TECHNOLOGY AND BILATERAL TRADE

Jonathan Eaton
Samuel Kortum

Working Paper **6253**

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ABSTRACT

We develop a Ricardian model to explore the role of trade in spreading the benefits of

innovation. The theory delivers an equation for bilateral trade that, on its surface, resembles a

gravity specification, but identifies underlying parameters of technology. We estimate the equation

using trade in manufactures among the OECD. The parameter estimates allow us to simulate the

model to investigate the role of trade in spreading the benefits of innovation and to examine the

effects of lower trade barriers. Typically foreigners benefit by only a tenth as much as the innovating

country, but in some cases the benefits to close neighbors approach those of the innovator.

Jonathan Eaton   Samuel Kortum
Department of Economics   Department of Economics
Boston University   Boston University
270 Bay State Road   270 Bay State Road
Boston, MA 02215   Boston, MA 02215
and NBER   and NBER
jeaton@bu.edu   kortum@bu.edu

1   Introduction

Countries share the benefits of each others innovations through at least two chan-
nels. They can adopt each others innovations into their own technologies, or
they can exchange goods embodying the innovations.[1] Trade pushes countries to
concentrate on the activities that they do relatively best. In this way, trade, like
diffusion, leads to sharing of technology. Here we develop a model of bilateral trade
which we use to assess the role of technology in shaping world trade patterns, and
the contribution of trade to pooling the world's technology.

The idea that technology is central to explaining trade goes back, of course,
at least to Ricardo. The Ricardian model has spawned very little empirical work,
however. Its simplicity, while starkly illustrating the gains from trade, has ren-
dered the model incapable of grappling with the complexity of the trade patterns
we observe.[2]

We provide an alternative formulation of the theory which is more amenable to
empirical analysis in a world of many countries and commodities. Moreover, unlike
the standard Ricardian model (or, for that matter, the factor-endowments model),
our framework can readily handle transport costs and trade in intermediates.[3] The
model not only has implications for a country's trade with the rest of the world,

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[1]Our previous work (Eaton and Kortum (1996, 1997a)) focused purely on the first mechanism.
This paper explores the second. To illustrate the distinction, U.S. consumers in the 1970's
benefitted from Japanese innovations in auto making by importing, even though these innovations
did not diffuse to U.S. producers until the 1980's. See Womack, Jones, and Roos (1990).

[2]What empirical work has been done focuses on bilateral comparisons of export shares. Mac-
Dougall (1951, 1952) is the classic reference. Deardorff (1984) and Leamer and Levinsohn (1995)
discuss it and subsequent contributions in this tradition. Grossman and Helpman (1995) survey
the (largely theoretical) literature on technology and trade. Trefler (1993) and Harrigan (1997)
introduce technological differences into a Heckscher-Ohlin framework to explain trade patterns
empirically.

[3]Not only can the analysis accommodate an arbitrarily large number of goods and countries, it
can also be extended to allow for multiple factors. Hence our framework nests both the Ricardian
and factor-endowments models of international trade. Our analysis here limits itself to a single
internationally-immobile factor.

but delivers predictions about specific bilateral trade patterns.

Our point of departure is the Dornbusch, Fischer, and Samuelson (1977) version of the Ricardian model with a continuum of goods. In that model each country is endowed with a distribution of productivities across commodities. By assuming that countries' productivities are drawn from extreme value distributions, the model extends readily to a world of many countries and trade impediments. In Kortum (1997) and Eaton and Kortum (1997a) we have shown how a process of innovation and diffusion can give rise to such distributions. As it turns out, this specification of technological frontiers simplifies enormously the problem of aggregation across countries and commodities. It allows us to derive a system of equations relating bilateral trade to wages, national levels of technology, and trade impediments.

While the trade equation is itself simple and intuitive, in general equilibrium wages depend on technologies and labor supplies in all countries. Except in the special cases of free trade and autarky, the general equilibrium implications of our model cannot be solved analytically but must be simulated.

To get the parameters we need for simulation, we estimate the bilateral trade equation delivered by the model with data on trade in manufactures among industrial countries. We capture technological sophistication with measures of research stocks and human capital. Wage data are readily available, but wages are endogenous. The model points to the total workforce as a natural instrument. Hence we estimate the model using the workforce, along with density, as instruments for wages. Finally, we proxy trade impediments with variables reflecting geographical, linguistic, and political ties.

The results are plausible. Distance plays a role similar to what has been found

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in the gravity literature. Our estimates imply an effect of research on output per worker in keeping with results from the productivity literature. A key parameter is the elasticity of substitution between labor services from different countries, which we estimate at about three and a half. More telling than the estimates themselves, however, is what the they imply for our simulations.

We embed our parameter estimates from the trade equation into the full model to address three issues. The first is the one we opened with, the importance of trade in spreading the benefits of technology. The second is the classic one of assessing the gains from trade. The third is the more current one of identifying winners and losers from regional integration. We address these issues under the alternative bracketing assumptions that labor is (1) in perfectly inelastic supply and (2) in perfectly elastic supply to the manufacturing sector.

The results imply that trade can serve as an important conduit for gains from improved technology. An improvement in a country's technology almost always benefits everyone. But the magnitude of the gains abroad approach those at home only in foreign countries enjoying proximity to the source and the flexibility to downsize their manufacturing labor forces.

Not surprisingly, all countries benefit from freer world trade, with small countries gaining more than big ones. Of greater interest are the implications for manufacturing in different countries. Some, such as Germany, are natural manufacturers whose sectors expand monotonically as barriers topple. Others, such as Spain, shift to nonmanufacturing. For the majority of countries, however, the effect of lower trade barriers on manufacturing depends on the point of departure.

More surprisingly, even freer trade within a region usually benefits everyone, even those outside. Members of the region tend to export more not just to each

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other but to those outside as well. Although integrated regions benefit nonmembers through lower prices, they also grab manufacturing production from them, especially from those nearby. Within regions, manufacturing usually rises in each member. The one exception is Spain in the European Community.

How does our work relate to the existing literature on bilateral trade? Our theory, like others, predicts that trade patterns can adhere to a standard gravity specification relating bilateral trade to the trade partners' GDPs. Helpman (1987) and Bergstrand (1989) derive such a relationship from a model of imperfect competition. Anderson (1979) and Deardorff (1995) derive it by assuming perfect competition among countries specializing in totally distinct sets of goods. In contrast, our equation arises from a Ricardian model in which any country is capable of producing any good. We can therefore address the question, going back at least to Ricardo, of how trade shapes what a country produces. Our model allows trade to generate specialization while delivering a straightforward formulation for bilateral trade patterns.

The fact that our model generates a gravity-like equation is obviously an empirical plus. These models can explain trade patterns both in the cross-section (see Deardorff (1984) for a review and for recent examples, Wei (1996), Jensen (1996), Rauch (1996), and Haveman and Hummels (1997)) and in the time-series (see Helpman (1987), Hummels and Levinsohn (1995), and Evenett and Keller (1996)). In our model, however, since GDP is endogenous the gravity specification does not identify the key structural parameters. Instead, we must dig beneath the surface of the equation to isolate the roles of technology and factor costs in determining export competitiveness.

Since our model has similar implications to others for fitting the data, we don't

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try to prove its worth by running it in an empirical horse race. Its purpose is to explain the data with a rich, yet parsimonious, underlying theory. The payoff is in answering questions about the effects of technological advances and reductions in trade barriers on resource allocation and welfare.[4]

Section 2, which follows, sets up the model. Section 3 describes our estimation procedures and results. Section 4 presents simulations that address the questions we are posing.

2 A Model of Technology and Trade

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 discuss below how the theory could be expanded to incorporate additional factors). 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 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 internal to international transac-

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[4] As Leamer and Levinsohn (1995, pg. 1341) exhort "Estimate, don't test" but "Work hard to make a clear and close link between the theory and the data."

tions, 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. We normalize $d_{ii} = 1$ for all i.[5] 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.[6]

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 potential suppliers $i = 1, ..., N$ to find the lowest price. Treating z as arising from a probability distribution, the likelihood 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 $i = 1, ..., N$. 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

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

[6]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.

for each good j the marginal distribution for country i's productivity is Fréchet:

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

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.[7]

Under these assumptions, country i presents country n with a distribution of prices $G_{ni}(p) = 1 - e^{-d_{ni}^{-\theta}\phi_i p^{\theta}}$. Here $\phi_i = T_i c_i^{-\theta}$ measures country i's technological sophistication tempered by its production costs. Shopping around the world for the lowest price, country n faces a price distribution:

$$G_n(p) = 1 - e^{-\tilde{\phi}_n p^{\theta}}.$$

Here

$$\tilde{\phi}_n = \sum_{i=1}^{N} \phi_i d_{ni}^{-\theta} = \sum_{i=1}^{N} T_i (c_i d_{ni})^{-\theta} \tag{2}$$

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. If transport costs are zero then this stock, and the consequent price distribution, is

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[7]For our analysis here, 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. All that we do in this paper stands, with T_i reinterpreted as $T_i^{1/\rho}$ and θ as θ/ρ. See, e.g., Small (1987).

the same for all countries, while, if international transport costs are prohibitive, $\tilde{\phi}_n$ reduces to ϕ_n.

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

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

its share in country n's trade-augmented technology.[8] 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.[9]

Having seen the convenience of assuming that productivities adhere to an extreme value distribution, a natural question is whether such a distribution could arise from the processes of technological innovation and diffusion? 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.[10] Kortum (1997) and Eaton and Kortum (1997a) develop specific models of invention that deliver a Fréchet technological frontier. These models provide a relationship between a country's technology T and the knowledge it has accumulated through its own

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[8] A country will export most widely the commodities it produces most efficiently. This implication of our model 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: Only good firms survive in export markets. We explore the implications of the model for productivity in Eaton and Kortum (1997b).

[9] 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.

[10] 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.

research and through the adoption of ideas from abroad.

2.2 International Trade

To complete the model we specify demand. Commodities find use both in final consumption and as intermediates. We make the simplest possible assumption, that preferences and technology are Cobb-Douglas, with each commodity having equal share. In this case country n's aggregate spending on each good equals its total spending X_n.

Spending by country n on goods from country i, X_{ni}, is just the measure of goods imported from there times total spending, or:

$$X_{ni} = \pi_{ni} X_n = \left(\frac{\phi_i d_{ni}^{-\theta}}{\tilde{\phi}_n} \right) X_n = \frac{T_i (c_i d_{ni})^{-\theta}}{\sum_{k=1}^{N} T_k (c_k d_{nk})^{-\theta}} X_n. \tag{3}$$

Equation (3) links technology and export share: Given wages 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. Even though demand is Cobb-Douglas, bilateral expenditures depend on relative costs: As country i's cost of serving market n rises, the range of goods it can sell there shrinks.[11]

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[11]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 following the estimation strategy suggested in Berry (1994).

2.3 Production Costs

We assume that production combines labor and material inputs with labor having a constant share β.[12] Our Cobb-Douglas assumptions imply that the appropriate aggregate index of prices in country i is simply the geometric mean of the distribution $G_i(p)$ of prices there:

$$P_i = \tilde{\phi}_i^{-1/\theta}. \tag{4}$$

Since this price index also applies to material inputs, $c_i = w_i^\beta P_i^{1-\beta} = w_i^\beta \tilde{\phi}_i^{-(1-\beta)/\theta}$ where w_i is the wage in country i. (Constants common to all countries have been dropped.) Substituting this expression into the definition (2) of $\tilde{\phi}$ gives the system of equations:

$$\tilde{\phi}_n = \sum_{i=1}^{N} d_{ni}^{-\theta} T_i w_i^{-\theta\beta} \tilde{\phi}_i^{1-\beta}. \tag{5}$$

In general there is no analytic solution. In our simulations below we calculate the $\tilde{\phi}_n$'s numerically. Under free trade ($d_{ni} = 1$ for all i, n) everyone has a common $\tilde{\phi} = \left(\sum_{i=1}^{N} T_i w_i^{-\theta\beta} \right)^{1/\beta}$. One result that we can eke out for the general case is that a proportional increase in T around the world by a factor of λ, given wages, raises all $\tilde{\phi}$'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).

Equations (3) and (5) form the basis of our empirical analysis. We estimate the model with data on the manufacturing sector, which accounts for most trade

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[12]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.

among OECD countries. We recognize that this sector employs only a minority of any country's labor force, so we allow wages to depend on forces outside this sector. Nevertheless, to understand the logic of the model it is useful to analyze its general equilibrium when it describes the entire economy.

2.4 Labor-Market Equilibrium

The model implies that labor demand L_i in country i is:

$$L_i = \sum_{n=1}^{N} \beta X_{ni}/w_i \quad i = 1, ..., N.$$ (6)

Suppose each country i supplies L_i workers inelastically, the labor market clears, and trade balances. National income is then $Y_i = w_i L_i = \beta X_i$ (since total spending is also total production). The conditions for labor-market equilibrium are then:

$$L_i = T_i w_i^{-(1+\theta\beta)} \tilde{\phi}_i^{1-\beta} \sum_{n=1}^{N} d_{ni}^{-\theta} \frac{w_n L_n}{\tilde{\phi}_n}$$ (7)

By Walras' Law, one equation is redundant. Hence this set of equations, along with (5), determine $N-1$ relative wages as functions of the labor forces, technologies, and trade impediments.

While (7) constitutes a highly-nonlinear set of equations, wages are homogeneous of degree 0 in all countries' labor forces. Furthermore, appealing to our result on the homogeneity of degree $1/\beta$ of the ϕ's in the T's, wages are homogeneous of degree 0 in all countries' technology levels.

2.4.1 Free Trade and Autarky

Under free trade, equations (7) simplify. A country's relative wage is proportional to $(T_i/L_i)^{1/(1+\theta\beta)}$: 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.

Now consider the *real* wage in country i:

$$w_i/P_i = T_i^{1/(1+\theta\beta)} \left[\sum_{k=1}^{N} T_k^{1/(1+\theta\beta)} \left(\frac{L_k}{L_i}\right)^{\theta\beta/(1+\theta\beta)} \right]^{1/(\theta\beta)}. \tag{8}$$

It 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 country possessing it relative to the size of the recipient. As the size of the labor force in the source country falls, its relative wage rises, diminishing the benefits of its technology to others.

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:

$$w_i/P_i = T_i^{1/(\theta\beta)}. \tag{9}$$

Note, of course, that there are gains from trade for everyone, as can be verified by observing that we derived (9) by removing positive terms from (8). Note also that trade has an equalizing effect in that the elasticity of the relative real wage with respect to relative technology levels 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.

2.4.2 A Gravity Equation

If we plug our results for free trade into our bilateral trade equation (3) we obtain the simple expression:

$$X_{ni} = \frac{\tilde{\phi}^{-\beta}}{\beta} Y_n Y_i.$$

Bilateral trade equals the product of the trade partners' incomes, up to a constant of proportionality common to all pairs. Exactly the same relationship has been derived from models of monopolistic competition, as in Helpman (1987) and Hummels and Levinsohn (1995). Since here it emerges in a very different context, its empirical success should not be interpreted as confirmation of the monopolistic competition trade paradigm.

3 Estimation

Having explored the special cases of free trade and autarky, we now turn to estimating the model's parameters for the general case. Equations (3) and (5) form the basis of our estimation using trade in manufactures among 19 OECD countries.

3.1 Specification

Before we can estimate these equations, however, they require additional manipulation. Furthermore there are econometric issues to confront.

3.1.1 The Price of Materials

We begin by using the model to solve for the price of materials. Rearranging the trade equation (3) as applied to home sales, $i = n$, we obtain $\tilde{\phi}_n = \phi_n X_n / X_{nn}$, while our analysis of production costs gives $\phi_n = T_n c_n^{-\theta} = T_n w_n^{-\theta\beta} \tilde{\phi}_n^{1-\beta}$. Solving for ϕ_n and $\tilde{\phi}_n$, plugging the results back into the trade equation, rearranging, and

taking logarithms:

$$\ln \frac{X'_{ni}}{X'_{nn}} = -\theta \ln d_{ni} + \beta^{-1} \ln \frac{T_i}{T_n} - \theta \ln \frac{w_i}{w_n}, \qquad (10)$$

where $\ln X'_{ni} = \ln X_{ni} - [(1 - \beta)/\beta] \ln(X_i/X_{ii})$ for all i and $\beta = .21$, the average labor share in gross manufacturing production in our sample. We refer to the left-hand-side variable as normalized bilateral imports since it is simply bilateral imports adjusted by home purchases X_{nn} and the openness of the importer X_n/X_{nn} relative to the exporter X_i/X_{ii}. Although our sample includes only 19 countries, materials prices reflect imports from all sources. Hence 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 any subset of countries.

Equation (10) relates normalized bilateral imports to transport costs, relative technology levels, and relative wages. While wage data are readily available, we require empirical counterparts to the T_i's and the d_{ni}'s.

3.1.2 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

$$T_i = \alpha_0 R_i^{\alpha_R} e^{-\alpha_H/H_i} e^{\tau_i}, \qquad (11)$$

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

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the fraction of world knowledge that a country exploits rises with H, approaching a maximum of one. We assume that the unobservables τ_i are i.i.d. with zero mean and variance σ_τ^2.

3.1.3 Trade Impediments

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

$$\ln d_{ni} = d_k + b + l + e_h + \delta_{ni}, \tag{12}$$

where the dummy variable associated with each effect has been suppressed for notational simplicity. In particular, 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, and e_h ($h = 1, 2$) is the effect of n and i both belonging to trading area h. 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].[13] The two trading areas are the European Community (EC) and the European Free-Trade Area (EFTA). Since we omit a constant, the parameter d_2, for example, reflects the transport 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.

To capture potentially important correlations, we assume that the unobserv-

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[13] An advantage of our formulation of distance effects is that it imposes little structure on how transport costs vary with distance. We explored the implications of the more standard specification of transport costs as a linear-quadratic function of distance. There were no differences worth reporting.

able impediments to trade δ_{ni} consist of several i.i.d. mean-zero components:

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

Since some countries may be closed to imports in general, regardless of source, we introduce a destination-country specific component δ_n^d, with variance σ_d^2. Since openness to a particular country may be reciprocal, we introduce a country-pair specific component δ_{ni}^2 (where $\delta_{ni}^2 = \delta_{in}^2$) affecting two-way trade, with variance σ_2^2. Finally δ_{ni}^1 is an idiosyncratic component affecting one-way trade, with variance σ_1^2.[14]

3.1.4 The Estimating Equation

We can now gather together results to obtain our econometric trade equation:

$$\ln \frac{X'_{ni}}{X'_{nn}} = -\theta d_k - \theta b - \theta l - \theta e_h + \frac{\alpha_R}{\beta} \ln \frac{R_i}{R_n} - \frac{\alpha_H}{\beta} \left(\frac{1}{H_i} - \frac{1}{H_n} \right) - \theta \ln \frac{w_i}{w_n} + \varepsilon_{ni}. \quad (13)$$

The error term is $\varepsilon_{ni} = -\theta \delta_{ni} + \beta^{-1} \tau_i - \beta^{-1} \tau_n$. Since equation (13) is a vacuous identity for $n = i$, we drop all of the home-country observations. Considering only $n \neq i$, we assume that the error ε_{ni} has zero mean conditional on all of the terms in equation (13) other than the wage term.

3.1.5 Wage Endogeneity

Our theory of 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). We therefore expect wages to be positively correlated with τ and hence relative wages to be positively correlated with ε_{ni}. Ordinary Least Squares (OLS) estimates of θ in equation (13) will be biased downward unless there is no error in

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[14]Some countries may also be particularly export oriented, suggesting a source-country-specific component. When we included such a component our estimate of its variance was small, so we omit it.

our specification of technology, which is very unlikely. The intuition is simple. A high-wage country is less competitive given its technology, but, if we can condition only imperfectly on technology, a high wage will at least partly reflect an advanced technology.

But, our theory also points to a good instrument, the work force. Equation (7) implies that the wage falls as the work force rises: As the number of workers rises the prices of what they make fall, since more is produced. Moreover, workers spread into sectors where productivity is lower. We use population density as another instrument for the wage, since the opportunity cost of labor outside manufacturing might depend on the availability of land. Using these instruments we estimate equation (13) with Two-Stage Least Squares (2SLS).

3.1.6 Variance Components

The error in equation (13) has an intricate covariance structure. The error in technology enters ε_{ni} as $\tau_i - \tau_n$, inducing correlation. Furthermore, the transport-cost error itself has several components to its variance. Incorporating these effects, the variance of the error is:

$$\sigma^2 = E[\varepsilon_{ni}\varepsilon_{ni}] = (2/\beta^2)\sigma_\tau^2 + \theta^2\sigma_d^2 + \theta^2\sigma_2^2 + \theta^2\sigma_1^2. \tag{14}$$

The nonzero covariances are:

$$E[\varepsilon_{ni}\varepsilon_{ni'}] = (1/\beta^2)\sigma_\tau^2 + \theta^2\sigma_d^2, \;\; i' \neq i, \qquad E[\varepsilon_{ni}\varepsilon_{n'i}] = (1/\beta^2)\sigma_\tau^2, \;\; n' \neq n,$$

$$E[\varepsilon_{ni}\varepsilon_{i'n}] = -(1/\beta^2)\sigma_\tau^2, \;\; i' \neq i \qquad E[\varepsilon_{ni}\varepsilon_{in}] = -(2/\beta^2)\sigma_\tau^2 + \theta^2\sigma_2^2.$$

The first covariance, for example, is that between observations with a common destination but different sources.

To incorporate this variance-covariance structure, we estimate the model with Generalized Least Squares (GLS). To impose this structure while instrumenting for wages, we apply Amemiya's (1985) Generalized Two-Stage Least Squares (G2SLS) estimator.[15]

3.2 Data

We think that the model describes best the trade in manufactures among industrial countries. Consequently we fit equation (13) to the manufacturing sector of 19 OECD countries. For each year there are 342 observations ($19^2 - 19$) of bilateral trade flows. Although we have estimated the model annually and on various averages within the period 1971-1990, we focus here on 1990. We report where our data come from in the appendix.

Table 1 summarizes some features of the trade data. We normalize trade by home purchases, constructed by subtracting manufactured exports from gross manufacturing output. Note that imports and exports are typically a fraction of what a country produces for itself. The exceptions are Belgium, the Netherlands, and, to a lesser extent Denmark. Most trade is with other countries in our sample, with the exception of Japanese imports. The last two columns of the table show each country's favorite source and destination. Note that a few large countries dominate, yet the biggest partner is typically nearby.

Table 2 presents the explanatory variables. To obtain relative wages, we translate the local-currency average manufacturing wage to U.S. dollars at the official exchange rate.[16] While data on trade and wages are directly available from of-

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[15]To impose the error structure we estimate the four variance parameters by the method of moments from the residuals of a first-step regression. For GLS the first-step regression is OLS while for G2SLS it is 2SLS. In estimating the variances, we do not make use of $E[\varepsilon_{ni}\varepsilon_{n'i}] = (1/\beta^2)\sigma_\tau^2$, hence the four variances are just identified.

[16]We use the official rather than the purchasing power exchange rate since it determines differ-

ficial sources, the determinants of technology must be constructed. Procedures vary, so we have used alternatives available in the literature and have created two ourselves. Coe and Helpman (1995) obtain their research stocks from cumulative business-sector R&D expenditures. We construct one alternative by removing government-funded R&D expenditure and another by using research employment rather than expenditure.[17] 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 research stock per-worker. We report the Coe-Helpman measure and the measure based on employment of R&D Scientists and Engineers in the table. Kyriacou (1991) and Barro and Lee (1993) provide different measures of average years of schooling.

3.3 Results

Table 3 reports results from estimating equation (13) by OLS, GLS, and G2SLS. Data are for 1990 and include Coe and Helpman's research stocks and Kyriacou's human capital measure. We explain somewhat over half of the variation in normalized bilateral imports. The coefficients almost all have the expected sign, and are usually plausible in magnitude with low standard errors.

Turning first to trade impediments, the estimates show a substantial impact of distance, somewhat attenuated by a shared language, while borders, the EC, and EFTA do not play a major role. The underlying parameter estimates are little affected by the method of estimation.

Both the R&D stock and years of education have a substantial impact on exports. Accounting for the variance-covariance structure of the error has only a

ences in costs of production. In our model, differences in purchasing power arise endogenously.

[17]In all cases the depreciation rate is five percent.

moderate influence on the point estimates but substantially raises their estimated standard errors.

The parameter of most interest is θ, the coefficient of the relative wage. It represents the elasticity of substitution among different countries' labor forces. All the estimates indicate fairly elastic demand. As expected, accounting for the endogeneity of wages raises our elasticity estimate.

To examine the relevance of our instruments we present Table 4, which reports the results of an OLS regression of the wage on the primary exogenous variables.[18] Note that they 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.

Our theory 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 given their wages). Hence we do not scale our trade equation by a measure of the source country's size. Scale does, of course, enter indirectly through the wage: Given its technology, a country must have a lower wage to employ more of its labor force in manufacturing. Our first stage regression implies that a one per cent increase in the labor force, given density and technology, lowers the wage by .35 per cent which, using our estimate of $\theta = 3.52$ from G2SLS, implies an increase in exports of 1.23 per cent. Note also that a one per cent increase in the R&D stock is predicted to increase the wage by .28 per cent, causing exports to fall by .99 per cent. Together with the direct effect of

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[18]Since our two-stage procedure included all 392 combinations of relative wages, the regression in Table 4 does not correspond exactly to the first stage of the 2SLS regression. We present it in order to illustrate how wages respond to the theoretically important instruments.

R&D on exports, the total effect is positive but small.

3.3.1 Some Implications

Manipulating the estimates lets us infer more meaning from them. We use those from G2SLS since they should be least biased.

Trade Impediments Dividing the various impediment parameters by θ and exponentiating gives us the associated percentage cost increases. At the low end, a hypothetical country pair less than 375 miles apart and sharing a border, a language, and membership in EFTA have to overcome a 64 per cent transport cost. At the opposite extreme, two countries more than 6000 miles apart with nothing in common must pay a premium of over 500 per cent.[19]

The Effect of Research 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 (11) into (9) implies an elasticity of productivity with respect to the R&D stock of $\alpha_R/(\theta\beta)$, which, based on our estimates, is .30. Griliches (1992), in surveying studies of the impact of R&D, reports that the upper range of existing estimates imply exactly this elasticity.

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[19]Wei (1996) obtains very similar results from a more standard gravity formulation derived from an assumption that each country produces a unique set of commodities. He does not separately estimate the elasticity of substitution between goods from different countries, but uses an elasticity of 10 as his base. Our estimate of θ implies an elasticity of substitution between the labor services of different countries of around 3.5. A higher value would of course imply lower impediments.

Sources of Error We can estimate the relative importance of the various components of the error in our equation by substituting the variance estimates from Table 3 into equation (14). Errors in our specification of technology account for 75 per cent of the total variance, which is not surprising since we represent technology levels by very imperfect proxies. The errors associated with each destination country account for another 15 per cent. The remaining 10 per cent of the variance is divided roughly equally between two-way and one-way bilateral trade errors.

3.3.2 Robustness

Our estimation has provided plausible parameter estimates with reasonable implications. We now investigate whether they stand up to various forms of scrutiny.

Alternative Technology Proxies As we mentioned above, we constructed alternative measures of the research stock. Removing government funded R&D from the Coe-Helpman measure of cumulative R&D expenditures made virtually no difference. Moving to a people-based measure improved the fit somewhat but yielded essentially the same estimates except for a slightly lower wage elasticity of 3.2.

Substituting the Barro-Lee measure of schooling for Kyriacou's resulted in a substantial deterioration in the fit. The effect of human capital using that measure was much smaller, while the point estimate of α_R/β rose to 1.27 and of θ rose to 4.6.[20]

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[20]We also experimented with alternative functional forms for human capital, replacing $e^{-\alpha_H/H}$ in equation (11) with either H^{α_H} (as we introduce the R&D stock) or with $e^{\alpha_H H}$ (as in Klenow and Rodriguez-Clare (1997)). There was virtually no effect on the fit or on the other parameter estimates.

Alternative Sample Periods Our data are annual observations from 1971 to 1990. We estimated equation (13) for each year and for averages over longer periods. There is little to report except that the estimated trade impediments have drifted downward throughout the period while the wage elasticity rose substantially in the early 1970s.

Nontradables Our theory has assumed that all commodities face the same transport costs in moving from any one country to another. One tractable generalization is to assume that some fraction λ of goods are not traded internationally at all. With this modification, a set of substitutions like those we performed to derive equation (10) yields the same equation but with the dependent variable:

$$\ln\left(\frac{X_{ni}}{X_{nn}}\right) - \frac{(1-\lambda)(1-\beta)}{\beta}\ln\left(\frac{X_{nn}/X_n - \lambda}{X_{ii}/X_i - \lambda}\right) - \ln\left(1 - \lambda\frac{X_n}{X_{nn}}\right).$$

To see what introducing nontraded goods would do to our results we reestimated equation (13) with this generalization of the dependent variable, setting λ at .1 and .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 4.8. Since this formulation is not that different in its implications, we stick with our simpler baseline.

Fixed Destination Effects We also estimated equation (13) with destination-specific fixed effects replacing the destination component of the error. The coefficient estimates and their standard errors change little. In particular, with G2SLS the estimate of θ rises slightly to 3.63 and its standard error falls to .99. The

destination fixed effects are very close to those we get by including a full set of source and destination effects, reported in Table (5). We now turn to the results from this alternative fixed-effects specification of the trade equation.

3.4 A Fixed Effects Alternative

Without imposing the restrictions implied by our specification of technologies, our theory implies that bilateral trade can be explained by a set of source-country effects along with trade impediments. Defining $S_i = \ln\left(T_i^{1/\beta} w_i^{-\theta}\right)$ as a measure of "competitiveness," we can rewrite equation (10) as

$$\ln \frac{X'_{ni}}{X'_{nn}} = -\theta \ln d_{ni} + S_i - S_n. \tag{15}$$

Rewriting the equation this way suggests that we can estimate the S_i as the coefficients on source and destination-country dummies, imposing the restriction that for each country the two sum to zero. We tie down the coefficients' overall level by restricting them to sum to zero across all countries. The competitiveness terms agglomerate the impact of a country's technology and its wage costs on export performance, without providing any hint about the contribution of each.

A cost of this less restrictive approach is that it does not identify the elasticity of substitution. Although θ appears in equation (15) it simply scales the effects of trade impediments.

In pursuing this alternative, we include a set of destination effects m_n. Equation (12) thus becomes:

$$\ln d_{ni} = d_k + b + l + e_h + m_n + \delta_{ni}, \tag{16}$$

where

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

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Table 5 reports the GLS estimates of this alternative bilateral trade equation. Our fixed-effects equation conditions on the two unobservables (unobservable determinants of technology and destination-country-specific unobservable determinants of trade impediments) that had accounted for about 90 percent of the variance in our earlier equation. Hence not surprisingly it fits is much better. 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 in terms of their ability to penetrate foreign markets. Note that trade impediments appear roughly as above. We can now, however, associate the openness of each country with m_n. The United States, Japan, and Belgium are the most open while Greece is least open.

We can strip the S_i of their wage component by using θ estimated above and wage data. We use the resulting estimates of technology levels to simulate the model, as described below. These estimates differ from those implied by our previous equation since they include the unobservable component, τ. In Figure 1 we compare the two measures, each normalized to the U.S. level. The vertical axis measures countries' technological prowess as revealed by their export performance, taking into account their wage. The horizontal axis shows the technological prowess implied by our measures of research stocks and human capital. For example, the United Kingdom appears as an export underachiever while Japan overachieved relative to its research stock and human capital.

4 Simulation

Since we have identified the structural parameters of our model, we can use it to ask some questions about technology and trade. To what extent does trade bring

the benefits of one country's technology to others? What are the gains from trade and how are they distributed? What are the effects of regional reductions in trade impediments?

Since our estimation has focussed only on manufacturing, answering these questions requires that we say more about the general equilibrium of our economies. We do not try to specify a realistic model of nonmanufacturing sectors. Instead we examine two simple cases which should bracket what any reasonable model would deliver. The first treats manufacturing workers as a specific factor in fixed supply. For this case we treat income produced by other sectors as given. The second treats manufacturing labor as perfectly elastically supplied at a fixed wage. For this case we treat total income as given. In neither case do we 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 OECD countries.

Incorporating these additional sources of income into our condition for labor market equilibrium we obtain:

$$w_i L_i = \beta \phi_i \sum_{n=1}^{N} \frac{d_{ni}^{-\theta}}{\tilde{\phi}_n} \left[\frac{1-\beta}{\beta} w_n L_n + \alpha Y_n \right] \tag{17}$$

where Y_n is total final demand in country n. The first term inside the square brackets captures demand for intermediate manufactures within the manufacturing sector while the second represents all other sources of demand for manufactures. The parameter α is final demand for manufactures (plus induced intermediate demand from nonmanufacturing sectors) as a fraction of final expenditure. When labor is fixed we set $Y_n = w_n L_n + Y_n^O$ and treat Y_n^O as exogenous. When the wage

is fixed we treat Y_n itself as exogenous. In either case real income is determined endogenously through the price of manufactures.

Stacking (17) across our countries we get:

$$Y^M = \Gamma[(1 - \beta)Y^M + \beta\alpha Y]$$

where Y is a vector of GDP's and Y^M is a vector of manufacturing labor incomes with typical element $w_i L_i$. The matrix Γ has typical element $\gamma_{in} = d_{ni}^{-\theta} T_i w_i^{-\theta\beta} \tilde{\phi}_i^{1-\beta} / \tilde{\phi}_n$. Solving for Y^M (given Γ), we get:

$$Y^M = [I - (1 - \beta)\Gamma]^{-1} \alpha\beta\Gamma Y. \qquad (18)$$

For the case of exogenous wages, the elements of Γ are given, and the solution delivers equilibrium manufacturing labor forces $L_i = Y_i^M / w_i$. For the case of exogenous labor supplies, however, the elements of Γ vary with wages. We then must solve (18) simultaneously with $\tilde{\phi}$ as implied by equation (5), which we can rewrite in matrix form as:

$$\tilde{\phi} = \Lambda \tilde{\phi}^{(1-\beta)} \qquad (19)$$

where $\tilde{\phi}$ is a vector with representative element $\tilde{\phi}_i$, $\tilde{\phi}^{(1-\beta)}$ is a vector with representative element $\tilde{\phi}_i^{1-\beta}$, and Λ is a matrix with representative element $\lambda_{ni} = d_{ni}^{-\theta} T_i w_i^{-\theta\beta}$. The solution is a set of equilibrium wages.

To calibrate the system of equations (18) and (19) we take $\theta = 3.52$ as estimated by G2SLS. We obtain estimates of technology levels T_i's by removing the effect of wages from the fixed-effects estimates of competitiveness (as shown in the vertical dimension of Figure 1). We also use the estimates of the fixed-effects equation to obtain the trade-impediment parameters.

We use GDP as a proxy for Y, translating 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 where P_n depends on $\tilde{\phi}_n$ as in equation (4).

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 $\beta = .21$). Here IMP_n is manufacturing imports and EXP_n is manufacturing exports. When we treat the labor force as exogenous we set it equal to the actual manufacturing labor force in each country.

Since we force all countries to have the same β and α, equation (18) does not fit exactly to the actual data on labor compensation in manufacturing. The root mean square error is 8.9 per cent. We overpredict labor compensation in Canada by one third but otherwise predictions are quite close. In our experiments we compare the counterfactual outcome with our baseline predictions rather than with actual data.

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 $Y_n P_n^{-\alpha}$. A second is the implication for the real wage of manufacturing workers $w_n P_n^{-\alpha}$, which we can decompose into price and (for the fixed-labor case) wage effects. For the fixed-wage case we can ask about implications for manufacturing employment. In all cases we can also examine how trade patterns change.

4.1 The Spread of Technology

To determine how much trade spreads the benefits of improved technology, we increase a country's technology level T_i and examine how it and other countries are affected. We first raise the U.S. level of technology by 20 per cent, and then

do the same for Germany. As shown in Table 6, in the country whose technology improves, manufacturing employment rises with fixed wages while, with fixed employment, the manufacturing real wage rises. Everywhere else the corresponding magnitudes fall.

The effects on trade patterns (not reported) are similar. Under either labor market assumption, the improvement in a country's technology raises its exports at the expense of everyone else's. Imports generally decline except where the country with the improved technology is a major supplier. Australia, Canada, and Japan, for example, import more when U.S. technology improves.

Even though an improvement in technology has the opposite effect on labor and on exports abroad than it has at home, almost everyone benefits from the resulting lower prices, as shown in Table 7. The exception is the effect on German welfare of improved U.S. technology with fixed labor. Since Germany has the largest share of its labor force in manufacturing, the gains to the rest of the German economy from lower manufacturing prices do not offset the lower real wage in manufacturing.

While almost all countries gain from an improvement in a country's technology, the benefits are heavily concentrated near where the improvement occurs. With fixed wages Canada gains almost as much as the United States from an improvement in U.S. technology. Gains in more remote countries are about 10 per cent of the recipient's. Foreign gains are usually greater if labor is able to exit the manufacturing sector. While the magnitude of the welfare gains even at home are modest, it should be remembered that they are gains from an improvement only in the technology to produce manufactures, which are only a small share of the economy. Technology elsewhere is held fixed.

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 advances. Second, the country needs to be able to reallocate its labor to activities outside of manufacturing.

4.2 The Gains from Trade

We evaluate the gains from trade with two experiments. First, we look at the world in autarky. Next, we consider what would happen if trade impediments between all countries fell 20 percent from current levels.[21]

As shown in Table 8, with wages fixed, autarky pushes most countries to do more manufacturing since they lose access to imports. The exceptions are Canada, Germany, Japan, Sweden, and the United Kingdom whose manufacturing sectors shrink due to loss of export markets. In most of the countries where autarky increases demand for local manufactures, manufacturing real wages rise if the labor force cannot expand.

Turning to the case of lower transport costs, with wages fixed, manufacturing employment also tends to rise. The exceptions here are Australia, Italy, Japan, Spain, and the United States. With labor fixed the real wage rises everywhere except in Australia, Japan, and the United States.

Note that the effect of lowering transport costs (from the upper bound of autarky to a 20 per cent reduction) is not necessarily monotonic: all four possible patterns occur. The most common pattern is that manufacturing expands with either move from the status quo. Autarky reduces competition from imports but freer trade lowers materials costs and opens up export markets. For other

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[21]For simplicity, in conducting these experiments we ignore any revenues that trade impediments might generate.

countries though, lower trade impediments appear to have a monotonic effect. The manufacturing sectors of Canada, Germany, Sweden, and the United Kingdom thrive under freer trade, while the opposite is true in Australia, Italy, Spain, and the United States. Japan is an anomaly in that its manufacturing sector is best served by the status quo.

Table 9 reports the expected result that a worldwide move to autarky lowers welfare everywhere under either labor market scenario, with a slightly greater decline when labor is fixed. The effect on the United States is a modest 2 per cent loss. Belgium suffers the most with a 21 per cent loss.

Moving in the other direction, lowering trade impediments raises welfare everywhere. Under either labor market assumption the gain ranges from about .5 per cent for Japan to over 3 per cent in smaller and more remote countries such as Greece, New Zealand, Norway, and Portugal. Not reported are the dramatic rises in trade volumes, averaging roughly 50 per cent under either assumption.

4.3 Regional Integration

What if the reduction in trade impediments is more regional? We examine the effect of lowering transport costs by 20 per cent among the 1990 membership in the European Community (EC) and between Canada and the United States. Table 10 reports the results for labor markets. A regularity is that manufacturing expands (through either higher employment or higher wages) within the region and falls elsewhere. The only exception is Spain where further EC integration lowers manufacturing employment.

The effect of regional integration on welfare is almost always positive and, for participants, sometimes large, as shown in Table 11. Greater integration with the

United States, for example, causes Canada's welfare to go up between 1 and 2 per cent. With fixed manufacturing labor supplies, North American integration generates negligible welfare losses for Germany and Japan, the only exceptions to the otherwise positive worldwide effects of regional integration.

Table 12 reports what happens to U.S. exports to and imports from the other 18 countries when U.S. trade barriers with Canada fall. Exports to Canada rise by 19 to 25 per cent, but exports also rise, by about 4 per cent, to everywhere else. In contrast, U.S. imports from everywhere except Canada fall. The effect of EC integration on trade patterns (not reported) is similar.

A general tendency is for regional integration to raise participants' exports to third markets. The reason is that integration lowers input prices for participants, increasing their competitiveness even among nonmembers. The availability of lower cost manufactures thus spreads the benefits of regional integration to those outside.

5 Conclusion

We have developed a Ricardian model of how technological know-how and transport costs determine patterns of trade. The theory leads quite naturally to an empirical equation for bilateral trade. We have estimated this equation using OECD trade in manufacturing. The results are promising in that the equation captures actual patterns of trade, and underlying determinants of trade have plausible magnitudes.

Using our parameter estimates, we put the model to work to answer a number of questions. The one that motived us in the first place is measuring the extent to which trade spreads the benefits of technological advances to other countries. The

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answer, based on simulating an increase in one country's technology, is that others typically benefit by about a tenth as much as the source. Benefits to countries nearby can approach those of the source, however, when they have the flexibility to downsize their manufacturing labor forces.

While our methodology was designed with the spread of technology in mind, it can be applied to a much wider range of questions such as identifying the winners and losers from regional and global integration. The model highlights the role of intermediates as well as technology and wage costs in determining export competitiveness.

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 straight-forward (although empirically challenging) and would bridge the gap between the Ricardian and Heckscher-Ohlin 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 in carving out comparative advantage.

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5.1 Data Appendix

Although most of our analysis is based on 1990 data for 19 OECD countries, we describe here how we construct a panel from 1971-1990 (the list of countries is given in Table 1). Data for the manufacturing sector are from the STAN database, OECD (1995). We use imports (c.i.f.), exports, labor compensation, and gross production (all measured in the local currency) as well as employment and the exchange rate.

Our dependent variable is a transformation of bilateral manufacturing imports. Imports from home are defined as gross manufacturing production less manufacturing exports. Imports from each of the other 18 countries, as a fraction of total manufactured imports, are calculated from the United Nations–Statistics Canada bilateral merchandise trade data by 4-digit SITC, as described in Feenstra, Lipsey, and Bowen (1997). We extract bilateral trade in manufactures by applying the concordance of Maskus (1991). (Using Feenstra et al.'s concordance made virtually no difference.) For most countries, trade in manufactures represents 75-90 per cent of total merchandise trade. The exceptions are Australian exports and Japanese imports.

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. We get data on them by translating compensation per worker in manufacturing (which includes employers' compulsory pension and medical payments) into U.S. dollars at the current exchange rates.

Distances between countries are used as a determinant of transport costs. 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).)

Stocks of research for each country are used as one determinant of technological know-how. Our baseline research stocks are taken 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.

Human capital is 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.

We use two variables to instrument for manufacturing wages. The first is aggregate workforces, taken from Summers and Heston (1991, version 5.6). The second is density, defined as the aggregate workforce divided by a country's land area.

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.

Table 1: Trade Data

Country	Imports/home sales total	Imports/home sales sample*	Exports/home sales total	Exports/home sales sample*	Gross man. pr./GDP	Major source country	Major destin. country
Australia	.31	.24	.14	.10	.44	U.S.	Japan
Austria	.68	.57	.61	.45	.68	Germany	Germany
Belgium	2.97	2.57	3.31	2.73	.74	Germany	Germany
Canada	.59	.53	.56	.54	.48	U.S.	U.S.
Denmark	1.03	.88	1.11	.90	.45	Germany	Germany
Finland	.46	.37	.52	.39	.57	Germany	Sweden
France	.42	.35	.39	.30	.57	Germany	Germany
Germany	.33	.26	.44	.33	.83	France	France
Greece	.75	.61	.28	.22	.37	Germany	Germany
Italy	.27	.21	.30	.22	.65	Germany	Germany
Japan	.07	.03	.13	.07	.83	U.S.	U.S.
Netherlands	2.02	1.68	2.20	1.71	.60	Germany	Germany
New Zealand	.57	.46	.50	.34	.52	Austra.	Austra.
Norway	.77	.66	.55	.70	.45	Sweden	U.K.
Portugal	.71	.60	.52	.46	.68	Germany	Germany
Spain	.32	.27	.23	.18	.56	Germany	France
Sweden	.60	.51	.67	.56	.60	Germany	Germany
United Kingdom	.46	.36	.38	.29	.62	Germany	Germany
United States	.17	.10	.13	.08	.52	Japan	Canada

All data are for 1990, and (except for GDP) the manufacturing sector. Home sales are gross manufacturing production less manufacturing exports. Sample* refers to the other 18 countries in our sample. See the appendix for complete definitions.

Table 2: 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.

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Table 3: Bilateral Trade Equation

Variable	param.	OLS	GLS	G2SLS
Distance [0,375)	$-\theta d_1$	-3.13	-3.25	-3.24
		(.47)	(.28)	(.28)
Distance [375,750)	$-\theta d_2$	-3.80	-3.78	-3.78
		(.31)	(.23)	(.23)
Distance [750,1500)	$-\theta d_3$	-4.67	-4.25	-4.24
		(.27)	(.22)	(.21)
Distance [1500,3000)	$-\theta d_4$	-5.50	-4.56	-4.56
		(.45)	(.28)	(.28)
Distance [3000,6000)	$-\theta d_5$	-5.47	-5.86	-5.86
		(.21)	(.21)	(.21)
Distance [6000,maximum]	$-\theta d_6$	-6.51	-6.45	-6.46
		(.23)	(.21)	(.21)
Shared border	$-\theta b$	.30	.30	.30
		(.47)	(.20)	(.20)
Shared language	$-\theta l$	1.17	.78	.78
		(.42)	(.20)	(.20)
European Community	$-\theta e_1$	0.33	.10	.10
		(.30)	(.17)	(.17)
EFTA	$-\theta e_2$	-.12	.40	.41
		(.60)	(.27)	(.27)
Research stock	$\frac{\alpha_R}{\beta}$	.78	.99	1.05
		(.05)	(.18)	(.19)
Human capital	$-\frac{\alpha_H}{\beta}$	-29.3	-28.1	-36.5
		(6.1)	(23.1)	(24.8)
Wage	$-\theta$	-2.68	-2.72	-3.52
		(.29)	(1.08)	(1.29)
Unobservable knowlege	$\beta^{-2}\sigma_\tau^2$		1.29	1.37
Unobservable trade impediments:				
Destination-specific	$\theta^2\sigma_d^2$		.55	.54
Two-way	$\theta^2\sigma_2^2$		.20	.20
One-way	$\theta^2\sigma_1^2$		.18	.18
Total Sum of Squares (about mean)		2937	2937	2937
Sum of squared residuals		1158	1316	1346
Number of observations		342	342	342

Estimated using 1990 data. The dependent variable is $\ln(X'_{ni}/X'_{nn})$ as defined in equation (10). Standard errors are in parentheses.

Table 4: Wage Regressed on Instruments

Variable	est.	s.e.
Constant	.14	(.11)
Research stock ($\ln R_i$)	0.28	(.04)
Human Capital ($1/H_i$)	-6.82	(2.95)
Density ($\ln(L_i/AREA_i)$)	-0.008	(.03)
Workforce ($\ln L_i$)	-0.35	(.06)
Total Sum of Squares (about mean)	2.55	
Sum of squared residuals	.28	
Number of observations	18	

The dependent variable is the the wage ($\ln w_i$). All variables are measured relative to their U.S. level. Estimation is by Ordinary Least Squares.

Table 5: Fixed-Effects Bilateral Trade Equation

Variable	param.	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)

Country	Competitiveness			Destination-specific trade impediments		
	param.	est.	s.e.	param.	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 using 1990 data. The dependent variable is $\ln(X'_{ni}/X'_{nn})$ as defined in equation (10). Estimation is by GLS. 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 6: The Spread of Technology: Employment and Wage Outcomes

| Country | Simulated effects of a 20 % increase in technology | | | |
| | Increase in U.S. technology | | Increase in German technology | |
	fixed wage % Δ employment	fixed labor % Δ real wage	fixed wage % Δ employment	fixed labor % Δ real wage
Australia	-12.7	-4.1	-4.8	-1.6
Austria	-10.7	-4.0	-6.2	-1.4
Belgium	-10.7	-4.0	-6.4	-1.4
Canada	-10.8	-2.9	-5.9	-1.8
Denmark	-11.0	-4.0	-3.4	-1.0
Finland	-10.7	-4.0	-11.3	-2.2
France	-10.5	-3.9	-11.8	-2.3
Germany	-11.8	-4.1	46.3	15.9
Greece	-7.4	-3.3	-9.1	-2.0
Italy	-10.1	-3.9	-11.9	-2.3
Japan	-8.6	-3.7	-5.1	-1.7
Netherlands	-11.0	-4.0	-11.2	-.5
New Zealand	-13.9	-4.2	-5.6	-1.7
Norway	-10.3	-3.9	-9.6	-2.0
Portugal	-10.3	-3.9	-9.9	-2.1
Spain	-8.7	-3.7	-11.2	-2.3
Sweden	-11.2	-4.0	-10.2	-2.1
United Kingdom	-11.6	-4.1	-10.9	-2.2
United States	22.3	11.8	-5.8	-1.8

Table 7: The Spread of Technology: Welfare Outcomes

Country	Simulated effects of a 20 % increase in technology			
	Increase in U.S. technology		Increase in German technology	
	fixed wage	fixed labor	fixed wage	fixed labor
	% Δ welfare	% Δ welfare	% Δ welfare	% Δ welfare
Australia	.7	.5	.2	.2
Austria	.3	.2	1.2	.4
Belgium	.4	.2	1.0	.4
Canada	2.3	.9	.2	.0
Denmark	.3	.2	1.2	.5
Finland	.3	.2	.7	.2
France	.3	.2	.8	.2
Germany	.3	-.2	2.0	3.8
Greece	.4	.5	.8	.4
Italy	.3	.2	.8	.2
Japan	.2	.0	.1	.0
Netherlands	.4	.2	1.3	.6
New Zealand	.9	.5	.3	.2
Norway	.4	.4	.9	.4
Portugal	.4	.3	.8	.3
Spain	.3	.3	.5	.2
Sweden	.4	.1	.8	.2
United Kingdom	.4	.1	.8	.2
United States	2.7	3.0	.2	.1

Table 8: The Gains From Trade: Employment and Wage Outcomes

Country	Simulated effects of autarky and lower trade impediments			
	Complete autarky		Impediments 20 % lower	
	fixed wage	fixed labor	fixed wage	fixed labor
	% Δ employment	% Δ real wage	% Δ employment	% Δ real wage
Australia	67.7	58.9	-12.2	-2.9
Austria	6.8	-1.1	17.6	9.3
Belgium	3.4	-18.7	46.6	22.2
Canada	-7.4	-19.7	5.9	5.8
Denmark	18.2	3.8	41.2	18.3
Finland	9.7	3.5	15.6	7.9
France	10.2	3.9	6.8	4.5
Germany	-29.9	-33.5	6.7	4.0
Greece	142.4	114.5	1.6	4.0
Italy	6.5	2.3	-.2	2.4
Japan	-9.6	-10.1	-7.3	-2.0
Netherlands	19.0	-2.9	43.3	20.1
New Zealand	47.6	36.4	17.1	8.9
Norway	46.7	31.5	32.5	14.4
Portugal	30.4	19.7	28.2	13.2
Spain	26.4	21.7	-7.6	.0
Sweden	-2.4	-9.5	27.2	11.8
United Kingdom	-3.4	-9.2	14.7	7.1
United States	8.6	6.3	-9.9	-2.6

Table 9: The Gains From Trade: Welfare Outcomes

Country	Simulated effects of autarky and lower trade impediments			
	Complete autarky		Impediments 20 % lower	
	fixed wage % Δ welfare	fixed labor % Δ welfare	fixed wage % Δ welfare	fixed labor % Δ welfare
Australia	-3.6	-5.2	2.1	1.9
Austria	-7.4	-7.4	2.9	3.2
Belgium	-21.4	-21.4	2.8	4.9
Canada	-13.2	-13.2	2.0	2.7
Denmark	-12.0	-12.1	3.1	4.3
Finland	-5.6	-5.6	2.8	3.0
France	-5.6	-5.7	2.4	2.3
Germany	-4.1	-5.2	2.0	2.0
Greece	-7.6	-11.5	3.2	3.0
Italy	-3.9	-3.9	2.2	1.9
Japan	-.5	-.6	.6	.4
Netherlands	-18.2	-18.4	2.8	4.3
New Zealand	-6.6	-7.6	2.6	3.0
Norway	-9.5	-10.3	3.2	3.7
Portugal	-7.8	-8.2	3.1	3.6
Spain	-3.4	-3.7	2.3	1.9
Sweden	-7.2	-7.2	2.8	3.5
United Kingdom	-6.0	-6.0	2.3	2.6
United States	-2.1	-2.1	1.1	.8

Table 10: The Effects of Regional Integration: Employment and Wage Outcomes

Country	Simulated effects of 20 % lower trade impediments			
	Within the EC		Canada-U.S.	
	fixed wage	fixed labor	fixed wage	fixed labor
	% Δ employment	% Δ real wage	% Δ employment	% Δ real wage
Australia	-5.3	-2.0	-1.6	-.5
Austria	-13.9	-3.8	-1.4	-.5
Belgium*	43.1	20.1	-1.6	-.6
Canada	-6.6	-2.4	19.6	9.5
Denmark*	35.2	15.8	-1.6	-.6
Finland	-14.1	-3.7	-1.5	-.6
France*	10.3	5.5	-1.4	-.5
Germany*	7.0	3.9	-1.6	-.6
Greece*	2.1	3.8	-1.0	-.5
Italy*	2.8	3.3	-1.4	-.5
Japan	-5.5	-2.3	-1.2	-.5
Netherlands*	39.4	18.1	-1.6	-.6
New Zealand	-6.4	-2.3	-2.1	-.6
Norway	-12.5	-3.8	-1.5	-.5
Portugal*	25.7	11.8	-1.5	-.6
Spain*	-3.8	1.2	-1.1	-.5
Sweden	-13.7	-3.9	-1.6	-.6
United Kingdom*	13.3	6.2	-1.7	-.6
United States	-6.4	-2.3	.5	.5

Members of the EC in 1990 appear with a *.

Table 11: The Effects of Regional Integration: Welfare Outcomes

Country	Simulated effects of 20 % lower trade impediments			
	Within the EC		Canada-U.S.	
	fixed wage % Δ welfare	fixed labor % Δ welfare	fixed wage % Δ welfare	fixed labor % Δ welfare
Australia	.3	.2	.07	.06
Austria	.8	.1	.02	.01
Belgium*	2.1	3.9	.03	.01
Canada	.2	.0	1.24	2.25
Denmark*	2.3	3.2	.03	.02
Finland	.6	.1	.03	.02
France*	1.8	1.8	.02	.02
Germany*	1.3	1.5	.02	-.03
Greece*	2.4	2.1	.03	.06
Italy*	1.6	1.4	.02	.01
Japan	.1	.0	.01	-.00
Netherlands*	2.0	3.4	.03	.02
New Zealand	.3	.2	.09	.05
Norway	.8	.3	.03	.04
Portugal*	2.3	2.8	.04	.03
Spain*	1.7	1.4	.02	.03
Sweden	.8	.0	.03	.01
United Kingdom*	1.6	1.8	.04	.00
United States	.2	.1	.30	.22

Members of the EC in 1990 appear with a *.

Table 12: Lower Canada–U.S. Barriers: Effects on U.S. Trade Patterns

Country	Simulated effects of 20 % lower Canada–U.S. barriers			
	Fixed-wage case		Fixed-labor case	
	% Δ exports	% Δ imports	% Δ exports	% Δ imports
Australia	3.2	-5.8	.3	-1.9
Austria	4.5	-6.7	.6	-2.2
Belgium	4.1	-6.5	.5	-2.1
Canada	25.1	29.2	19.4	19.5
Denmark	4.2	-6.5	.5	-2.1
Finland	4.4	-6.6	.6	-2.1
France	4.5	-6.6	.6	-2.2
Germany	4.2	-6.7	.5	-2.1
Greece	4.8	-6.5	.8	-2.2
Italy	4.6	-6.7	.7	-2.2
Japan	4.9	-6.8	.9	-2.4
Netherlands	4.2	-6.5	.5	-2.1
New Zealand	2.4	-5.4	.0	-1.6
Norway	4.3	-6.5	.6	-2.1
Portugal	4.2	-6.4	.5	-2.1
Spain	4.8	-6.7	.8	-2.3
Sweden	4.1	-6.5	.5	-2.1
United Kingdom	3.9	-6.4	.4	-2.0
United States	-1.2	-1.2	-1.0	-1.0

All percent changes are for U.S. trade with others. Imports of the United States from itself and exports to itself are both equal to home sales.

Figure1: Alternative Estimates of Technology

Technology implied by research stock and schooling