is that we can derive the extreme value distribution from deeper assumptions about the R&D process. Below, we exploit the similarities in the two approaches by borrowing from the estimation strategy suggested in Berry (1994).

in the technologies for individual goods in different countries. As technologies become more tightly distributed around their means, (as reflected by a higher θ), trade becomes more price sensitive.

Pursuing the empirical implications of equation (5) requires saying more about what underlies factor costs c_i. We take this up in Section 5. But we can examine (6) as it stands (i) to see if the relationship goes in the predicted direction and (ii) to gauge the magnitude of θ.

3 Trade and Prices: An Empirical Interlude

Figure 1 depicts the relationship given by equation (6), as it applies to 1990 manufacturing in 19 OECD countries, with the bilateral trade variable on the vertical axis and the price variable on the horizontal, each in logarithms.[18] Observe that, while the scatter is fat, there is an obvious negative relationship, as the theory predicts. The correlation is -0.40.

While we used standard data to capture our model's concept of trade, our measure of prices, and particularly trade frictions, required some ingenuity (or heroism). The United Nations International Comparison Program 1990 benchmark study gives, for over 100 GDP categories, the price in each of our countries relative to the price in the United States. We choose 50 that are most closely linked to manufacturing outputs, giving us $p_i(j)$, the logarithm of the price of good j in country i. We measure the logarithm of country i's price level $\ln P_i$ as the simple mean of $p_i(j)$ across j. To get at d_{ni} we use our model's prediction that, for any commodity j, $p_n(j) - p_i(j)$ is bounded above by $\ln d_{ni}$, with this bound attained for goods that i exports to n. Every country in our sample does in fact export to every other. The diagram uses the (second) highest value of $p_n(j) - p_i(j)$ across commodities to obtain a measure of $\ln d_{ni}$.[19]

[18]When $i = n$ the equation degenerates to an identity. Hence we depict only the 342 cases in which importer and exporter are distinct. We use country n's manufactured imports from country i to obtain X_{ni} and country $n's$ absorption of manufactures from all countries of the world to obtain X_n. Note that the bilateral trade variable $\ln[(X_{ni}/X_n)/(X_{ii}/X_i)]$ is always negative, reflecting home bias. The appendix describes our sources of data.

[19]We used the second highest (rather than highest) value of $p_n(j) - p_i(j)$ to mitigate the effect of possible

The relationship in Figure 1 not only confirms one prediction of the model, its slope provides a first cut at the value of θ. However, our price measures pose at least three problems in estimating the slope.

First, since they apply to fairly broad categories of goods, aggregation may mask greater price differentials that apply at a more detailed level. Since we are then underestimating price variability, we overestimate θ.

Second, our prices are what domestic consumers pay rather than what domestic producers receive. They thus include taxes and retail markups. Fortunately, to the extent that factors specific to individual countries but common to all goods drive the deviation between consumer and producer prices, the resulting errors in our measures of P_i/P_n and d_{ni} cancel each other.

Third, there is reason to think that much error remains in our measure of $P_i d_{ni}/P_n$. In particular, our procedure for obtaining d_{ni} is obviously very rough. Such errors in variables will lead to an underestimate of θ.

A linear regression through the scatter in Figure 1 yields a slope of -4.57 with an intercept of -2.17 (with respective standard errors 0.6 and 0.3). Our theory, however, implies a zero intercept. The fact that OLS yields an intercept substantially and significantly negative is highly symptomatic of errors in variables, biasing the OLS estimate of θ toward zero.[20] Imposing a zero intercept yields a slope coefficient of -8.03 (with a standard error of 0.2). Imposing the zero intercept implied by theory mitigates, but does not eliminate, the problem. A simple method-of-moments estimator for θ that is immune to errors-in-variables bias is the mean of the left-hand side variable over the mean of the right-hand side variable. The implied θ is

measurement error in the prices for particular commodities. Indeed, the second order statistic correlates more with the trade data than the first, and more than higher order statistics. Office and computing equipment is often an outlier. An alternative strategy is just to drop this sector from the calculation and use the highest value of the remaining $p_n(j) - p_i(j)$ to measure $\ln d_{ni}$. The correlation is almost identical to the one in the scatter. While direct measures of the cost of transporting goods exist, they fail to capture all the costs involved in buying things from far away, such as delay and the difficulty of negotiation across space.

[20] The reasoning is exactly that in Friedman's (1957) critique of the Keynesian consumption function: Errors in the right-hand-side variable flatten the scatter and generate a spurious intercept.

8.28.[21]

We use this method-of-moments estimate of θ in our simulations below. A remaining problem, however, is aggregation bias, suggesting that this estimate overstates the true value. In light of this problem we turn to equation (5) for a different handle on θ. Moreover, we use this equation to estimate the remaining parameters of the model, and to simulate various scenarios.

4 General Equilibrium

In order to put equation (5) to work in estimation or in simulation we need to know what determines input costs c. First, we specify what inputs are and then turn to how their prices are determined.

4.1 Production

We assume that production combines labor and materials with labor having a constant share β.[22] Furthermore, we take the same CES aggregator to apply to both materials in production and goods in consumption. The appropriate aggregate index of materials prices in country i is then simply P_i, which, recall, is proportional to $\widetilde{\phi}_i^{-1/\theta}$. Thus

$$c_i = w_i^{\beta} P_i^{1-\beta} = w_i^{\beta} \widetilde{\phi}_i^{-(1-\beta)/\theta}, \tag{7}$$

where w_i is the wage in country i. (Constants common to all countries have been dropped.)

The determination of wages and prices completes the model. But these magnitudes emerge from a worldwide equilibrium, so we have to specify a simultaneous system for the N countries

[21] We examined how the three components $\ln P_i$, $\ln P_n$, and $\ln d_{ni}$ contributed individually to explaining trade patterns. Entering these variables separately into the regressions yielded the respective coefficients -4.9, 5.5, -4.6 (with a constant) and -9.0, 6.4, -6.8 (without a constant). The coefficients all have the predicted signs and the differences among them are not substantial. For 42 of our 50 goods similar price data are available from the 1985 Benchmark Study. Relating 1985 trade data to these price data yields very similar estimates of θ.

[22] This specification is roughly consistent with capital serving as a factor of production with a constant output elasticity as long as the depreciation rate plus the growth of the capital stock is approximately the same as the depreciation rate plus the interest rate. Baxter (1992) shows how a model in which capital and labor serve as factors of production delivers Ricardian implications if the interest rate is given. Ishii and Yi (1996) develop a model of trade in which material inputs play a signficant role.

of the world. We first use equation (3) to derive prices $\mathbf{P}$ conditional on wages $\mathbf{w}$. (The term $\mathbf{x}$ denotes the vector $\{x_1, ..., x_N\}$.) From this result we get the matrix of trade shares $\mathbf{\Pi}$ (with representative element π_{ni}) as a function of $\mathbf{w}$. We then impose conditions for labor market equilibrium to determine $\mathbf{w}$.

4.2 The Determination of Prices

Without trade in intermediates, prices would fall out directly from wages, technologies, and trade frictions. Intermediates trade, however, makes prices everywhere depend on prices everywhere else.

To see how prices are mutually determined we can substitute $c_i = w_i^{\beta} \widetilde{\phi}_i^{-(1-\beta)/\theta}$ into (3) to obtain the system of equations:

$$\widetilde{\phi}_n = \sum_{i=1}^{N} d_{ni}^{-\theta} T_i w_i^{-\theta\beta} \widetilde{\phi}_i^{1-\beta}, \tag{8}$$

which we can write in matrix form:

$$\widetilde{\boldsymbol{\phi}} = \mathbf{\Lambda} \widetilde{\boldsymbol{\phi}}^{(1-\beta)}, \tag{9}$$

where $\widetilde{\boldsymbol{\phi}}^{(1-\beta)}$ is a vector with representative element $\widetilde{\phi}_i^{1-\beta}$ and $\mathbf{\Lambda}$ is a matrix with representative element $\lambda_{ni} = d_{ni}^{-\theta} T_i w_i^{-\theta\beta}$. We can write the solution as $\widetilde{\boldsymbol{\phi}}(\mathbf{w})$.[23]

From this result we know prices and trade shares, given wages: $P_n(\mathbf{w}) = \left[\widetilde{\phi}_n(\mathbf{w})\right]^{-1/\theta}$ while, from expression (4),

$$\pi_{ni}(\mathbf{w}) = \frac{T_i w_i^{-\theta\beta} \left[\widetilde{\phi}_i(\mathbf{w})\right]^{1-\beta} d_{ni}^{-\theta}}{\widetilde{\phi}_n(\mathbf{w})}. \tag{10}$$

[23]Note that a proportional increase in T around the world by a factor of λ, given wages, raises all $\widetilde{\phi}$'s by a factor of $\lambda^{1/\beta}$. This augmentation is the manifestation of the well-known Domar (1961) effect (from the interaction of Hicks-neutral technological change and intermediate inputs).

4.3 Labor-Market Equilibrium

Manufacturing labor income in country i derives from country i's manufacturing exports around the world, including its sales at home. Thus:

$$w_i L_i^M = \sum_{n=1}^{N} \beta X_{ni}, \tag{11}$$

where L_i^M is manufacturing workers. In turn, each country n spends a fraction π_{ni}, given in equation (4), of its total manufacturing expenditure X_n on imports from country i. We can specify total manufacturing expenditures as:

$$X_n = \frac{1-\beta}{\beta} w_n L_n + \alpha Y_n.$$

The first term captures demand for manufactures as intermediates by the manufacturing sector itself. In the second term the parameter α is final demand for manufactures (plus induced intermediate demand from nonmanufacturing sectors) as a fraction of final expenditure Y_n. Labor income in manufacturing then becomes:

$$w_i L_i^M = \sum_{n=1}^{N} \pi_{ni}(\mathbf{w}) \left[(1-\beta) w_n L_n^M + \alpha\beta Y_n \right] \tag{12}$$

Final expenditure Y_n consists of value-added in manufacturing $w_n L_n^M$ plus income generated in other sectors Y_n^O.[24]

To close the model as simply as possible we make a specific-factors assumption that labor combines with another factor to produce other output with (potentially) diminishing returns. Hence:

$$Y_n^O = A_n \left(L_n^O \right)^{\gamma}$$

where L_n^O is labor employed outside manufacturing, A_n is a nonmanufacturing productivity term, and $0 \leq \gamma \leq 1$. We assume that (at least some of) the output of the other good can be

[24] Our treatment lumps capital income in manufactures with material inputs.

traded costlessly, and use it as our numeraire.[25]

Each country n has a fixed endowment of labor $L_n = L_n^M + L_n^O$. The labor market clears to equate the wage across sectors. Hence the manufacturing sector faces a supply of labor:

$$L_n^M(w_n) = L_n - \left(\frac{\gamma A_n}{w_n}\right)^{1/(1-\gamma)} \tag{13}$$

(With $\gamma = 1$ the manufacturing labor supply is perfectly elastic at $w_n = A_n$.) Substituting equation (13) into equation (12) gives the condition for labor market equilibrium.

We define $\mathbf{Y}^M(\mathbf{w})$ as a vector of manufacturing labor incomes with typical element $w_i L_i^M(w_i)$ and $\mathbf{Y}^O(\mathbf{w})$ as a vector of nonmanufacturing GDP's with typical element $Y_i^O(w_i)$. Stacking the condition for labor-market equilibrium, equation (12) across countries and rearranging we get:

$$\mathbf{Y}^M(\mathbf{w}) = \left\{\mathbf{I}_N - (1-\beta+\alpha\beta)\left[\mathbf{\Pi}(\mathbf{w})\right]'\right\}^{-1} \alpha\beta\left[\mathbf{\Pi}(\mathbf{w})\right]' \mathbf{Y}^O(\mathbf{w}). \tag{14}$$

where $\mathbf{I}_N$ is the NxN identity matrix. The solution gives $\mathbf{w}$. (If $\gamma = 1$ then $w_i = A_i$ and equation (14) gives manufacturing labor forces L_i^M.)

Together, equations (9), (10), and (14) determine equilibrium prices, trade shares, and wages as functions of technologies, labor supplies, and trade frictions.

4.4 Two Special Cases

Two special cases deliver closed-form solutions. In each, manufacturing is the only activity (so that $A = 0$ everywhere and $\alpha = 1$). Hence each country i supplies L_i workers inelastically to manufacturing and manufacturing trade balances. National income is then $Y_i = w_i L_i = \beta X_i$. Since there is no other output we use the wage in country N as numeraire.

In the first case trade frictions disappear, so that $\widetilde{\phi}$, and hence prices, are the same every-

[25] Assuming that nonmanufactures are costlessly traded is not totally innocuous, as pointed out by Davis (1998). We could also use one country's wage as numeraire, as we do in the special case in which there is no other sector ($\alpha = 1$ and $A = 0$).

where. From expression (8) the price level is:

$$P = \left(\sum_{i=1}^{N} T_i w_i^{-\theta\beta} \right)^{-1/(\theta\beta)}.$$

The conditions for labor-market equilibrium are then:

$$w_i L_i = T_i w_i^{-\theta\beta} \widetilde{\phi}^{-\beta} \sum_{n=1}^{N} w_n L_n. \quad (15)$$

Dividing by the expression for $i = N$ we get:

$$w_i = \left(\frac{T_i / L_i}{T_N / L_N} \right)^{1/(1+\theta\beta)}. \quad (16)$$

The wage is higher in a country with more advanced technology, given its labor force. As the labor force increases workers must move into production of goods in which the country is less productive, driving down the wage.

Dividing by P to get the real wage yields:

$$w_i / P = T_i^{1/(1+\theta\beta)} \left[\sum_{k=1}^{N} T_k^{1/(1+\theta\beta)} \left(\frac{L_k}{L_i} \right)^{\theta\beta/(1+\theta\beta)} \right]^{1/(\theta\beta)} \quad (17a)$$

which increases with any country's level of technology. An increase anywhere lowers prices relative to wages everywhere. An increase at home confers an extra benefit, however, because it raises the home wage relative to those abroad. The benefit of improved foreign technology depends on the size of the source relative to the size of the recipient. If the labor force in the source country is small, its relative wage rises more, diminishing the benefits to others of its technological improvement.

Turning to the opposite extreme of autarky, consider the case of infinite d_{ni} for all but the home country. We can solve for a country's autarky real wage by solving for its free-trade real wage in a one-country world. Doing so, we get:

$$w_i / P_i = T_i^{1/(\theta\beta)}. \quad (18)$$

Note, of course, that there are gains from trade for everyone, as can be verified by observing that we derived (18) by removing positive terms from (17a). Note also that trade has an equalizing effect in that the elasticity of the real wage with respect to one's own technology level is smaller under free trade than under autarky. The reason is that, with trade, foreigners grab some of the benefit of an increase in a country's technology since they can buy its goods more cheaply.

If we plug our results for free trade into our bilateral trade equation (5) we obtain a simple gravity equation:

$$X_{ni} = \frac{Y_n Y_i}{\beta Y^W},$$

where Y^W is world income: Bilateral trade equals the product of the trade partners' incomes relative to world income, scaled up by the ratio of gross production to value added. Note that this relationship masks the underlying structural parameters, T_i and θ. For this reason we do not use a gravity formulation as the basis of our empirical analysis, to which we now return.

5 Trade and Technology: Further Empirics

Having now spelled out the complete model, we return to the estimation of equation (5) which relates trade to technology, trade impediments, and input costs. This estimation will deliver the parameter values needed for simulation.

We begin with input costs c_i, which comprise wages and intermediate goods prices. While we have some confidence in direct measures of wages, internationally comparable measures of intermediate goods prices are more suspect. But we can use equation (5) as it applies to home sales, together with equation (7) for input costs, to obtain:

$$P_i = w_i \left(T_i \frac{X_i}{X_{ii}} \right)^{-\frac{1}{\theta\beta}}.$$

Plugging this expression into our trade equation (5) as it applies to imports, normalizing by the importer's home sales, and rearranging gives us, in logarithms:

$$\ln \frac{X'_{ni}}{X'_{nn}} = -\theta \ln d_{ni} + \frac{1}{\beta} \ln \frac{T_i}{T_n} - \theta \ln \frac{w_i}{w_n}, \tag{19}$$

where $\ln X'_{ni} \equiv \ln X_{ni} - [(1-\beta)/\beta] \ln(X_i/X_{ii})$. Equation (19) forms the basis of our remaining empirical analysis.

Since, for $n = i$, equation (19) degenerates to a vacuous identity, we estimate it only for observations that involve international trade. With our sample of 19 countries we are left with a cross section with 342 observations.

We form the left-hand variable from our data on 1990 bilateral trade in manufactures, setting $\beta = .21$, the average labor share in gross manufacturing production in our sample. Since materials prices reflect imports from all sources, X_n includes imports from all countries in the world. In other respects this bilateral trade equation lets us ignore the rest of the world, allowing us to focus on trade among our 19 countries.

In specifying the right hand side of equation (19) we take two approaches, the second of which builds on the first.

5.1 Fixed Effects Estimation

We begin by combining the separate effects of technology and wages into a single source-country effect. Specifically, we define

$$S_i \equiv \frac{1}{\beta} \ln T_i - \theta \ln w_i \tag{20}$$

as a measure of country i's "competitiveness," its level of technology adjusted for its labor costs. Equation (19) becomes:

$$\ln \frac{X'_{ni}}{X'_{nn}} = -\theta \ln d_{ni} + S_i - S_n. \tag{21}$$

We can estimate the S_i as the coefficients on source-country dummies.[26] While these estimates are of some interest on their own, they take on more meaning when decomposed into their technology and wage components. Our first approach takes the estimate of θ yielded

[26]We impose the model's restriction that for each country the source and destination effects sum to zero. We tie down the coefficients' overall level by restricting them to sum to zero across all 19 countries.

by our price data ($\theta = 8.28$), along with data on labor costs, to back out values for technology. The second approach relates the estimated S_i to indicators of technological sophistication and to wage costs to obtain a separate estimate of θ.

5.1.1 Trade Impediments

Either way, identifying the source-country effects S_i requires a specification of trade impediments d_{ni}. One strategy is to use the maximum price ratios introduced in Section 3. As we pointed out, however, these measures are rough. Moreover, country-specific markups will render errors in them that correlate with our competitiveness measures. Instead we use proxies for trade frictions suggested by the gravity literature.

In particular, we relate the impediments in moving goods from i to n to geography, language, and treaties. Since $d_{nn} = 1$, we have, for all $i \neq n$:

$$\ln d_{ni} = d_k + b + l + e_h + m_n + \delta_{ni}, \tag{22}$$

where the dummy variable associated with each effect has been suppressed for notational simplicity. Here d_k ($k = 1, \ldots, 6$) is the effect of the distance between n and i lying in the kth interval, b is the effect of n and i sharing a border, l is the effect of n and i sharing a language, e_h ($h = 1, 2$) is the effect of n and i both belonging to trading area h, and m_n ($n = 1, ..., 19$) is an overall destination effect. The term δ_{ni} captures all unobservable impediments to trade. The six distance intervals (in miles) are: [0,375); [375,750); [750,1500); [1500,3000); [3000,6000); and [6000,maximum]. The two trading areas are the European Community (EC) and the European Free-Trade Area (EFTA).[27]

[27] An advantage of our formulation of distance effects is that it imposes little structure on how trade impediments vary with distance. We explored the implications of the more standard specification of trade impediments as a quadratic function of distance. There were no differences worth reporting. Since we omit a constant, the parameter d_2, for example, reflects the cost (in logs) of getting goods to a country between 375 and 750 miles away. The parameters b, l, e_1, and e_2 capture the potentially lower cost of trade between countries that share a border, a language, or membership in the EC or EFTA, respectively. The parameter m_n captures the relative openness of destination n to imports.

5.1.2 Variance Components

Unobserved sources of trade impediments introduce the error δ_{ni}. Identification of the other parameters, of course, requires that δ_{ni} has zero expectation for each source and destination.[28] To capture potential reciprocity in trade frictions, we assume that unobservable impediments to trade δ_{ni} consist of two components:

$$\delta_{ni} = \delta_{ni}^2 + \delta_{ni}^1.$$

The country-pair specific component δ_{ni}^2 (with variance σ_2^2) affects two-way trade, so that $\delta_{ni}^2 = \delta_{in}^2$, while δ_{ni}^1 (with variance σ_1^2) affects one-way trade.

This error structure implies that the variance-covariance matrix of δ has diagonal elements $E(\delta_{ni}\delta_{ni}) = \sigma_1^2 + \sigma_2^2$ and certain nonzero off-diagonal elements $E(\delta_{ni}\delta_{in}) = \sigma_2^2$.

5.1.3 Results

Imposing this error structure and the specification of trade impediments (22), we obtain:

$$\ln \frac{X'_{ni}}{X'_{nn}} = S_i - S_n - \theta m_n - \theta d_k - \theta b - \theta l - \theta e_h + \theta \delta_{ni}^2 + \theta \delta_{ni}^1, \qquad (23)$$

which we estimate by Generalized Least Squares (GLS).[29]

Table 2 reports the results. The estimated source-country parameters indicate that Japan is the most competitive country in 1990, closely followed by the United States. Belgium and Greece are the least competitive. The United States, Japan, and Belgium are the most open while Greece is least open. Increased distance substantially inhibits trade, with its impact somewhat attenuated by a shared language, while borders, the EC, and EFTA do not play a major role.

[28] This specification thus rules out exporter-specific differences in trade frictions. Such differences would introduce a source error x_i into $\ln d_{ni}$ which is not separately identified from S_i and m_n. One alternative identifying assumption is that the country-specific component to trade frictions applies symmetrically to exports and imports, so that $x_i = m_i$. Under this alternative the estimates of S_i and θm_n would equal the ones we present less half our current estimate of θm_n. We did not pursue this alternative since it works much worse in our instrumental variables estimation, described in Section 5.3.

[29] To obtain the parameters of the variance-covariance matrix for GLS estimation we first estimate the equation by OLS to obtain a set of residuals $\widehat{\varepsilon}_{ni}$. We then estimate $\theta^2\sigma_2^2$ by averaging $\widehat{\varepsilon}_{ni}\widehat{\varepsilon}_{in}$ and $\theta^2(\sigma_2^2+\sigma_1^2)$ by averaging $(\widehat{\varepsilon}_{ni})^2$.

On their own, the competitiveness measures and the trade impediment effects reflect a combination of underlying factors. We need to disentangle these factors to obtain the parameters that we need for our simulations. We pursue two alternative approaches.

5.2 Uncovering Structural Parameters from Trade and Prices

Our exploration of the relationship between bilateral trade and prices yielded an estimate of θ that we can use to extract the technology and trade friction parameters we need from our fixed-effects estimates.

First, with knowledge of wage costs, we use equation (20) to strip the S_i of their wage component to obtain measures of technology. We describe our wage measure, which applies for manufacturing and adjusts for the effects of education, in the appendix. The first column of Table 6 shows the implied technology levels T_i when $\theta = 8.28$, our estimate from the price relationship. Note that while our estimates of S_i imply that Japan is more "competitive" than the United States, we find that her edge is the consequence of lower wage costs rather than a higher level of technology. At the other end, our low estimate of Belgium's competitiveness derives in large part from her high wage costs.

Dividing each trade friction parameter by θ and exponentiating gives the percentage cost increase it imposes. The second column of Table 7 reports the results. A typical country in the closest distance category faces a 45 per cent friction relative to home sales, rising to 121% in the farthest distance category. Sharing a border reduces the friction by 4 per cent while sharing a language reduces it by 6 per cent. It costs 25 per cent less to export into the United States, the most open country, than to the average country. At the high end it costs 33 per cent more to export to Greece than to the average country.[30]

[30] Wei (1996) obtains very similar results from a gravity model making the Armington assumption that each country produces a unique set of commodities. He does not estimate the elasticity of substitution between goods from different countries, but picks a value of 10 as his base. The parameter θ plays the role of the elasticity of substitution in our model. Hummels (1998) relates data on actual freight costs for goods imported by the United States and a small number of other countries to geographical variables. His finding of a .3 elasticity of cost with respect to distance is reflected, roughly, in our estimates here.

5.3 Uncovering Structural Parameters from Sources of Competitiveness

Our second approach to identifying the underlying technology and trade friction parameters uses definition (20) to relate S_i to indicators of technological sophistication and to wage costs. This approach delivers an alternative estimate of θ as the coefficient on the wage.

We face two problems, however. First, we need proxies for technological prowess T_i. Second, although internationally-comparable wage data exist, our model implies that any error in our proxies for T_i will be positively correlated with wages, biasing the estimate of θ downward. We attack these problems in turn:

5.3.1 Technology

The derivation of the technological frontier for a closed economy in Kortum (1997) suggests that a country's level of technology T is related to its stock of past research effort. Moreover, in Eaton and Kortum (1996) we find that a higher stock of human capital allows a country to absorb more ideas from abroad. Hence we assume that

$$T_i = \alpha_0 R_i^{\alpha_R} e^{-\alpha_H/H_i} e^{\tau_i}, \tag{24}$$

where R_i is cumulative research investment in country i, H_i is the average years of education of a worker there and τ_i represents unobserved determinants of technology in country i. The functional form of the human-capital effect implies that the fraction of world knowledge that a country exploits rises with H, approaching a maximum of one.

5.3.2 A Competitiveness Relationship

Substituting (24) into the definition of competitiveness (20) we get:

$$S_i = \frac{1}{\beta}\ln\alpha_0 + \frac{\alpha_R}{\beta}\ln R_i - \frac{\alpha_H}{\beta}\left(\frac{1}{H_i}\right) - \theta\ln w_i + \frac{1}{\beta}\tau_i. \tag{25}$$

One estimation approach is to substitute (25) into equation (23) and to estimate the full set of parameters together. Instead, we pursue the alternative of estimating equation (25) using the S_i obtained from our fixed effects regression as the dependent variable. This alternative has the virtue of simplicity, and does not deliver noticeably different parameter estimates.

5.3.3 Wage Endogeneity

We treat the R&D stock R and level of human capital H as exogenous. However, in our complete model w is clearly endogenous. Hence there is reason to think that the error term τ will not have mean zero conditional on $\ln w$. In particular, labor-market equilibrium suggests that a country's wage will be increasing in its level of technology (as we showed explicitly for the case of free trade), introducing a positive correlation. Ordinary Least Squares (OLS) estimates of θ in equation (25) will be biased downward. The intuition is simple. A high-wage country is less competitive given its technology, but, conditioning only on an imperfect proxy for technology, a high wage may reflect advanced technology.

A relevant instrument must affect equilibrium wages but, to be valid, it must be independent of τ. Particularly relevant and also valid are factors affecting manufacturing labor supply. Equation (13) indicates that supply is greater, given the wage, the greater the total workforce L and the lower productivity in other endeavors A. Hence our key instrument is the total workforce. We also use population density as a proxy for low productivity outside manufacturing.

The ability of our key instrument, L, to identify θ depends on an exclusion restriction implied by our theory. It predicts that the size of a country's labor force, *given* its level of technology, affects exports only through the wage (e.g., Americans buy a lot from Japan not because it is big, but because Japanese workers are highly productive at making a wide range of goods while receiving relatively low wages). Hence we do not include L directly in our competitiveness equation. Instead, L enters indirectly through the wage: Given its technology, a large country must have a lower wage to employ more people in manufacturing.

5.3.4 Results

Table 4 reports results from estimating equation (25) by OLS and 2SLS. We explain about three-fourths of the variability in competitiveness.

The R&D stock has a substantial impact on competitiveness while years of schooling has the expected effect but is imprecisely estimated.[31] The parameter of most interest is θ, the coefficient of the relative wage. Both the OLS and 2SLS estimates of θ are significant and of the correct sign, but lower than suggested by the price data. As expected, accounting for the endogeneity of wages raises our elasticity estimate. Since the 2SLS corrects for wage endogeneity, we use the estimate 3.6 in our simulations.[32]

Proceeding as in Section 5.2 above, we use our new estimate of θ, along with wage data, to strip the S_i of their wage component to obtain alternative estimates of T_i. The second column of Table 6 reports the results.[33] Similarly, our alternative estimate of θ implies different trade impediments as reported in the last column of Table 7.[34]

[31] While we have estimated the effect of R&D on trade, our parameters have implications for its impact on productivity. To check the plausibility of our estimates, we compare their implication for this relationship with more direct evidence. To do so we rely on the case of autarky, for which we have a simple expression for productivity. (In autarky productivity equals the real wage.) Substituting equation (24) into (18) implies an elasticity of productivity with respect to the R&D stock of $\alpha_R/(\theta\beta)$, which, based on our 2SLS estimates, is .30. Griliches (1992), in surveying studies of the impact of R&D, reports that the upper range of existing estimates imply roughly this elasticity.

[32] To examine the relevance of our instruments we present Table 5, which reports the the first stage of our 2SLS procedure. Note that the instruments explain relative wages well with all variables having the expected sign. Of the two instruments excluded from the second stage, the labor force has a powerful effect on wages.

[33] Alternatively, we could have used the fitted values from equation (24) reported in the last column of Table 6 as technology parameters. We chose not to since they exclude the unobservable component τ. Comparing the fitted values with the estimates based on export competitiveness we find, for example, that Japan overachieves as an exporter, given her stock of research and schooling, while the United States is a notable underachiever.

[34] A tractable generalization of our model is to treat a fraction λ of goods as inherently immobile. The appropriate dependent variable in equation (25) then becomes:

$$S_i^{'} = S_i + \frac{(1-\beta)}{\beta}\left[(1-\lambda)\ln\left(X_{ii}/X_i - \lambda\right) - \ln\left(X_{ii}/X_i\right)\right].$$

Setting λ at either .1 or .2. (The fraction of Belgium's total absorption of manufactures produced at home imposes an upper bound on λ of .25.) the fit is not as good. Not surprisingly, as the fraction of goods deemed nontraded rises, the implied transport costs for the remaining traded goods fall. In the very extreme case of $\lambda = .2$ the estimate of θ rises to 4.9. Since this formulation is not that different in its implications, we stick with our simpler baseline.

6 Simulation

We return to the general equilibrium determination of price levels, relative wages, and trade shares described by equations (9), (10), and (14) to simulate the effect of changes in technology, trade impediments, and trade policy. Specifically we ask: What are the gains from trade and how are they distributed? To what extent does trade bring the benefits of one country's technology to others? How does comparative advantage evolve as trade impediments fall? What are the effects of unilateral and multilateral tariff reductions?

To explore these questions we parameterize the model as follows:

1. We use our two alternative estimates of θ (the value of 8.28 obtained from the price relationship and the value of 3.6 obtained from estimating the effect of wages on competitiveness), along with the corresponding technology and trade impediment parameters reported in the first two columns of Table 6 and the last two columns of Table 7. As it turns out, the two sets of estimates yield roughly similar implications for the questions we ask. The exception is the gains from trade, which are substantially greater when θ is smaller.[35]

2. Rather than trying to estimate the parameter γ, which governs the elasticity of labor supply into manufacturing, we consider two polar cases that bracket any plausible values. In one case we set $\gamma = 0$, so that manufacturing workers are a specific factor in fixed supply. For this case income produced by other sectors is simply A_n. In the other case set $\gamma = 1$, in which case manufacturing labor is perfectly elastically supplied at a fixed wage A_n.

[35] Our two estimates of θ, obtained from different data using different methodologies, differ by a factor of two. Nonetheless, they lie within the range of Armington elasticities for imports used in computable general equilibrium models. For example, the baseline elasticities for different commodities used in the GTAP model (see Hertel, 1997) span a nearly identical range.

3. We estimate $\alpha = .13$ from the relationship:

$$X_{nn} + IMP_n = (1 - \beta)(X_{nn} + EXP_n) + \alpha Y_n$$

summed across our sample (with $\beta = .21$) in 1990. Here IMP_n is manufacturing imports and EXP_n is manufacturing exports, and Y_n is total GDP, each translated from local currency values into U.S. dollars at the official exchange rate.

The dollar price of nonmanufactures serves as our numeraire. The price level in country n is therefore P_n^{α}. We do not impose balanced trade in manufactures, since our specification admits traded nonmanufactures. For purposes of simulation we ignore sources of manufactures from outside our sample of 19 OECD countries.

In simulating the model we wish to distinguish the effects of any counterfactual from the initial misfit of our model. We therefore compare the outcomes of our counterfactual simulations with a baseline simulation which solves for equilibrium wages, trade patterns, and price levels given actual 1990 manufacturing labor forces $\mathbf{L}^M$, forcing $\mathbf{Y}$ to equal actual GDP.[36]

In simulating counterfactuals we make two alternative assumptions about what happens to GDP, the manufacturing labor force, and the wage depending upon whether $\gamma = 1$ or $\gamma = 0$. With $\gamma = 1$ we assume that GDP stays at its actual level and $\mathbf{w}$ at its baseline; $\mathbf{L}^M$ then equilibrates (14). With $\gamma = 0$ we solve for a new equilibrium $\mathbf{w}$ fixing $\mathbf{L}^M$ at its actual 1990 level. In these simulations we fix Y_n^O at actual GDP less baseline Y_n^M and set $Y_n = w_n L_n^M + Y_n^O$ in equation (14) using the new equilibrium $\mathbf{w}$ and actual $\mathbf{L}^M$.

In performing experiments with the model there are a number of different outcomes that we can examine. One is the implication for overall welfare in country n, which we can measure as $Y_n P_n^{-\alpha}$. For the fixed-labor case we consider the implications for the real wage of manufacturing workers $w_n P_n^{-\alpha}$. For the fixed-wage case we ask about implications for manufacturing employment. We also look at how trade patterns change.

[36] In fitting actual wages in manufacturing, the baseline has a root mean square error of 8.8 per cent. We overpredict the Canadian wage by one third but otherwise predictions are quite close.

6.1 The Gains from Trade

Table 8 presents our model's estimates of the gains from trade. It shows first the percentage welfare gains in moving from autarky to the baseline case and then from the baseline to a world with no trade impediments. We consider four different scenarios depending on the structure of the labor market and the value of θ.[37]

As expected, gains are positive everywhere under each scenario. Very striking, however, is the implication, under any scenario, that trade impediments at their current levels allow the world to exploit only a small fraction of the potential gains from trade. The welfare gains of moving from autarky to the baseline are puny compared with what would be gained if trade were unencumbered. An optimistic spin on these results is that much of the gains from trade remain to be reaped.[38]

Also note that gains are greater when comparative advantage is more heterogeneous, as reflected by our lower estimate of θ. Greater heterogeneity, of course, implies that countries have greater differences to exploit through trade.

In our remaining simulations the value of θ had a less dramatic effect on the outcome. In the interest of parsimony we focus on the case $\theta = 8.28$, noting any striking differences that emerge when $\theta = 3.6$ in passing.

6.2 The Benefits of Foreign Technology

To determine how much trade spreads the benefits of a local improvement in technology, we increase a country's technology level T_i by 20 per cent, first for the United States and then for Germany. Manufacturing expands (through more employment with fixed wages and through higher wages with fixed employment) where the improvement occurs and contracts everywhere else.

[37] For simplicity, we ignore any tariff revenues that trade impediments might generate. We consider the effect of reducing tariff barriers, taking revenue effects into account, in Section 6.4 below.

[38] Another implication is that, at least in terms of the gains from trade, assuming no trade seems closer to the mark than treating trade as costless, as is done in mainstream trade models.

Nevertheless, other countries almost always share the welfare gains through lower prices. Table 9 reports what happens to welfare in different countries of the world as a percentage of the effect locally. Note that, except for Greece's response to a U.S. technology improvement, the benefits are spread more widely when countries have the flexibility to downsize their manufacturing labor forces. Two countries with large baseline manufacturing labor forces, Germany and Japan, actually experience welfare losses in response to technological improvements elsewhere when their labor forces cannot be reallocated away from manufacturing.

The percentage benefits decay dramatically with distance and size. With a flexible labor supply the gain in nearby countries approaches that where the improvement occurred. Canada, for example, benefits almost as much as the United States from a U.S. technological improvement. Germany's smaller neighbors experience more than half the gain from an improvement in German technology as Germany itself. At the other extreme, Japan, which is both distant and large, gets little from either Germany or the United States.

The results point to the conclusion that trade does allow a country to benefit from foreign technological advances. But for big benefits two conditions must be met. First, the country must be near the source of the advance. Second, the country needs to be able to reallocate its labor to activities outside of manufacturing.

6.3 Technology vs. Geography

We now turn to the question, raised in the economic geography literature, of the role of geography, relative to technology, in determining comparative advantage. In the standard Ricardian model in which trade impediments are either absent or so high as to eliminate trade, a country's location makes no difference to the resources it devotes to different activities. Take the case in which the labor forces in our model are flexible at a wage $w_i = A_i$. With no trade impediments the fraction of a country's labor force devoted to manufacturing is proportional to $(T_i/L_i)/w_i^{1+\theta\beta}$. When trade impediments are prohibitive the fraction is simply α, so that not even technology matters. But in neither case is location relevant.

Location does start to matter when trade impediments are present, but do not fully inhibit trade. Countries that are small or isolated are disadvantaged because intermediates are likely to be more expensive there.

To examine how technology and geography compete in shaping comparative advantage we look at what happens to the fraction of the labor force a country devotes to manufacturing as trade barriers fall from a prohibitive level to nothing. Two basic patterns emerge. For smaller countries manufacturing shrinks as trade impediments diminish from their autarky level. Production shifts to larger countries where inputs are cheaper. As trade impediments continue to fall, however, the forces of technology take over, and the fraction of the labor force grows, often exceeding its autarky level. The results for Denmark, depicted in Figure 2, illustrate this pattern nicely.

For the largest countries in our sample, Germany, Japan, and the United States, the pattern is reversed. Their manufacturing at first grows and then shrinks as trade barriers fall. Germany, also depicted in Figure 2, illustrates the pattern most starkly.

The current levels of trade impediments seem roughly at the transition between a world where the effects of geography dominate and one where technology governs comparative advantage. The results suggest that further declines in trade frictions will lead to specialization more along Ricardian lines, with large countries losing their edge.

How much does trade expand as trade frictions fall? The elasticity appears to be around 2 to 3. For example, with $\theta = 8.28$ a 20 per cent drop in trade impediments from their baseline raises total imports by 43 per cent with fixed labor supplies and by 56 per cent with labor supply flexibility. (With $\theta = 3.60$ the corresponding figures are 35 per cent and 42 per cent.)

6.4 Eliminating Tariffs

In our analysis so far we have ignored, for simplicity, any revenues generated by trade impediments, treating them as natural. Our framework can, however, readily incorporate revenue-generating barriers. We assume that country n's imports from country i are subject to an *ad valorem* tariff t_{ni} (on the c.i.f. price). Trade impediments then decompose into their tariff $1+t_{ni}$ and natural d^*_{ni} components, so that $d_{ni} = (1+t_{ni})d^*_{ni}$. We augment income Y_n by tariff revenue TR_n, where:

$$TR_n = \sum_{i \neq n} \frac{t_{ni}}{1+t_{ni}} X_{ni}$$

We calculate a baseline world in which countries impose a uniform 5 per cent tariff on all imports.[39] We then ask what happens when: (1) all countries remove tariffs, (2) the United States removes its tariff unilaterally, and (3) members of the European Community (as of 1990) drop tariffs against each other.

6.4.1 General Multilateral Tariff Elimination

The welfare benefits of all 19 countries jointly removing tariffs are substantially greater with labor supply flexibility. The benefits vary from a high of 1.31 per cent for Belgium to a low of 0.21 per cent for Japan, with most countries gaining around one per cent. With manufacturing labor fixed the gains are much lower, never exceeding half a per cent. Germany actually experiences a 0.05 per cent loss.

6.4.2 U.S. Unilateral Tariff Elimination

If the United States removes tariffs on its own, everyone benefits except the United States, which, for standard optimal tariff reasons, suffers a welfare loss of 0.005 per cent with flexible employment (0.13 per cent with fixed employment). The biggest gainer is Canada, which enjoys a welfare gain of 0.5 per cent with flexible employment (1.1 per cent with fixed employment). With labor supplies flexible, the percentage gains for other countries roughly equal or exceed

[39]This figure corresponds roughly to average statutory rates among the OECD. See, e.g., Hertel (1997).

the U.S. loss. The results point to the importance of pursuing freer trade multilaterally since the benefit of U.S. freer trade to the rest of the world far exceed the cost to the United States.

6.4.3 Trade Diversion in the European Community

Table 10 reports some effects of eliminating tariffs within the 1990 European Community. Who gains and who loses depends very much on labor-supply flexibility. As the second column reports, with fixed labor supplies the major losers are nonmembers nearby, whose manufacturing wages must fall in order for them to remain competitive suppliers to the EC. EC members consequently benefit from lower external prices and a greater premium placed on their own manufacturing workers. With labor supply flexibility, however, the losers (as reported in the first column) are the northern EC members. In this scenario nonmembers move workers to other activities rather than lowering their wage costs. The trade diversion effects come to dominate the outcome for the northern EC members. Note from the third and fourth columns that intra-EC trade and EC exports outside expand much more with labor supply flexibility. Moreover, as reported in the last two columns, more of this increase constitutes trade diversion in the scenario in which labor supplies adjust.

7 Conclusion

We have developed a Ricardian model of how technological know-how and location determine patterns of trade. The theory leads quite naturally to empirical equations for bilateral trade, which we have investigated with data on manufacturing from the OECD. Using the parameter estimates delivered by these empirics, we put the model to work to answer a number of questions. Key findings are: (i) the extent to which trade barriers leave the gains from trade largely unrealized, (ii) the geographic concentration of the gains to country-specific technological advance, (iii) the likelihood that reductions in trade barriers will shift manufacturing to smaller countries, and (iv) the potential for regional trade agreements to create losers.

The results here are just the first returns from our methodology. The model is stripped down, and we apply it only to aggregate manufacturing employing only a single factor of production. Adding more factors is analytically straightforward (although empirically challenging) and would bridge the gap between the Ricardian and HOV approaches. Adding a sectoral dimension is also straightforward analytically (although it requires much more detail in specifying interindustry relationships). The potential payoff is identifying the role of research and location in carving out comparative advantage within manufacturing.

As it stands, the analysis is static. But it could be seen as a snapshot of a dynamic model of innovation and international diffusion of the sort we pursue in Eaton and Kortum (1998a). In that model, technologies improve over time, but countries don't trade. In fact, international trade significantly complicates modeling the incentive to innovate. Overcoming this hurdle could provide insight into how incentives for research around the world govern the evolution of comparative advantage.

References

Anderson, James E. "A Theoretical Foundation for the Gravity Equation." *American Economic Review 69* (March 1979): 106-116.

Barro, Robert J., and Lee, W.-J. "International Comparisons of Educational Attainment." *Journal of Monetary Economics* 32 (December 1993): 363-394.

Baxter, Marianne. "Fiscal Policy, Specialization, and Trade in the Two-Sector Model: The Return of Ricardo?" *Journal of Political Economy* 100 (August 1992): 713-744.

Bernard, Andrew B. and Jensen, J. B. "Exceptional Exporter Performance: Cause, Effect, or Both?" mimeo, MIT (1996).

Bergstrand, Jeffrey. "The Generalized Gravity Equation, Monopolistic Competition, and Factor Proportions Theory in International Trade." *Review of Economics and Statistics* 71 (February 1989): 143-153.

Berry, Steven T. "Estimating Discrete-Choice Model of Product Differentiation." *Rand Journal of Economics* 71 (Summer 1994): 242-262.

Billingsley, Patrick. *Probability and Measure,* 2nd edition. New York: John Wiley & Sons, 1986.

Bils, Mark and Klenow, Peter J. "Does Schooling Cause Growth or the Other Way Around?" mimeo, University of Chicago (1998).

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

Crucini, Mario J., Telmer, Chris I., and Zachariadis, Marios. "What Can We Learn From Deviations From The Law of One Price?" mimeo, Ohio State University (1998).

Davis, Donald R. "The Home Market, Trade, and Industrial Structure." *NBER Working Paper No. 6067* (1997).

Deardorff, Alan V. "Testing Trade Theories and Predicting Trade Flows." In *Handbook of International Economics, Volume I,* edited by Ronald Jones and Peter Kenen. Amsterdam: North-Holland, 1984.

Domar, Evsey D. "On the Measurement of Technological Change." *The Economic Journal* 71 (December 1961): 709-729.

Dornbusch, Rudiger, Fischer, Stanley and Samuelson, Paul A. "Comparative Advantage, Trade, and Payments in a Ricardian Model with a Continuum of Goods." *American Economic Review* 67 (December 1977): 823-839.

Eaton, Jonathan and Kortum, Samuel. "Trade in Ideas: Patenting and Productivity in the OECD." *Journal of International Economics* 40 (May 1996): 251-278.

Eaton, Jonathan and Kortum, Samuel. "International Technology Diffusion: Theory and Measurement." forthcoming in *International Economic Review* (1998a).

Eaton, Jonathan and Kortum, Samuel. "A Rising Tide Raises All Ships: Trade and Diffusion as Conduits of Growth." Forthcoming in *Finance, Research, Education and Growth,* edited by Edmund S. Phelps and Luigi Paganetto. Oxford: Macmillan, 1998b.

Eaton, Jonathan and Tamura, Akiko. "Bilateralism and Regionalism in Japanese and U.S. Trade and Direct Foreign Investment Patterns." *Journal of the Japanese and International Economies* 8 (December 1994): 478-510.

Engel, Charles and Rogers, John H. "How Wide is the Border?" *American Economic Review* 86 (December 1996): 1112-1125.

Evenett, Simon and Keller, Wolfgang. "Bilateral Trade Flows: One Prediction of Several Theories Estimated in Nine Thousand and Two Samples." mimeo, University of Wisconsin (1996).

Feenstra, Robert C., Lipsey, Robert E. and Bowen, Henry P. "World Trade Flows, 1970-1992, with Production and Tariff Data." *NBER Working Paper No. 5910* (1997).

Friedman, Milton. *A Theory of the Consumption Function.* Princeton University Press, 1957.

Griliches, Zvi. "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94 (Supplement 1992): 29-47 .

Grossman, Gene M. and Helpman, Elhanan. "Technology and Trade." In *The Handbook of International Economics, Volume III,* edited by Gene M. Grossman and Kenneth Rogoff. Amsterdam: North-Holland, 1995.

Harrigan, James. "Technology, Factor Supplies, and International Specialization: Estimating the Neoclassical Model." *American Economic Review* 87 (September 1997): 475-494.

Haveman, Jonathan and Hummels, David. "What Can We Learn from Bilateral Trade? Gravity and Beyond." mimeo, Purdue University (1997).

Helpman, Elhanan. "Imperfect Competition and International Trade: Evidence from Fourteen Industrial Countries." *Journal of Japanese and International Economics* 1 (March 1987): 62-81.

Hertel, Thomas W. *Global Trade Analysis: Modeling and Applications.* Cambridge University Press, 1997.

Hooper, Peter and Vrankovich, Elizabeth. "International Comparisons of the Levels of Unit Labor Costs in Manufacturing." *International Finance Discussion Papers No. 527* (1995).

Hummels, David. "Towards a Geography of Trade Costs," mimeo, University of Chicago (1998).

Hummels, David and Levinsohn, James. "Monopolistic Competition and International Trade: Reconsidering the Evidence." *Quarterly Journal of Economics* 110 (August 1995): 799-836.

Ishii, Jun and Yi, Kei-Mu. "The Growth of World Trade: Evidence and Explanations," mimeo, Federal Reserve Bank of New York (1996).

Jensen, Paul E. *Essays on Trade Patterns and Policy Reform in Models with Differentiated Products,* Ph.D. Dissertation, Pennsylvania State University, 1996.

Johnson, Norman L. and Kotz, Samuel. *Continuous Univariate Distributions.* Boston, MA: Houghton & Mifflin, 1970.

Kortum, Samuel. "Research, Patenting and Technological Change." *Econometrica* 65 (November 1997): 1389-1419.

Krugman, Paul R. *Geography and Trade.* MIT Press, 1991.

Krugman, Paul R. "Increasing Returns, Imperfect Competition, and the Positive Theory of International Trade." In *The Handbook of International Economics, Volume III,* edited by Gene M. Grossman and Kenneth Rogoff. Amsterdam: North-Holland, 1995.

Kyriacou, G. "Level and Growth Effects of Human Capital." *C.V. Starr Center Working Paper 91-26* (1991).

Leamer, Edward. *Sources of International Comparative Advantage: Theory and Evidence.* MIT Press, 1984.

Leamer, Edward. and Levinsohn, James. "International Trade Theory: The Evidence." In

The Handbook of International Economics, Volume III, edited by Gene M. Grossman and Kenneth Rogoff. Amsterdam: North-Holland, 1995.

MacDougall, G.D.A. "British and American Exports: A Study Suggested by the Theory of Comparative Costs." *Economic Journal* 61 (Part I: December 1951): 697-724, 62 (Part II: 1952): 487-521.

Maskus, Keith. "Comparing International Trade Data and Product and National Characteristics Data for the Analysis of Trade Models." In International Economic Transactions: *Issues in Measurement and Empirical Research National Bureau of Economic Research Studies in Income and Wealth, Volume 55,* edited by Peter Hooper and J. David Richardson. University of Chicago Press, 1991.

McFadden, Daniel. P. "Conditional Logit Analysis of Qualitative Choice Behavior." In *Frontiers in Econometrics,* edited by P. Zarembka. New York: Academic Press, 1974.

OECD. "Science and Technology Statistics." 1991.

OECD. "The OECD STAN Database." 1995.

OECD. "Basic Science and Technology Statistics." 1996.

OECD. "Main Science and Technology Indicators." 1997.

Rauch, James. E. "Networks vs. Markets in International Trade." *NBER Working Paper No. 5617* (1996).

Small, Kenneth. "A Discrete Choice Model for Ordered Alternatives." *Econometrica* 55 (March 1987): 409-424.

Summers, Robert and Heston, Alan. "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950-1988." *The Quarterly Journal of Economics* 106 (May 1991): 327-368.

Trefler, Daniel. "International Factor Price Differences: Leontief Was Right!" *Journal of Political Economy* 101 (December 1993): 961-987.

Trefler, Daniel. "The Case of the Missing Trade and Other Mysteries." *American Economic Review* 85 (December 1995): 1029-1046.

Wei, Shang-Jin. "How Reluctant are Nations in Global Integration." *NBER Working Paper No. 5531* (1996) .

World Bank, International Economics Department. "Purchasing Power of Currencies, Comparing National Incomes Using ICP Data." Washington, DC (1993).

A Data Appendix

Our analysis uses data for manufacturing in the 19 OECD countries listed in Table 1.

A.1 Years

Except for the price data that we use in Section 3, our data set covers 1971-1990. We estimated equations (23) and (25) for a number of different cross sections. The estimates are stable over time, except that the estimated trade impediments have drifted downward throughout the period while the estimated wage elasticity rose substantially in the early 1970s. Since the estimates form the basis of our simulations, which we want to be as up-to-date as possible, we report the results only for 1990.

A.2 Trade

Our dependent variables are various transformations of bilateral manufacturing imports. Country i's imports from home are gross manufacturing production less manufacturing exports. Its total manufacturing expenditures are home purchases plus imports from everywhere else. These measures are reported by the STAN database in local currencies (OECD, 1995). We calculate imports from each of the other 18 countries, as a fraction of total manufactured imports, from the United Nations–Statistics Canada bilateral merchandise trade data by 4-digit SITC, as described in Feenstra, Lipsey, and Bowen (1997).[40] All import measures are c.i.f. Since our dependent variables normalize imports either by home sales or by total expenditures, no exchange rate translation is required.

Table 1 summarizes imports, normalized by home purchases. Note that imports are typically only a fraction of what a country produces for itself. The exceptions are Belgium, the Netherlands, and, to a lesser extent Denmark. The last two columns of the table show each country's favorite source and destination. Note that a few large countries dominate, yet the

[40]We used the concordance of Maskus (1991) to determine those SITC codes corresponding to manufactures. Using Feenstra et al.'s concordance made virtually no difference.

biggest partner is typically nearby.

A.3 Prices

Prices in 1990 for over 100 GDP categories in each of our 19 countries are from World Bank (1993). We use the 50 items identified by Hooper and Vrankovich (1995) as corresponding to either: (i) textile, apparel, and leather products, (ii) machinery, equipment, and fabricated metal products, or (iii) other manufactured products. We dropped the many items related to food and chemicals since we thought their prices would be unduly influenced by proximity to natural resources and taxes on petroleum products, two factors absent from our model.

A.4 Proxies for Trade Frictions

Distances between countries serve as a determinant of trade impediments. The distances are in thousands of miles measured between central cities in each country. (A list of the cities is in Eaton and Tamura, 1994.) Language groups are: (i) English (Australia, Canada, New Zealand, United Kingdom, United States), (ii) French (Belgium and France), and (iii) German (Austria and Germany).

A.5 Wages

Since we use the model itself to solve for the price of materials, the only factor costs entering our empirical trade equations are manufacturing wages. Annual compensation per worker in manufacturing (which includes employers' compulsory pension and medical payments) are reported by the OECD (1995) in local currency. We translate into U.S. dollars at the current exchange rates to obtain measured compensation $comp_i$, reported in the first column of Table 3.[41] We then adjust by worker quality, setting $w_i = (comp_i)e^{-gH_i}$, where H_i is average years of schooling and g is the return to education. Columns four and five of Table 3 report the two measures that we use for H_i. We set $g = .06$, which Bils and Klenow (1998) suggest is a

[41] We use the official rather than the purchasing power exchange rate since it determines differences in costs of production. In our model, differences in purchasing power arise endogenously.

conservative estimate.

We use two variables to instrument for wage costs. The first is aggregate workforce $work_i$, from Summers and Heston (1991, version 5.6), shown in the sixth column of Table 3. As with wages, we adjust for education setting $L_i = (work_i)\, e^{gH_i}$. The second instrument is density, defined as the aggregate workforce divided by a country's land area, shown in the last column of Table 3.

A.6 Proxies for Technology

Stocks of research R_i for each country are one determinant of technological know-how. Our baseline research stocks are from Coe and Helpman (1995). They use the perpetual inventory method (assuming a depreciation rate of five per cent) to add up real R&D investment by business enterprises.

Following their methodology, we construct two other measures. One removes government-funded R&D from total business enterprise R&D investment and the other uses business enterprise employment of R&D Scientists and Engineers (from OECD (1991, 1996)). Missing data were interpolated.

The various measures are roughly similar. They are all obviously highly influenced by the scale of the economies concerned, but they also display similar variation in per-worker terms. We report the Coe-Helpman measure and the measure based on employment of R&D Scientists and Engineers in the second and third columns of Table 3.

Removing government funded R&D from the Coe-Helpman measure of cumulative R&D expenditures made virtually no difference to our estimates. Moving to a people-based measure improved the fit somewhat but yielded essentially the same estimates except for a slightly lower estimate of θ (3.18 instead for 3.60).

The human capital measure that we use to adjust wages and labor forces is also our other determinant of technological know-how. We use Kyriacou's (1991) measure of years of schooling as our baseline. As an alternative, we use the measure constructed by Barro and Lee (1993). In either case we interpolated between the available five-year time intervals, and for 1986-1990 we used the 1985 data.

Using the Barro-Lee measure of schooling instead of Kyriacou's resulted in a substantial deterioration in the fit. The direct effect of human capital using that measure was much smaller, while the point estimate of α_R/β rose to 1.32 and of θ rose to 4.52.[42]

A.7 Income

In our simulations we require total income in 1990. We use local-currency GDP in 1990 (from OECD (1997)) translated into U.S. dollars at the 1990 exchange rate.

[42]We also experimented with alternative functional forms for human capital, replacing $e^{-\alpha_H/H}$ in equation (24) with either H^{α_H} (as we introduce the R&D stock) or with $e^{\alpha_H H}$ (as in Bils and Klenow (1998)). There was virtually no effect on the fit or on the other parameter estimates.

Table 1: Trade Data

Country	Imports per home sales		Manufacturing production per GDP	Biggest source for imports	Biggest destination for exports
	total	sample[1]			
Australia	0.31	0.24	0.44	U.S.	Japan
Austria	0.68	0.57	0.68	Germany	Germany
Belgium	2.97	2.57	0.74	Germany	Germany
Canada	0.59	0.53	0.48	U.S.	U.S.
Denmark	1.03	0.88	0.45	Germany	Germany
Finland	0.46	0.37	0.57	Germany	Sweden
France	0.42	0.35	0.57	Germany	Germany
Germany	0.33	0.26	0.83	France	France
Greece	0.75	0.61	0.37	Germany	Germany
Italy	0.27	0.21	0.65	Germany	Germany
Japan	0.07	0.03	0.83	U.S.	U.S.
Netherlands	2.02	1.68	0.60	Germany	Germany
New Zealand	0.57	0.46	0.52	Australia	Australia
Norway	0.77	0.66	0.45	Sweden	U.K.
Portugal	0.71	0.60	0.68	Germany	Germany
Spain	0.32	0.27	0.56	Germany	France
Sweden	0.60	0.51	0.60	Germany	Germany
United Kingdom	0.46	0.36	0.62	Germany	Germany
United States	0.17	0.10	0.52	Japan	Canada

All data are for 1990, and (except for GDP) the manufacturing sector. Manufacturing production is gross of the value of materials used in manufacturing. Home sales are manufacturing production less manufacturing exports.

1. In column 2, "sample" refers to the other 18 countries in our sample. See the appendix for a complete description of all data sources.

Table 2: Fixed-Effects Bilateral Trade Equation

Variable		est.	s.e.			
Distance [0,375)	$-\theta d_1$	-3.10	(.16)			
Distance [375,750)	$-\theta d_2$	-3.66	(.11)			
Distance [750,1500)	$-\theta d_3$	-4.03	(.10)			
Distance [1500,3000)	$-\theta d_4$	-4.22	(.16)			
Distance [3000,6000)	$-\theta d_5$	-6.06	(.09)			
Distance [6000,maximum]	$-\theta d_6$	-6.56	(.10)			
Shared border	$-\theta b$	.30	(.14)			
Shared language	$-\theta l$	.51	(.15)			
European Community	$-\theta e_1$	.04	(.13)			
EFTA	$-\theta e_2$	.54	(.19)			
	Source-country competitiveness			Destination-country trade impediments		
Country		est.	s.e.		est.	s.e.
Australia	S_1	.19	(.15)	$-\theta m_1$	.24	(.27)
Austria	S_2	-1.16	(.12)	$-\theta m_2$	-1.68	(.21)
Belgium	S_3	-3.34	(.11)	$-\theta m_3$	1.12	(.19)
Canada	S_4	.41	(.14)	$-\theta m_4$	.69	(.25)
Denmark	S_5	-1.75	(.12)	$-\theta m_5$	-.51	(.19)
Finland	S_6	-.52	(.12)	$-\theta m_6$	-1.33	(.22)
France	S_7	1.28	(.11)	$-\theta m_7$	.22	(.19)
Germany	S_8	2.35	(.12)	$-\theta m_8$	1.00	(.19)
Greece	S_9	-2.81	(.12)	$-\theta m_9$	-2.36	(.20)
Italy	S_{10}	1.78	(.11)	$-\theta m_{10}$	.07	(.19)
Japan	S_{11}	4.20	(.13)	$-\theta m_{11}$	1.59	(.22)
Netherlands	S_{12}	-2.19	(.11)	$-\theta m_{12}$	1.00	(.19)
New Zealand	S_{13}	-1.20	(.15)	$-\theta m_{13}$	.07	(.27)
Norway	S_{14}	-1.35	(.12)	$-\theta m_{14}$	-1.00	(.21)
Portugal	S_{15}	-1.57	(.12)	$-\theta m_{15}$	-1.21	(.21)
Spain	S_{16}	.30	(.12)	$-\theta m_{16}$	-1.16	(.19)
Sweden	S_{17}	.01	(.12)	$-\theta m_{17}$	-.02	(.22)
United Kingdom	S_{18}	1.37	(.12)	$-\theta m_{18}$	.81	(.19)
United States	S_{19}	3.98	(.14)	$-\theta m_{19}$	2.46	(.25)
Unobservable trade impediments:						
Two-way	$\theta^2\sigma_2^2$	.05				
One-way	$\theta^2\sigma_1^2$	.16				
Total Sum of Squares (about mean)		2937				
Sum of squared residuals		71				
Number of observations		342				

Estimated by Generalized Least Squares using 1990 data. The specification is given in equation (23) of the paper. The parameters are normalized so that $\sum_{i=1}^{19} S_i = 0$ and $\sum_{n=1}^{19} m_n = 0$. Standard errors are in parentheses.

Table 3: Explantory Variables

Country	Manuf. wages	Research stocks: Coe and Helpman	Research stocks: R&D S&E's	Years of schooling: Kyria-cou	Years of schooling: Barro and Lee	Workers	Density
Australia	0.61	0.0087	0.0110	8.7	10.2	0.066	0.08
Austria	0.70	0.0063	0.0048	8.6	6.6	0.030	3.43
Belgium	0.92	0.0151	0.0099	9.4	9.2	0.034	12.02
Canada	0.88	0.0299	0.0286	10.0	10.4	0.108	0.10
Denmark	0.80	0.0051	0.0045	6.9	10.3	0.023	4.47
Finland	1.02	0.0053	0.0050	10.8	9.5	0.021	0.55
France	0.92	0.1108	0.0679	9.5	6.5	0.211	3.88
Germany	0.97	0.1683	0.1421	10.3	8.5	0.250	9.50
Greece	0.40	0.0005	0.0004	8.4	6.7	0.031	2.87
Italy	0.74	0.0445	0.0350	9.1	6.3	0.190	7.16
Japan	0.78	0.2492	0.3425	9.5	8.5	0.637	12.42
Netherlands	0.91	0.0278	0.0155	9.5	8.6	0.051	13.64
New Zealand	0.48	0.0010	0.0012	9.3	12.0	0.012	0.47
Norway	0.99	0.0057	0.0061	9.2	10.4	0.018	0.49
Portugal	0.23	0.0007	0.0006	6.5	3.8	0.036	4.01
Spain	0.56	0.0084	0.0068	9.7	5.6	0.115	2.88
Sweden	0.96	0.0206	0.0165	9.6	9.5	0.036	0.71
United Kingdom	0.73	0.1423	0.1574	8.5	8.7	0.231	8.76
United States	1.00	1.0000	1.0000	12.1	11.8	1.000	1.00

All data are for 1990 except years of schooling which are for 1985. Wages, research stocks, workers, and density are all relative to the United States. The relative wage is for manufacturing while workers are for all sectors. See the appendix for complete definitions.

Table 4: Competitiveness Equation

		Ordinary Least Squares est.	Ordinary Least Squares s.e.	Two-Stage Least Squares est.	Two-Stage Least Squares s.e.
Constant		3.75	(1.89)	3.82	(1.92)
Research stock, $\ln R_i$	$\frac{\alpha_R}{\beta}$	1.04	(.17)	1.09	(.18)
Human capital, $1/H_i$	$-\frac{\alpha_H}{\beta}$	-18.0	(20.6)	-22.7	(21.3)
Wage, $\ln w_i$	$-\theta$	-2.84	(1.02)	-3.60	(1.21)
Total Sum of Squares (about mean)		80.3		80.3	
Sum of squared residuals		18.5		19.1	
Number of observations		19		19	

Estimated using 1990 data. The specification is given in equation (25) of the paper. The dependent variable is the estimates $\hat{S}_i$ of source-country competitiveness shown in Table 2. Standard errors are in parentheses.

Table 5: First Stage Equation for the Wage

Variable	est.	s.e.
Constant	-.04	(.26)
Research stock, $\ln R_i$	.28	(.04)
Human Capital, $1/H_i$	-3.82	(2.88)
Density, $\ln(L_i/AREA_i)$	-0.002	(.025)
Workforce, $\ln L_i$	-0.36	(.06)
Total Sum of Squares (about mean)	2.09	
Sum of squared residuals	.30	
Number of observations	19	

Estimated by Ordinary Least Squares using 1990 data. The dependent variable is the the log of the wage adjusted for years of schooling. Standard errors are in parentheses.

Table 6: Technology Parameters

Country	Based on source-country competitiveness[1]		Predicted by R&D and Human Capital[2]
	$\theta = 8.28$	$\theta = 3.60$	
Australia	0.27	0.36	0.32
Austria	0.26	0.30	0.30
Belgium	0.24	0.22	0.38
Canada	0.46	0.47	0.46
Denmark	0.35	0.32	0.25
Finland	0.45	0.41	0.32
France	0.64	0.60	0.61
Germany	0.81	0.75	0.70
Greece	0.07	0.14	0.16
Italy	0.50	0.57	0.48
Japan	0.89	0.97	0.73
Netherlands	0.30	0.28	0.44
New Zealand	0.12	0.22	0.20
Norway	0.43	0.37	0.30
Portugal	0.04	0.13	0.15
Spain	0.21	0.33	0.34
Sweden	0.51	0.47	0.42
United Kingdom	0.49	0.53	0.61
United States	1.00	1.00	1.13

1. The first two columns are based on the estimates $\hat{S}_i$ of source-country competitiveness parameters shown in Table 2, $T_i = (e^{\hat{S}_i} w_i^{\theta})^{\beta}$. Each column is normalized to the United States' value.

2. The last column is based on the parameter estimates in Table 4, hence the predicted level of technology is $\hat{T}_i = a_0(R_i^{1.09} e^{-22.7/HK_i})^{\beta}$. The value a_0 is chosen so that the ratio of the third column to the second column is $e^{-\beta\hat{\tau}_i}$ where $\hat{\tau}_i$ is the residual from estimating equation (25).

Table 7: Implied Trade Impediments

Source of Impediment	Estimated parameter	Implied Percentage Effect on Cost $\theta = 8.28$	Implied Percentage Effect on Cost $\theta = 3.60$
Distance [0,375)	-3.10	45.39	136.51
Distance [375,750)	-3.66	55.67	176.74
Distance [750,1500)	-4.03	62.77	206.65
Distance [1500,3000)	-4.22	66.44	222.75
Distance [3000,6000)	-6.06	108.02	439.04
Distance [6000,maximum]	-6.56	120.82	518.43
Shared border	0.30	-3.51	-7.89
Shared language	0.51	-5.99	-13.25
European Community	0.04	-0.44	-1.02
EFTA	0.54	-6.28	-13.85
Destination country:			
Australia	0.24	-2.81	-6.35
Austria	-1.68	22.46	59.37
Belgium	1.12	-12.65	-26.74
Canada	0.69	-7.99	-17.42
Denmark	-0.51	6.33	15.15
Finland	-1.33	17.49	44.88
France	0.22	-2.61	-5.90
Germany	1.00	-11.39	-24.27
Greece	-2.36	32.93	92.45
Italy	0.07	-0.86	-1.97
Japan	1.59	-17.43	-35.62
Netherlands	1.00	-11.42	-24.33
New Zealand	0.07	-0.80	-1.83
Norway	-1.00	12.85	32.06
Portugal	-1.21	15.69	39.82
Spain	-1.16	14.98	37.85
Sweden	-0.02	0.30	0.69
United Kingdom	0.81	-9.36	-20.23
United States	2.46	-25.70	-49.49

The estimated parameters governing trade impediments are the same as those shown in Table 2. For an estimated parameter $\hat{d}$, the implied percentage effect on cost is $100(e^{-\hat{d}/\theta} - 1)$.

Table 8: The Welfare Gains From Trade

Country	Simulated per cent welfare gains from trade							
	Assuming $\theta = 8.28$				Assuming $\theta = 3.60$			
	fixed wage		fixed labor		fixed wage		fixed labor	
	from auty.	to free	from auty.	to free	from auty.	to free	from auty.	to free
Australia	1.5	22.9	3.1	29.3	3.6	59.5	5.4	73.7
Austria	3.3	23.5	3.3	33.9	7.8	61.3	7.9	84.5
Belgium	10.8	19.8	10.8	23.9	26.5	50.6	26.5	59.0
Canada	6.7	20.0	6.8	19.8	14.8	50.7	14.9	48.8
Denmark	5.6	22.5	5.8	32.9	13.3	58.3	13.5	83.1
Finland	2.5	23.5	2.5	36.6	5.8	61.4	5.8	92.5
France	2.5	19.9	2.5	18.6	5.8	51.0	5.9	47.7
Germany	1.7	18.4	3.2	14.3	4.1	46.8	5.4	38.4
Greece	3.3	26.5	7.6	36.5	8.0	70.3	12.8	97.3
Italy	1.7	20.2	1.8	19.7	3.9	51.8	4.0	49.9
Japan	0.2	17.6	0.3	13.3	0.5	43.9	0.6	34.8
Netherlands	9.0	19.8	9.3	22.9	21.7	50.8	22.0	57.0
New Zealand	2.9	24.2	3.8	47.0	6.9	63.2	8.0	128.5
Norway	4.4	23.6	5.6	34.4	10.2	61.6	11.3	89.3
Portugal	3.5	24.3	3.9	42.0	8.2	63.8	8.7	110.6
Spain	1.4	22.6	1.7	26.1	3.4	58.8	3.8	65.3
Sweden	3.2	21.6	3.2	30.6	7.6	55.7	7.6	75.6
United Kingdom	2.6	19.4	2.7	19.0	6.2	49.5	6.2	48.2
United States	0.8	16.9	0.9	1.1	2.1	42.2	2.1	31.2

Figures are the percentage welfare gain in moving from autarky to baseline ("from auty.") and from baseline to unimpeded trade ("to free").

Table 9: The Benefits of Foreign Technology

Country	Simulated % change in welfare from increased technology			
	Better U.S. technology		Better German technology	
	fixed wage	fixed labor	fixed wage	fixed labor
Australia	27.1	14.9	12.3	4.4
Austria	9.3	2.9	61.8	5.4
Belgium	13.2	3.0	50.7	4.8
Canada	87.4	19.9	9.3	1.3
Denmark	12.2	6.2	62.5	7.1
Finland	11.3	4.3	37.5	3.0
France	10.1	4.2	39.2	3.0
Germany	9.7	-11.6	100.0	100.0
Greece	14.0	18.3	38.9	8.0
Italy	9.7	3.9	38.4	3.0
Japan	6.6	-0.8	5.9	-0.2
Netherlands	12.8	6.8	63.5	8.3
New Zealand	33.8	13.5	15.6	3.9
Norway	13.2	11.7	43.8	6.1
Portugal	14.3	8.6	39.6	4.7
Spain	9.6	7.0	27.3	3.3
Sweden	12.8	1.1	42.7	2.3
United Kingdom	14.6	0.5	38.3	1.6
United States	100.0	100.0	9.7	1.4

We assume a 20 per cent increase in technology in either the United States or Germany. Figures refer to the percentage welfare gain as a percent of the gain in the country experiencing technological expansion. The simulations assume $\theta = 8.28$.

Table 10: The European Community: Welfare, Trade Creation, and Trade Diversion

Country	Simulated effect of removing all tariffs on intra-EC trade					
	% Δ welfare		% Δ imports from the EC		% of new EC imports diverted from others	
	fixed wage	fixed labor	fixed wage	fixed labor	fixed wage	fixed labor
Australia	0.13	0.11	27.7	2.8		
Austria	0.32	-0.07	-1.9	-3.4		
Belgium*	-0.91	0.54	61.3	26.3	4.0	9.0
Canada	0.01	0.01	28.0	2.2		
Denmark*	-0.27	0.18	49.9	30.8	9.0	9.4
Finland	0.28	-0.02	4.6	-2.9		
France*	0.08	0.05	46.3	33.7	8.2	5.0
Germany*	-0.03	-0.03	58.5	41.9	12.3	5.2
Greece*	0.28	0.13	30.8	24.0	31.5	22.9
Italy*	0.14	0.04	44.9	36.4	12.5	6.1
Japan	0.07	-0.01	32.4	2.3		
Netherlands*	-0.58	0.33	56.3	26.9	4.9	8.9
New Zealand	0.14	0.09	24.1	1.9		
Norway	0.34	0.05	3.2	-2.9		
Portugal*	0.03	0.10	44.0	32.8	14.5	10.1
Spain*	0.21	0.05	43.7	34.3	14.8	8.5
Sweden	0.31	-0.10	2.0	-3.3		
United Kingdom*	-0.02	0.02	51.9	36.1	13.8	8.6
United States	0.10	0.03	27.8	2.2		

In the baseline all trade is subject to a 5 per cent tariff. The counterfactual is to remove tariffs between members (as of 1990) of the EC (appearing with a *). The simulations assume $\theta = 8.28$.