Testing the Heckscher-Ohlin-Vanek Paradigm in a World with Cheap Foreign Labor

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Abstract

Measuring factors services, not quantities, we examine the technologies and endowments of thirty-nine countries and five factors in 2005. We conduct three tests of the Heckscher-Ohlin-Vanek paradigm: (1) the conventional one; (2) a benchmark where every country has America's technology; and (3) a test that converts foreign endowments into international efficiency units. The first predicts the direction of trade better than any former study. The second shows no statistically significant evidence of missing trade. The third performs just as well, and it accounts for international differences in both factor prices and unit input requirements.

***The data and the Matlab programs that are used in this paper are available upon request.**

Keywords: Heckscher-Ohlin-Vanek theory, factor services, international productivity comparisons

1. Introduction

By now it is well known that the predictions of the Heckscher-Ohlin-Vanek paradigm fail because countries have different technologies. Not only are their technologies different, their factor prices vary by at least an order of magnitude.[1] Although two generations of scholars since Leontief (1953) have tested the theory, almost all tests are based upon aggregating physically homogenous units, such as hectares of land or person-years of skilled labor, to predict which countries are abundant in which factors. Some authors make adjustments for the quality of a factor and base predictions upon efficiency units. But they are still adding physical units of quality-adjusted factors. This practice is wrong, and it is responsible for the horribly inaccurate predictions about the direction of the factor content of trade. Since the predictions are wrong, the rejections of the theory are spurious.

What do we do that's different? First, we return to basics. The factor content of trade in labor is not an exchange of person-years, but *trade in the services of labor*. A unit of labor is the annual value added attributed to a worker. For example, compensation to employees constituted about 57% of GDP in the United States in 2005. The analog in our sample of countries was 50% of aggregate GDP, indicating that American workers are much better paid than foreign labor. According to the strict logic of the Heckscher-Ohlin-Vanek paradigm, the United States is abundant in labor, even though its physical workforce is only seven percent of the sample aggregate. Indeed, the conventional application of the paradigm predicts that United States should *export* $587 billion of labor services, but it actually imports $306 billion.[2] This wrong

[1] Table 1 in Trefler (1993) shows that wages in Bangladesh are 5% of those in the United States.
[2] All values in this paper are measured in 2005 international dollars. The share of American labor measured as physical workers in the sample aggregate was computed from FAO Statistical Yearbook 2007-2008, Table A.3.

prediction is an anomaly, and it occurs because American wages are so high. For a large majority of countries, the direction of trade in labor services is predicted correctly.

In Heckscher-Ohlin-Vanek theory, a factor is mobile between sectors and immobile across countries. Land is surely such a factor. The rent paid to land in the United States was about 0.9% of GDP, and the analog for sample aggregate was 2.4%, indicating that the United States is scarce in land. Again this argument has nothing to do with how much arable land America has or how big its footprint is in the temperate zone. In this case, the prediction is that United States should import $210 billion of the services of land, but it actually imports only $11 billion. Now the direction of factor trade is correct, but its magnitude is too small.

We conduct three simple tests that strongly confirm the broad validity of the Heckscher-Ohlin-Vanek paradigm: (1) the conventional approach; (2) a benchmark where every country has an identical technology; and (3) one based upon converting all factors into common international efficiency units. In this literature, it is customary to begin by rejecting the theory resoundingly; then one analyzes increasingly arcane modifications that eventually confirm some ancillary versions of the paradigm. Since our tests confirm the theory, it is unnecessary to consider any complicated modifications of it. Indeed, our fundamental contribution is to give the theory its due, to treat the data with respect, and to develop corrections for international differences in productivity that are rooted in economic theory.

Data on the values of factor payments already include important corrections for productivity. *The services of labor incorporate local wages, an excellent measure of skill, and the services of land include local rents that reflect crop yield, another good measure of quality*. These market-based adjustments have a profound empirical implication. In fact, when endowments and factor trade are measured properly, the conventional approach predicts the direction of trade better than any simple test before. In a sample of thirty-nine countries and five factors, it predicts 123 of 195 cases correctly. Under the null hypothesis that the paradigm predicts the direction of factor trade no better than a coin flip, the *p*-value of this statistic is 0.01%. *One only had to measure and predict factor services, not factor quantities.*

Although the direction of factor trade is predicted accurately, its magnitude is much too small. This finding reconfirms Trefler's (1995) missing trade. The second approach uses a simple benchmark in which every country's output is converted to factor services it would employ if it had to produce its output using the United States' technology. This benchmark predicts 168 of 195 cases correctly. Also, using the simplest possible regression and a Wald test of conventional size, one cannot reject the null hypothesis that measured factor trade matches the predictions completely. So this benchmark solves the mystery of missing trade.

The benchmark confirms that *the main reason for missing trade is that countries have different technologies.* In particular, the paradigm's demand-side assumptions are innocuous. This finding has several important empirical implications. First, one can assume that all goods and services are traded. Second, there is no need to adjust for home bias in consumption. Third, there is no need to account for transportation costs or other barriers to trade in final goods and services. Fourth, it is not necessary to keep track of which intermediate inputs are made where. Fifth, assumptions about imperfect competition or intra-industry trade are not relevant. In sum, the simple assumption that every country consumes its absorption share of the world endowment works very well.

The reader may feel uncomfortable with the benchmark because it involves a virtual world. The third and final step is to make an adjustment—based fully in economic theory—to the actual endowments of each country to convert them into efficiency units comparable with the American endowment. This adjustment has two alternative interpretations. First, it lists the American factor content of foreign Rybczynski effects. Second, its transpose lists the Stolper-Samuelson effects in the foreign country of an exogenous change in American factor prices that affects world prices. Factor conversion matrices arise directly from data on technologies by country. These matrices generalize factor-specific international productivity differences, and they are the best linear mapping between factor uses by sector in different countries. A factor conversion matrix is an important theoretical contribution in its own right, and we hope trade theorists might benefit from studying its properties closely.

These international productivity adjustments are novel. Measuring factors in terms of services already incorporates factor prices, the best scalar adjustment for international differences in factor quality. But countries' technologies differ more fundamentally than a lack of factor price equalization. Factor conversion matrices make the necessary second adjustment. Indeed, in this third test, there are 159 correct predictions about the direction of trade, and there is no statistical evidence of missing trade. *Using raw data on endowments and technologies, converting them into American efficiency units, estimating nothing, and making no ancillary demand-side assumptions, we find overwhelming support for the Heckscher-Ohlin-Vanek paradigm in a wide sample of countries*.

How does this technique help to account for the anomalous prediction about American labor services? In a world of cheap foreign labor, the American labor endowment is too large. Once one adjusts for differences in technology, America's share of world labor, measured in efficiency units, becomes smaller. Then the theory correctly predicts that the United States will import labor: the prediction is imports of $214 billion and the measure is imports of $306 billion.

If countries have identical technologies and factor prices are the same everywhere, the difference between physical units and the services of factors is moot; indeed, it's just the common world wage-rentals ratio in a model with two factors. Hence, once one scales factor content—as is the norm in the literature—there is no harm in thinking either in terms of quantities of a factor or the services (value added) attributed to it. When one acknowledges that technologies and factor prices differ across countries, the distinction between a person year and the annual services of a worker is fundamental. Under the assumption of perfect competition, the labor's compensation exactly matches its value added in GDP. So measures in values are fundamentally consistent, both with local national accounts and across countries. Working with physical quantities of factors has outlived its usefulness for empiricists interested in Heckscher-Ohlin-Vanek theory. Our contribution is to push this insight as far as it will go.

2. Review of the Literature

Leontief (1953) measured the local factor content of capital in 1947 dollars per million dollars of exports and the local factor content of labor in man-years per million dollars of exports. His work was predicated upon the assumption of identical technologies, and he wanted to calculate American resources saved by importing goods instead of producing them locally. The early work on the American input-output table focused on quantities of labor for good reason. As Evans and Hoffenberg (1952) explain, the initial research at Harvard and the Bureau of Labor Statistics on the American input-output table was designed to predict the employment effects of the demobilization after World War II. The unintended consequence was that Leontief began the practice of measuring labor in physical units and the capital stock in real dollars.

Many important contributions in this literature continued to measure quantities of factors, not their services. This practice made sense when researchers could only use the United States input-output matrix and data on factor uses by sector in foreign countries were recorded only in physical units. Leamer's (1984) monograph is the classic contribution that has influenced a generation of scholars. Examining quantities of factors and using the United States as a reference country, Bowen, Leamer, and Sveikauskas (1987) tested the assumption of Hicks-neutral international technological differences. They concluded that differences in technology were likely behind the failure of tests of the theory. Trefler (1993) extended this work by computing a complete list of country-specific and factor-specific productivity differences that fit the measured factor content of trade exactly. He did not have as rich a set of data as we have, and part of our analysis evaluates Trefler's productivity adjustments. We find that such simple modifications do not account properly for the heterogeneity of technologies across countries.

Analyzing consistent input-output data on ten countries, Davis and Weinstein (2001) made a path-breaking contribution. They emphasized that it was obvious by inspection that countries do not have the same technologies, but they followed the tradition of measuring factors as quantities. Hakura (2001) recognized the difficulty of testing the theory when countries have different local production techniques. She cautions, "Biased factor contents of trade in the strict HOV can lead to a discrepancy between the calculated factor content of trade and that predicted from endowments." Romalis (2004) analyzed a model with imperfect competition, but his empirical work was based on factor usages in quantities. Again using quantities to measure factors, Maskus and Nishioka (2009) estimate factor-specific productivity adjustments that improve predictions about the factor content of North-South trade.

When countries produce the same thing in different ways, it may be important to trace the path of value added to calculate the factor content of trade. This is Reimer's (2006) approach, and Trefler and Zhu (2010) build on it by constructing an input-output matrix for the world. They prove two theorems that show how to measure factor content in a world with arbitrary technical differences. Their measure of factor content is quite appealing; it is Deardorff's (1982) "actual factor content of trade". If it takes one hour of Mexican labor to make a sombrero and one hour of American labor to retail it in California, then the "actual factor content" of the retailed sombrero is two hours of world labor. Trefler and Zhu establish necessary and sufficient conditions under which this measure is equal to Vanek's putative prediction.

Unfortunately, Trefler and Zhu describe Vanek's prediction incorrectly. They implement their ideas empirically by studying (scaled) person years of labor. But Vanek himself was careful in his dissertation (1963) and his famous article (1968) to define the factors with "each content being measured in its money-value." *The factor content of trade is trade in the value of factor services, not trade in the physical units of the factors themselves*.[3] Leamer (1987, p. 985) emphasized this point by stating, "The theory … is properly interpreted to refer to value added, not to gross output." Appendix A shows that Trefler and Zhu's theorems are true, but they may have an opaque economic interpretation.

None of these scholars analyzed factor services instead of factor quantities. Hence, we return to Vanek's original formulation of factor content as payment for the *services* of capital,

[3] That's why Vanek (1968) uses factor prices in his equations (2) and (3) on p. 752.

labor, and land, not their physical quantities. This approach was implemented in a few early studies; Eysenbach (1976), Harkness (1978), and Vanek (1963) are good examples. Still, those authors did not have consistent input output tables from many countries. We are the first to apply this approach with a large set of countries at diverse levels of economic development.[4] Our work imposes in a natural way the basic national income identities. We anticipate that the techniques we develop will help in future research to evaluate the contribution of international differences in factor usage and factor payments.

3. The Measured Factor Content of Trade and the Predicted Factor Content of Trade

Because we agree with Trefler and Zhu (2010, p. 195) that "definitional mistakes are endemic" in this literature, we are going to be painstakingly clear about what we predict and what we measure. There are n goods and f factors. Country c's technology matrix is an observable $f \times n$ matrix Θ_c whose columns sum to unity. [5] Each column gives an industry's cost shares for the direct and indirect uses of factors. Every country's endowment is an observable $f \times 1$ vector of factor services v_c, each of whose elements is measured in international dollars per year. The world endowment is $v = \sum_c v_c$.[6]

Let y_c be country c's output vector and $x_c - m_c$ be its vector of net exports. Both of these $n \times 1$ vectors are observable. Again, each element is measured in international dollars per year, but these vectors have many more elements than the endowment vectors. It is worth hammering this point home: every measure is consistent with national income accounts, including exports, imports, output by sector, final demands, the trade balance, and so on.

[4] Marshall (2011) looks at China's measured and predicted factor trade for the year 2000 using a value-based measure of world endowments, but she does not use factor conversion matrices to adjust for technology differences.
[5] In the empirical work, we use the finest aggregation so that there are no inactive sectors in any country. Hence no technology matrix has a column of zeros.
[6] In our tests, we make an adjustment for the factor content of the net trade vector with the rest of the world.

Let Θ_0 be the reference country's (America's) technology. The measure of the factor content of trade for every test is:

$$\Theta_0(x_c - m_c). \quad (1)$$

Each element of this $f \times 1$ of vector is measured in international dollars per year. It shows the factor content in the reference country of the net trade vector of country *c*. This simple measure is exactly what Leontief first explored. Also, it follows almost the whole literature, except now everything is measured in values. Simplicity is the essence of science, and when one departs from the assumption of identical technologies, it is easy to be confused about what to measure and what to predict. Since the factor content of trade is measured in one way only, *these tests stand or fall only on how one predicts the factor content of trade.*

Let s_c be country *c*'s share of absorption. Vanek's predicted factor content of trade is:

$$v_c - s_c v. \quad (2)$$

The first term shows local factors supplied and the second shows local demand for world factors. Let's again be clear about the units. Each element of this $f \times 1$ vector is measured in international dollars per year. Equation (2) is implemented in three ways. The first *conventional test* just measures v_c as reported in that country's national accounts; there are no adjustments. The second *benchmark test* defines a virtual world; in that case, one defines $v_c = \Theta_0 y_c$, where Θ_0 is the reference country's (America's) technology. The third *factor conversion test* converts local endowments into American efficiency units.

4. Factor Conversion Matrices

This section gives a simple exposition of how to adjust foreign factors into American efficiency units. It also illustrates some of the general properties of factor conversion matrices. It presents the theory using simple examples from the data, and it gives an introduction to the ideas described in greater generality in Appendix B. These factor conversion matrices extend Fisher and Marshall (2011) to international productivity comparisons.

Table 1 constructs three "even" technology matrices by aggregating the data for Canada, China, and the United States. The rows refer to four factors of production and the columns to four different broad sectors in the economy. For the moment, consider only square technology matrices that have full rank and are column stochastic.[7] The columns are the direct and indirect cost shares of the four factors in an industry. One can see right away that factor-specific productivity adjustments cannot explain these differences. If labor in the United States were twice as productive as that in China, every activity in the United States would use half as many workers but pay each one twice as much. Then the labor cost shares in every industry would be identical in every country. The same fact is true for every factor, and these cost share matrices would have to be identical for every country.

The full employment condition is:

$$v_c = \Theta_c y_c,$$

[7] Because these factor conversion matrices are novel both theoretically and empirically, we wanted to make this exposition quite accessible. In this section, these matrices are tables with 16 numbers. The detailed work identifies five factors, including indirect taxes that we call rents on social capital. Thus the actual matrices have 25 elements. The aggregation here attributes 1/3 of indirect taxes to the cost of physical capital and 2/3 to that of labor.

where the endowment vector v_c has payments to land, natural resources, capital, and labor. Likewise, y_c is a list of the values of outputs in food, mining, manufacturing, and services. Fix factor prices, and let dx denote differentiation in levels. The Rybczynski effects are:

$$dy_c = \Theta_c^{-1} dv_c.$$

This equation states that an increase in the physical quantity of any endowment will have deterministic effects on the physical quantities of outputs. Two facts are known about Θ_c^{-1}: (1) each column has a negative element; and (2) each row has an element greater than unity.

Table 1. Simplified technology matrices

	United States			
Factors/Sectors	Food	Mining	Manufactures	Services
Land	0.43	0.00	0.02	0.00
Natural Resources	0.02	0.48	0.05	0.01
Capital	0.16	0.12	0.34	0.37
Labor	0.39	0.39	0.59	0.62
	Canada			
	Food	Mining	Manufactures	Services
Land	0.28	0.00	0.02	0.00
Natural Resources	0.05	0.67	0.12	0.03
Capital	0.18	0.08	0.32	0.36
Labor	0.50	0.25	0.54	0.60
	China			
	Food	Mining	Manufactures	Services
Land	0.07	0.00	0.01	0.01
Natural Resources	0.02	0.34	0.06	0.03
Capital	0.14	0.23	0.44	0.48
Labor	0.78	0.42	0.49	0.48

Note: Each matrix reports direct and indirect factor costs per international dollar of output. Each was constructed by aggregating the OECD input-output tables converted to international dollars with the ICP purchasing power parity exchange rates.

Let $\hat{x} = dx/x$ denote logarithmic differentiation. Also, let p be the vector of common world prices of output and w_0 be the vector of factor prices in the reference country. Now consider changes in factor prices in the reference country that affect world prices:

$$\hat{p} = \Theta_0^T \widehat{w_0}.$$

These price changes have Stolper-Samuelson effects in country c:

$$\widehat{w_c} = (\Theta_c^T)^{-1} \Theta_0^T \widehat{w_0}.$$

This equation shows how exogenous changes in factor prices in the reference country influence factor prices in country *c*, under the assumption that world price changes are passed through completely to changes in local goods prices.

The factor conversion matrix

$$F(0, c) = \Theta_0 \Theta_c^{-1}$$

has two interpretations. First, it gives the factor content in the reference country of the Rybczynski effects in country c. Second, its transpose shows the Stolper-Samuelson effects in country *c* of exogenous factor price changes in the reference country. Both interpretations are complementary ways of understanding international factor productivity differences. If the two countries have identical technologies then the factor conversion matrix is just the identity matrix. This observation hints at a deeper fact. The factor conversion matrix is the best linear mapping that captures productivity differences between two countries, including both factor-specific and sector-specific technical differences.

The Rybczynski matrix Θ_c^{-1} is column stochastic because at fixed factor prices a dollar increase in the endowment of any factor will raise GDP in country *c* by exactly a dollar. Hence the sum of all the positive and negative Rybczynski effects will be just one dollar. This fact implies that the factor conversion matrix is also column stochastic. If trade equalizes goods prices, an extra dollar of world GDP must translate into a dollar increase in the sum of factor payments in the reference country. So the factor conversion matrix has a special structure because each technology matrix describes cost shares.

Here is the matrix for Canada, with United States as the reference country.

Table 2: Simplified Factor Conversion Matrix for Canada

	Land in Canada	Natural Resources in Canada	Capital in Canada	Labor in Canada
Land in the US	1.05	-0.13	-1.19	0.72
Natural Resources in the US	-1.49	0.34	-3.38	2.05
Capital in the US	0.54	0.24	2.48	-0.90
Labor in the US	0.89	0.56	3.09	-0.87

Consider the meaning of a representative column. Fix goods prices and thus local factor prices. A $1 increase in the endowment of land in Canada will have Rybczynski effects given by the first column of the inverse of the Canadian technology matrix. The factor content of those effects in the United States is: (1) a $1.05 increase in the endowment land; (2) a $1.49 *decrease* in the endowment of natural resources; (3) a $0.54 increase in capital; and (4) a $0.89 increase in the endowment of labor. (These four numbers add to $0.99 because of rounding.)

Now consider the meaning of a representative row. Fix factor supplies in the United States and Canada, and consider a 1% exogenous increase in the rent on land in the United

States. The unit costs of all goods produced in that country will change. These cost changes will affect world prices, causing these Stolper-Samuelson effects in Canada: (1) the rent on Canadian land will rise by 1.05%; (2) the rent on Canadian natural resources will *drop* by 0.13%; (3) the rent on capital in Canada will *drop* by 1.19%; and the wage in Canada will rise by 0.72%.

In sum, reading down a column gives the factor content in the reference country of the Rybczynski effects in Canada, and reading across a row gives the Stolper-Samuelson effects in Canada of an exogenous change in factor prices in the reference country.

Here is the matrix for China, again with the United States as reference country.

Table 3: Simplified Factor Conversion Matrix for China

	Land in China	Natural Resources in China	Capital in China	Labor in China
Land in the US	1.87	-0.27	-0.49	0.48
Natural resources in the US	1.72	1.55	0.06	-0.17
Capital in the US	-3.13	-0.39	0.43	0.40
Labor in the US	0.54	0.11	0.99	0.28

It may be helpful to think of friends and enemies. Labor in the United States is a friend of every factor in China. If the wage in the United States rises, then it has positive effects on all factor prices in China. Capital in the United States is an enemy of Chinese land and an enemy of natural resources in China. If there is a rise in the rent on capital in the United States, then rent on land in China and rent on natural resources there must fall if all the world changes are passed through completely to all sectors in the Chinese economy.

The technology matrices that international economists study are not square, so they are not invertible. Assume now that there are n goods and f factors. Instead of working with regular inverses, one works with generalized inverses. The Moore-Penrose inverse of the technology matrix has an elegant symmetry property that makes it the correct interpretation for the Rybczynski or Stolper-Samuelson matrix. When a square matrix has full rank, then the Moore-Penrose pseudo-inverse is its regular inverse; everything from the simple case carries over. In fact, the general case has even more beautiful properties. It does not matter if there are more goods than factors or fewer, and it is not necessary that any technology matrix have full rank.

Consider now the *general definition of the factor conversion matrix:*

$$F(0,c) = \Theta_0 \Theta_c^{+}, \tag{3}$$

where the $n \times f$ matrix Θ_c^{+} is the Moore-Penrose inverse of country *c*'s technology matrix. The factor conversion matrix has *f* rows and *f* columns. It has two alternative and complementary interpretations. First, fix factor supplies in both countries, and consider exogenous factor price changes in the reference country. Under the assumption that goods prices changes in the reference country are *approximately* equal to changes in local unit costs in country *c*, each row of the factor conversion matrix gives *the best estimates* of the relevant Stolper-Samuelson effects in country *c*. Second, assume that local factor prices and thus local goods prices are fixed. Then each column of the factor conversion matrix gives the local factor content in the reference country of an increase in the relevant factor endowment in country *c*. In empirical applications, there are typically more goods than factors, and the supply correspondence is not single-valued. The factor conversion matrix gives the local factor content in the reference country of *the Rybczynski effects in country c that have the smallest possible magnitude.*

These matrices adjust for factor productivity differences across countries. They are grounded in theory, and they work in practice. They have an intuitive structure; for example, if both technology matrices have full rank, then each column of a factor conversion matrix sums to unity. Likewise, if factor price differences exactly offset factor-specific productivity differences or if two countries have identical technologies, then the factor conversion matrix is just the identity. Factor conversion matrices will capture factor-specific technical differences, total factor productivity differences by sector, or Hicks-neutral differences across countries. These matrices are an important theoretical contribution in their own right, and empirically oriented trade economists may adopt them in the future.

This section concludes by tying up one loose end. The third factor-conversion test computes country c's endowment in American efficiency units as $F(0,c)v_c$ and the world endowment as $v = \sum_c F(0,c)v_c$. We are now ready to look at the data and conduct the tests.

5. The Data

The data on factor uses, endowments, absorption, exports, and imports are from OECD input-output tables, assuring consistency with national income accounts and across countries. We convert all local currency values to 2005 international dollars using the purchasing power parity exchange rates from the World Bank International Comparison Project. We study these countries: Australia, Austria, Belgium, Brazil, Canada, Chile, the People's Republic of China, the Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Great Britain, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, New Zealand, Poland, Portugal, Romania, the Slovak Republic, Slovenia, Sweden, Thailand, Turkey, Taiwan, the United States, and South Africa. Although many of these countries have high gross domestic product per capita, the sample includes eight countries with

GDP per capita below $10,000, including China, Brazil, Indonesia, and India. These economies have disparate factor prices and endowments, and they constitute 83 percent of world GDP.

The input-output tables report three measures of value added: compensation to employees, gross operating surplus, and indirect taxes. We attribute all of gross operating surplus in the agriculture sector to land and all of gross operating surplus in the mining sector to natural resources. These are imperfect measures because they combine payments to physical capital with the payments to land or natural resources in those two sectors. Still, we also avoid the thorny problem of estimating stocks of capital or finding consistent international data on land and natural resources. We measure the services of capital by gross operating surplus in all remaining sectors, and we measure labor by compensation to employees in all sectors.

Every scholar working with input-output data must account for indirect taxes. They are recorded as a part of value added in national accounts because these costs are passed on to the consumers of each sector's gross output. We measure them as payments to a separate factor called social capital. It is not unjustified for a trade theorist to consider these taxes as rents on social capital. Consider two countries with identical technologies but different sector-specific patterns of indirect taxation. Even if world trade equalized commodity prices, these countries would have different factor prices and disparate factor uses. There is an important qualification: a sector may be subsidized. Although factor shares always sum to unity, social capital's share in one sector might be negative, and the sum of labor, capital, natural resources, and land's shares might be greater than one. Still, indirect taxes are treated identically with the payments to all other factors, and logical and empirical consistency compel us to define an aggregate factor called social capital for each country.[8]

Although our factor conversion matrices demonstrate that differences in technology are not fully captured by differences in factor prices, we stress that our definitions of efficiency units start with endowments measured as payments to these five factors of production. The raw data on endowments incorporate local factor prices that adjust for large differences in productivity across countries. Measuring endowments as factor services is more consistent with trade data by sector because these data never disentangle the separate effects of prices and quantities.

Knowing that the rest of the world has 17% of the world's GDP, observing the aggregate net trade vector for these countries, and assuming homothetic preferences, one can construct world output. Let the subscript r indicate the rest of the world. Aggregate output for our sample is $\sum_c y_c$, and net trade satisfies $x_r - m_r = -\sum_c(x_c - m_c)$. Absorption for the sample countries is the sum of these two vectors. The world output vector is $y = (\sum_c y_c + x_r - m_r)/0.83$, using the assumption that all countries have identical homothetic preferences. Hence the output vector for the rest of the world is $y_r = y - \sum_c y_c$. Since we measure all factor content of trade using the United States technology, we compute the rest of the world's endowment using that technology matrix. Then the predicted factor content of trade for the rest of the world is automatically equal to its measured factor content of trade, and we never use these five data points in our tests. This technique implements Kemp and Wan's (1976) theorem, where equilibrium is conditional upon the observed net trade vector from the rest of the world.[9]

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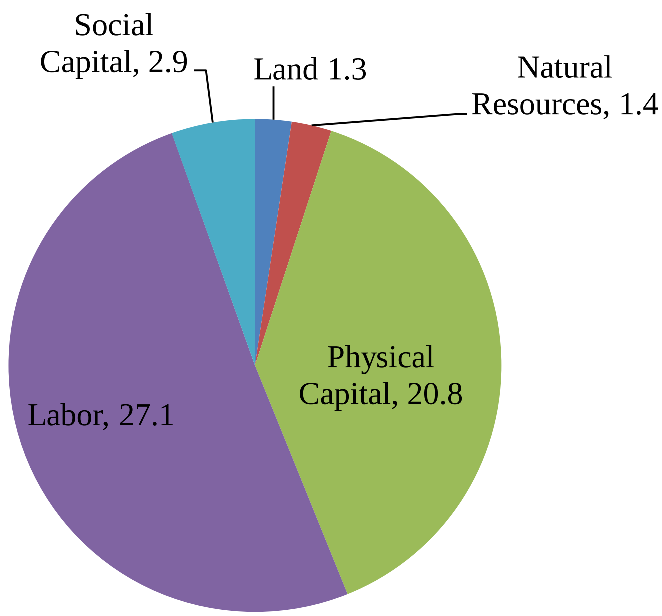
[8] Among the thirty-nine sample countries, the median share of aggregate indirect taxes in GDP is four percent. These shares range from fourteen percent in China to two percent in Indonesia.

[9] The net trade vector for a country satisfies $x_c - m_c = y_c - s_c(\sum_c y_c + x_r - m_r)$. The local factor content of the first term in the summation is $\sum_c \Theta_c y_c = \sum_c v_c$ for the conventional test and $\Theta_0 \sum_c y_c$ for the benchmark. We compute the factor content of the extra term in the summation exactly as we measure the factor content of trade:

Figure 1 presents the world endowment of all five factors. It illustrates the advantages of working with the values of factor services because the aggregation across countries simply sums payments by factor. The world value of labor exceeds that of all four other endowments combined. Indeed, by this raw measure the United States has a larger share of world labor than China and India combined, even though the combined labor force of China and India is 1.3 billion person years, more than eight times the physical labor force of the United States.



World Endowments, trillions of 2005 international dollars

$v_r = \Theta_0(x_r - m_r)$. For each prediction we include this term in $v = \sum_c v_c + v_r$. Because the rest of the world obviously does not have the America's technology, we have introduced unavoidable measurement error.

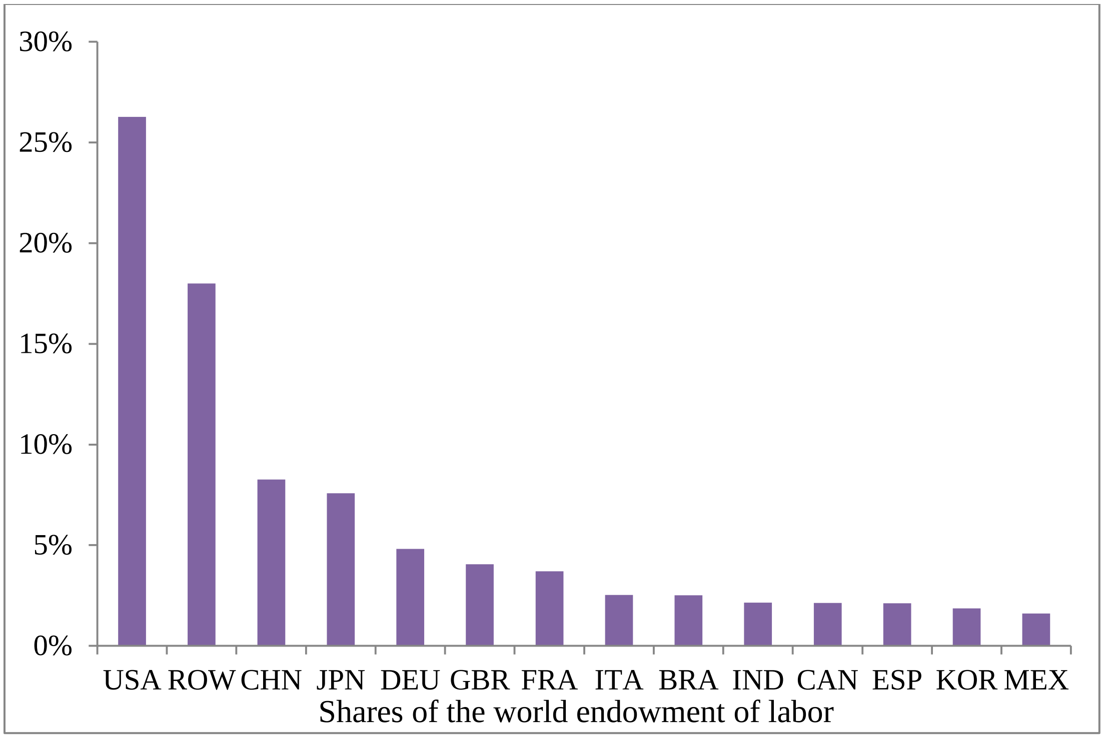


Fig. 1. Value-based measures of world endowments

If there is substantial intra-industry trade, the factor content of trade will be attenuated according to Heckscher-Ohlin-Vanek theory. Let the scalar

$$\frac{|x_i - m_i|}{x_i + m_i}$$

be the *index of conventional trade* for industry *i*, where the country subscript has been dropped for notational convenience and the variables have their usual meanings. This quantity is one minus the Grubel-Lloyd index. The raw data have 37 sectors, but many countries record no output in several sectors. The finest level of aggregation that allows for all industries to be active in all countries has 26 sectors; Appendix C gives the concordance. The shares of the top five sectors in the value of world trade are: (1) electrical machinery (23%); chemical products and refined petroleum (12%); mining, including petroleum (10%); motor vehicles, trailers, and semi-trailers (7%); and wholesale and retail trade (6%). Their corresponding indices of conventional trade, averaged across the 39 countries in the sample, are: (1) electrical machinery (27%); chemical products and refined petroleum (25%); mining, including petroleum (73%); motor vehicles, trailers, and semi-trailers (36%); and wholesale and retail trade (80%). These figures show that most industries exhibit substantial conventional trade at this level of aggregation.

Figure 2 depicts GDP per capita against each country's trade-weighted index of conventional trade.[10] For the United States and Japan, the index of conventional trade exceeds 40 percent, and the same measure exceeds 50 percent for six countries in our sample. A few small countries seem to have a high degree of intra-industry trade.

[10] For a given country, this index is $\sum_i \frac{|x_i - m_i|}{x+m}$, where $x + m = \sum_i (x_i + m_i)$.

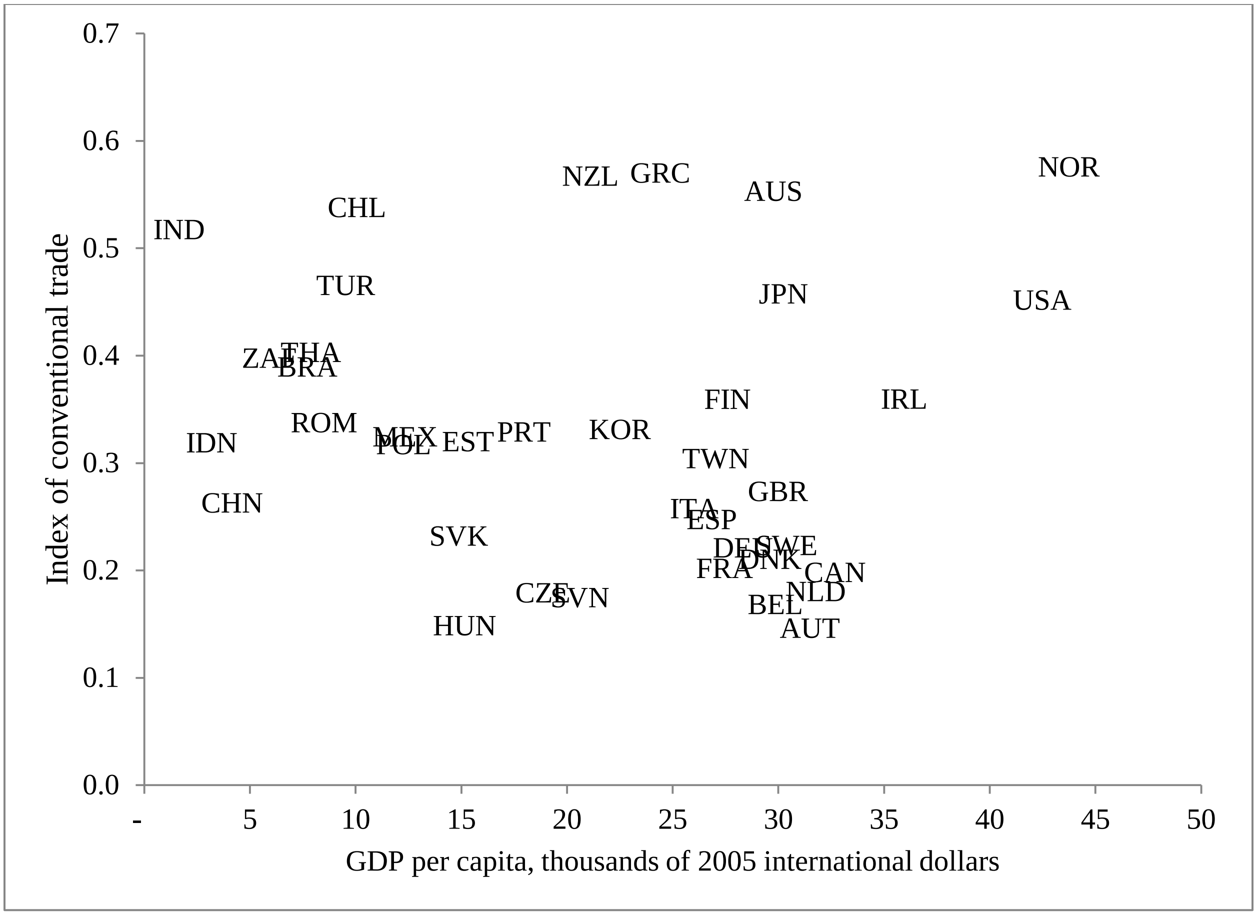


Fig. 2. Trade between industries and real GDP. The figure excludes Luxembourg with GDP per capita of $64,000 and inter-industry trade index of 0.26.

6. The Results

The literature has two common tests. The first is the sign test that computes the number of correct predictions of the direction of factor trade. Leamer (1984) famously observed that the paradigm does no better than a coin toss. The second is a regression of measured factor trade on the paradigm's predictions, where an observation is a country-factor pair. Let y_{cf} be the measured factor content of trade in equation (1) for country c and factor f, and let x_{cf} be the analogous predicted factor content of trade in (2). Consider a regression based on:

$$y_{cf} = \alpha + \beta x_{cf} + \varepsilon_{cf}, \tag{4}$$

where ε_{cf} is an error term that has mean zero, conditional on the predicted factor content of trade. The strictest test is the joint hypothesis that $\alpha = 0$ and $\beta = 1$, although the literature frequently reports only the estimate of β.

Consider first the null and alternative hypotheses for the sign test. It is based on the outcomes of a binomial random variable that has probability of success 0.5 under the null. The received scientific wisdom for two generations has been that the conventional predictions are abysmal; so this null hypothesis is natural. There are 195 predictions, and the critical region for a one-sided test of size 5% is to observe 110 or more correct ones. The simplest alternative hypothesis is that the model predicts perfectly because equations (1) and (2) are tautologically equal if the assumptions of the theory are true. The power of the sign test is 100% under this simple alternative, since one would never make a Type II error if the model were true. In fact, the sign test is 99% powerful against the composite alternative that the Heckscher-Ohlin-Vanek paradigm predicts the direction of factor trade with probability 0.65 or better.

The regression (4) compares measured factor content of trade with the relevant prediction. Now consider its null and alternative hypotheses. The null is that (4) measures the volume of predicted factor trade perfectly. Then the critical region is the area outside an ellipse centered at $\alpha = 0$ and $\beta = 1$. A simple alternative is that factor trade is completely missing; this outcome occurs when every country remains near autarky. Then the estimates of the intercept and slope are both zero, and it would be extremely unlikely to accept the null if this alternative were actually true. We are loath to make any distributional assumptions about the error term, so we cannot report the exact power of this test. But it is assuredly extremely powerful against the simple alternative that measured factor trade is completely missing.

A. The Conventional Test

Figure 3 gives the results for the conventional test. This figure and all subsequent ones plot predictions on the horizontal axis and measured factor trade on the vertical axis. There are 123 correct predictions; the probability of that many successes or more is 0.01% under the null. To the best of our knowledge, this result has never before been observed, and the only innovation is measuring and predicting factor content using values, not quantities. Of course, Trefler's (1995) observation that there is substantial missing trade is true in these data too. The first empirical conclusion is: *if one follows Vanek's strict logic and focuses on factor services, not quantities, then the paradigm predicts the direction of factor trade accurately.*

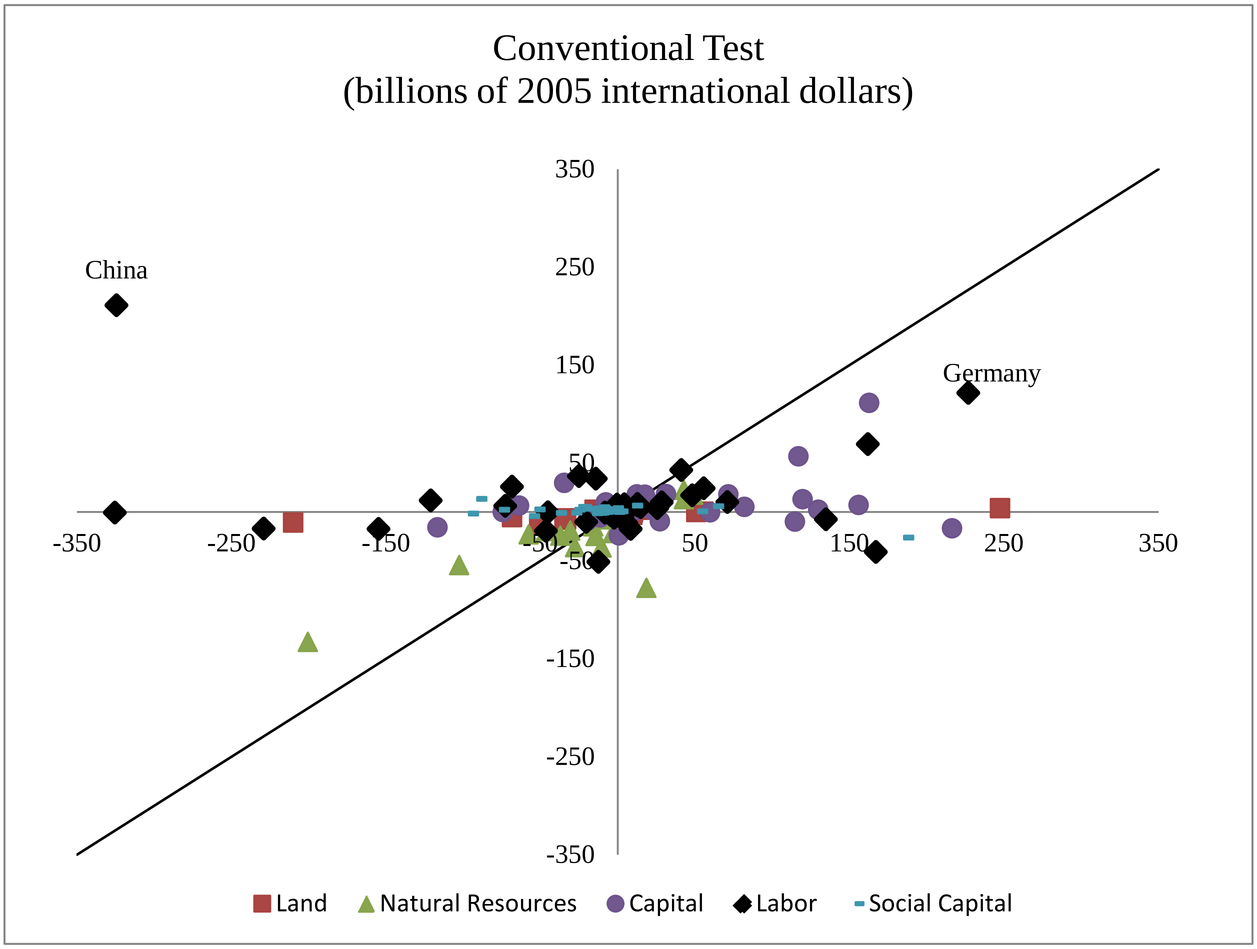


Fig. 3. Predicted factor trade is on the horizontal axis, and measured factor trade is on the vertical axis. There are 123 correct predictions. The figure excludes labor for the USA, with predicted factor trade of $590 billion and measured factor trade of -$306 billion.

B. The Benchmark Test

Figure 4 shows the results for our second test. There are 168 correct predictions, but the model predicts poorly for land. *Still, there is no statistically significant evidence of missing trade.* The measured factor content of trade is the same as before; only the predictions have changed. Now each country has a benchmark endowment $v_c = \Theta_0 y_c$.[11] The United States is correctly predicted to import the services of labor, and China is correctly predicted to export them. What happened? In the conventional test, China was predicted to import labor because its global share of labor services was less than its share of absorption. The benchmark adjustment suggests that China has low wages and produces goods that have high labor cost shares in the United States. If China had America's technology, then it would need a bigger share of world labor to produce its output. Because the United States has high wages, it has high labor cost shares in many industries. Indeed, if every country used America's technology, the world would need a lot more labor to keep the pattern of world production the same. America would go from being abundant in labor services to scarce in them.

Even with this adjustment, the measured factor content of trade is "only" 72% of what it is predicted to be. Still, one cannot reject the null hypothesis of no missing trade for a test of size 5%. Again, what happened? The measured factor content of trade is the same in Figures 3 and 4. *The predicted factor content of trade is more attenuated in this benchmark.* The literature conventionally measures a country as using a lot of person years of labor when wages are cheap locally. There is substantially more variability in the quantity of factors than in their services.

[11] Please recall that one observes the output vector of every country in these data. Also, these benchmark endowments do not change any country's real GDP, since every column of the technology matrix sums to unity. They only redistribute factor shares in local GDP. That's why we keep each country's absorption share s_c unchanged for these predictions.

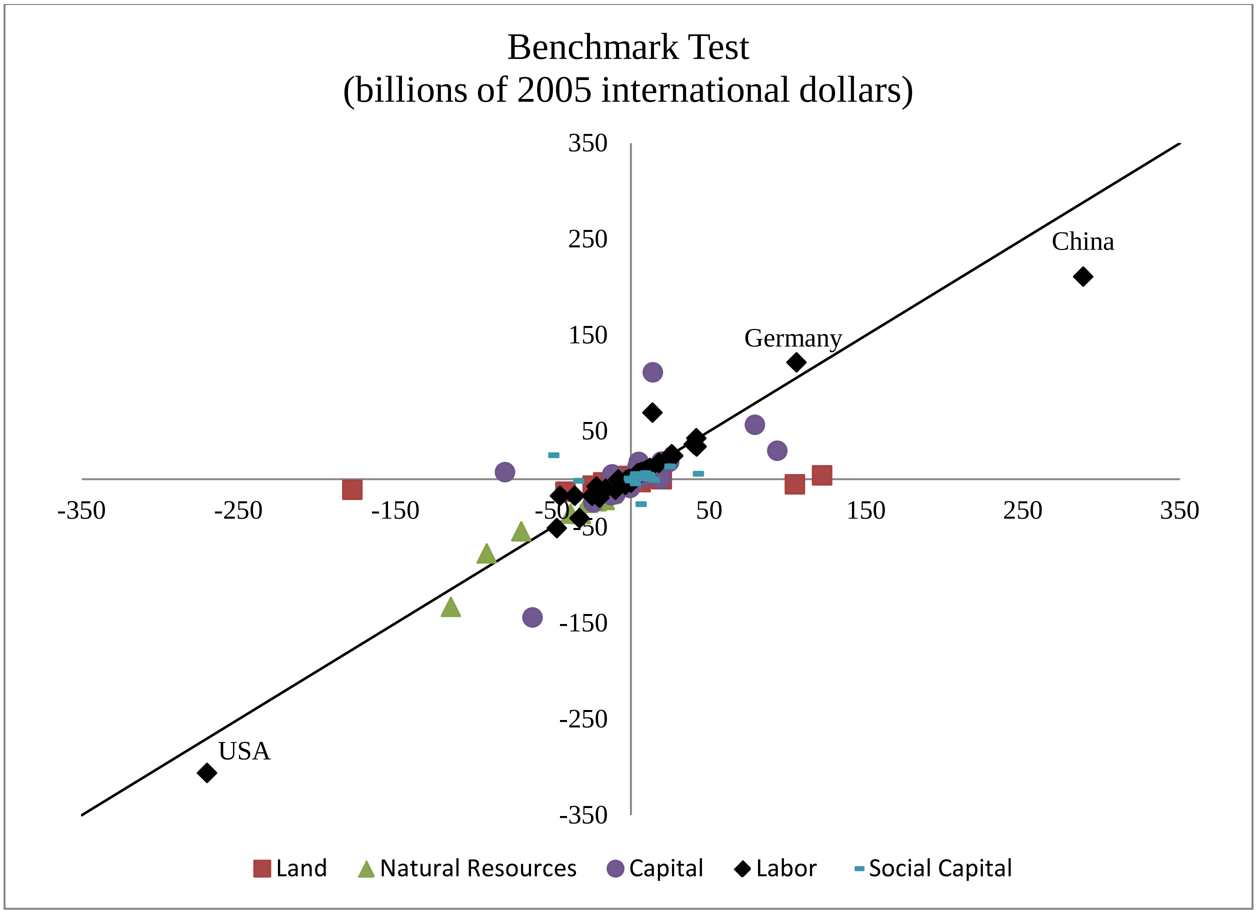


Fig. 4. Predicted factor trade is on the horizontal axis, and measured factor trade is on the vertical axis. There are 168 correct predictions.

A simple computation is useful. America's absorption share is 24.6%. Its labor endowment is $7.1 trillion, and the world endowment of labor is $26.5 trillion. So the conventional Vanek prediction is 7.1 - 0.246*26.5 = 0.581, and the United States is predicted to *export* $581 billion of labor services. However, if one adjusts for differences in technology by imposing the American technology matrix on each country's actual production, the world endowment of labor is $30 trillion. Now the benchmark prediction is 7.1 - 0.246*30 = -0.280, near the measured labor content of American imports.

One would be remiss not to mention that the paradigm's demand-side assumptions hold in these data. In particular, every one of these postulates seems valid statistically: (1) all goods and services are traded; (2) there is no home bias in consumption; (3) trade costs are negligible; (4) intermediate inputs do not matter; and (5) considerations of imperfect competition or intra-industry trade are not important. The second empirical conclusion is: *if one follows Vanek's strict logic and focuses on factor services, not quantities, and if every country has the same technology, then the paradigm predicts the direction and volume of factor trade accurately. Also, no demand-side correction is necessary.*

C. The Factor Conversion Test

Figure 5 shows the test based upon the factor conversion matrices. Again, only the predictions, not the measures, have changed. There are 159 correct predictions. Now each country's endowment is converted into America efficiency units. Again, this conversion has no effect on any country's real GDP; hence it has no effect on the absorption shares used in equation (2). Figure 5 looks like Figure 4; this similarity is reassuring because the factor conversion matrices—the American factor content of foreign Rybczynski effects or the foreign Stolper-Samuelson effects of exogenous changes in American factor prices—convert foreign factor services into American efficiency units appropriately. Factor conversion matrices do not depend upon any country's particular output vector. This fact is important because the exact composition of output is not determined when there are more goods than factors. The third empirical conclusion is: *if one follows Vanek's strict logic and focuses on factor services, not quantities, it is still necessary to account properly for technology differences if one wants to explain the volume of factor trade. Again, no demand-side adjustments are necessary.*

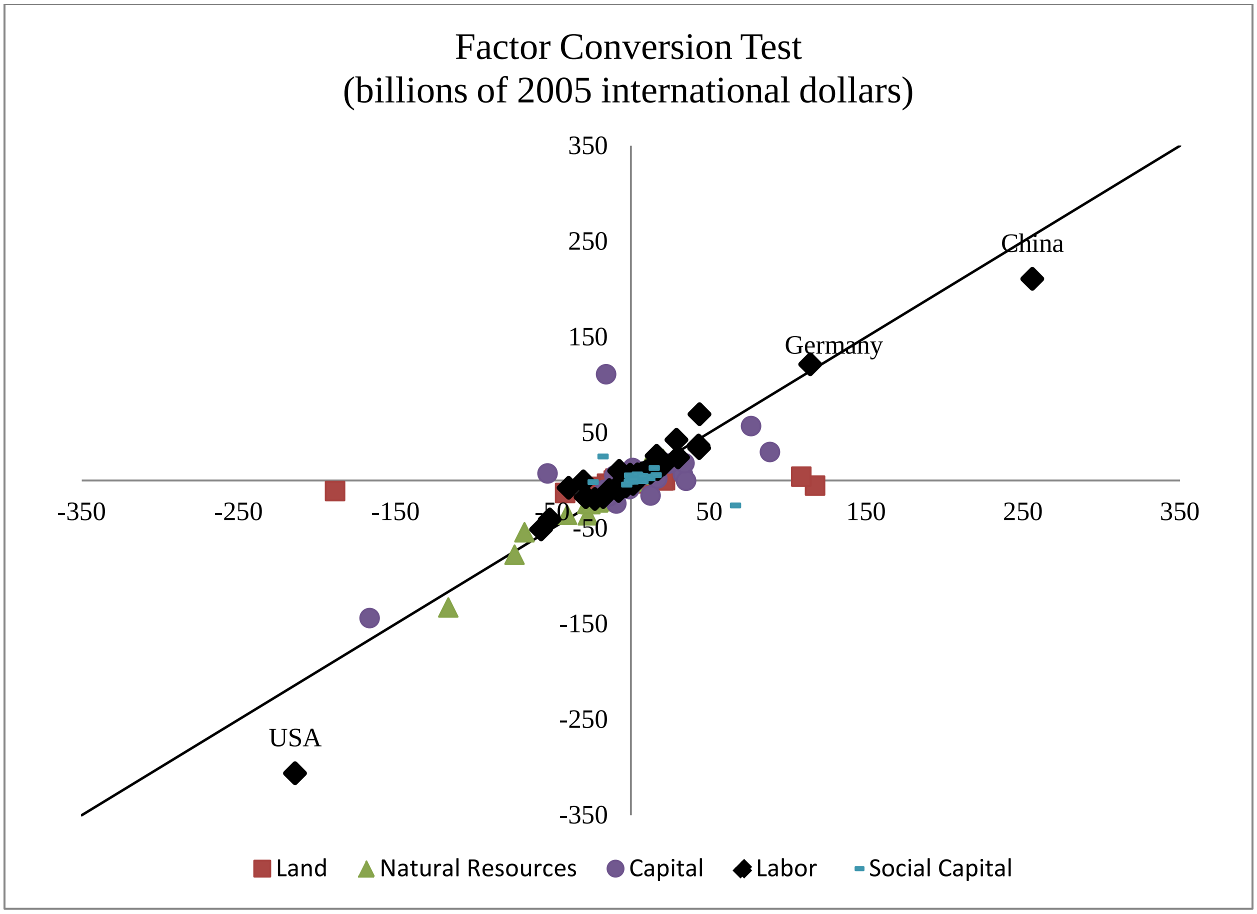


Fig. 5. Predicted factor trade is on the horizontal axis, and measured factor trade is on the vertical axis. There are 159 correct predictions.

D. Missing Trade Regressions

Table 4 gives the regressions based on (4). Since the first $\bar{R}^2$ is essentially zero, the conventional model explains almost none of the variability in the data, a result that reprises Trefler's (1995) missing trade. On the other hand, the benchmark model explains about two-thirds of the variability in the data. The Wald test based on the null hypothesis of no missing trade has a *p*-value of 0.06; since the estimate of the slope coefficient is 0.72, there is some evidence of missing trade, but one cannot reject the null for a test of conventional size. Finally, the third regression fits the data slightly worse than the second one; its $\bar{R}^2$ has declined slightly, and the two coefficients are estimated less precisely. The effect is to make the *p*-value of the Wald test 0.11. There is no evidence of statistically significant missing trade, and there is no need to make any demand-side corrections. Since the second and third regressions have such similar results, one can conclude that the factor conversion matrices are accurate summaries of differences in technology. It is not necessary to assume that all countries have America's technology. Instead, one can make a conversion based upon observable endowments (not output vectors) and technologies that transforms local factors into common efficiency units.

Table 4: Volume of Predicted Factor Trade Regressions

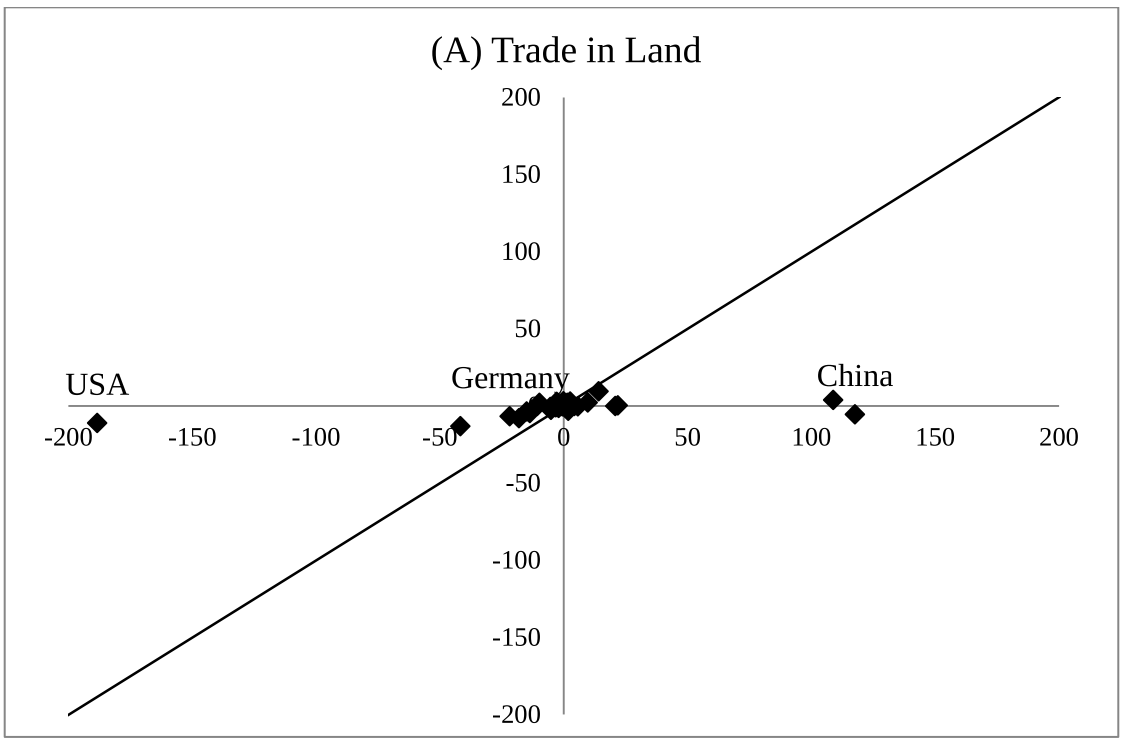
Dependent variable: measured factor content of trade using America's technology

Regressor	(1)	(2)	(3)
Conventional prediction	0.00		
	(0.10)		
Benchmark prediction		0.72	
		(0.13)	
Factor-conversion prediction			0.72
			(0.15)
Intercept	-1022	-289	-286
	(2583)	(1441)	(1498)
$\bar{R}^2$	0.00	0.66	0.63
F-statistic	53.20	2.90	2.24
p-value	0.00	0.06	0.11

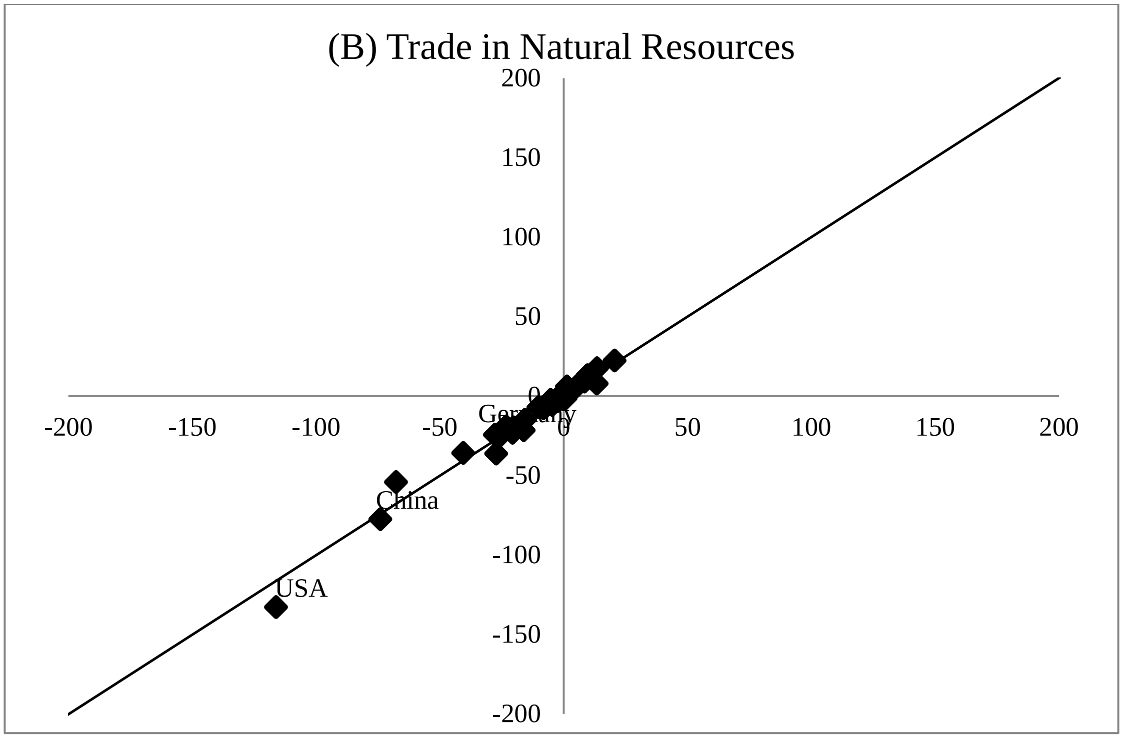
Notes: Robust standard errors are in parentheses. Each regression has 195 observations. The null hypothesis for the Wald test is that the slope is unity and the intercept is zero.

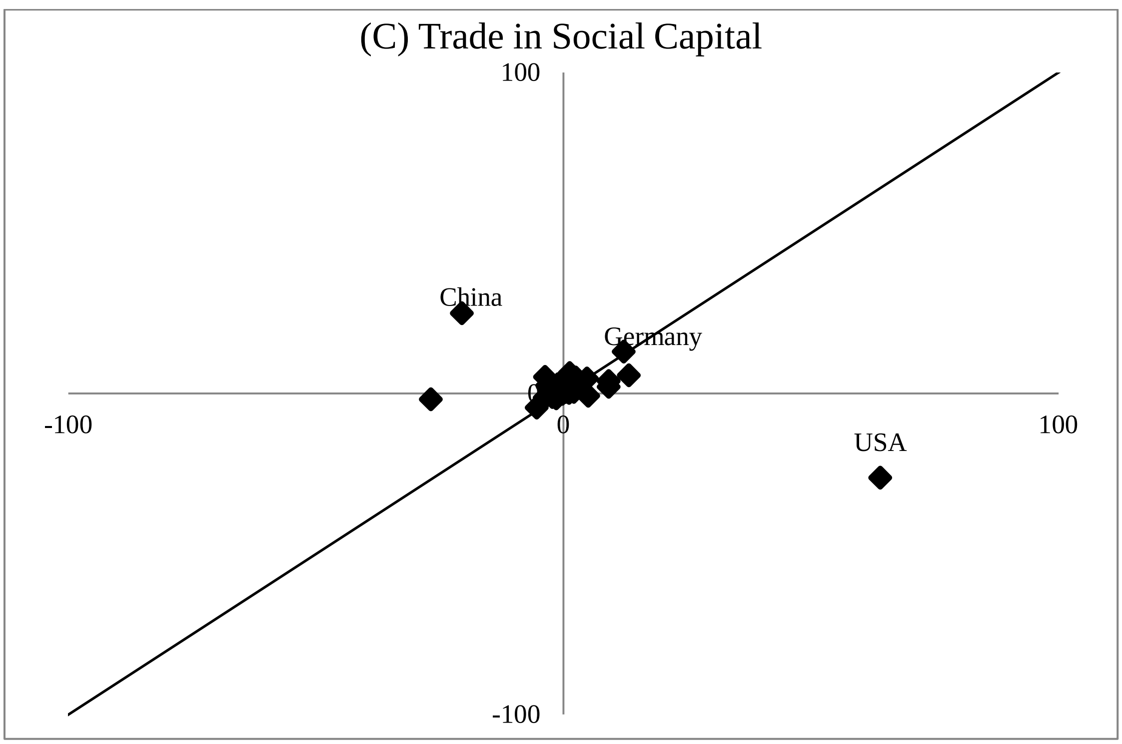
E. A Closer Look at the Factor Conversion Test

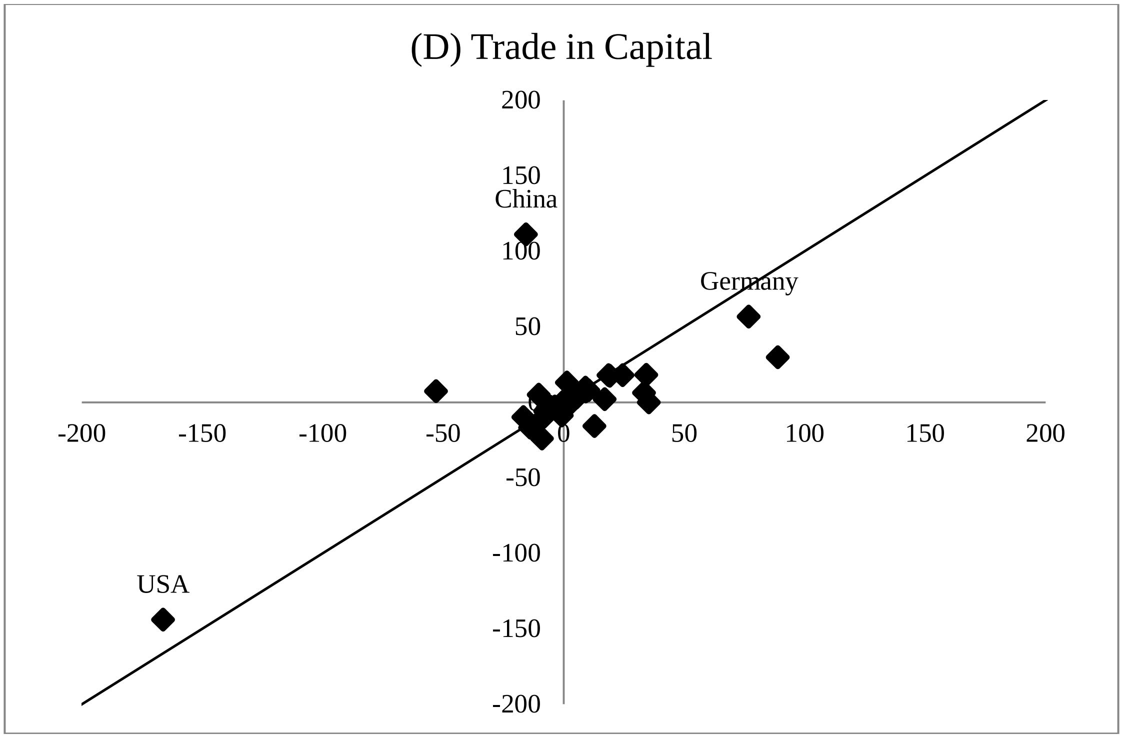
Each panel of Figure 6 shows one of the five factors from Figure 5. Panel 6.A gives the predictions and measures for land. The paradigm fails miserably for this factor, even when factors are adjusted into efficiency units. Perhaps ubiquitous agricultural subsidies have diverted world trade or affected local land rents.[12] The contrast with factor trade in natural resources could not be more apt. Panel 6.B shows that factor. The stark difference between these panels suggests that attributing gross operating surplus in each sector to rents on land or natural resources is not a likely source of measurement error. Please recall that every sector in the economy uses land and natural resources indirectly, even though by construction only agriculture uses land directly and only mining uses natural resources directly.



[12] See Anderson, Martin, and Van der Mensbrugghe (2006) for an account of the impact of agriculture policies.


(B) Trade in Natural Resources
200
150
100
50
0
-50
-100
-150
-200
-200
-150
-100
-50
0
50
100
150
200
Germany
China
USA


(C) Trade in Social Capital
100
0
-100
-100
0
100
China
Germany
USA



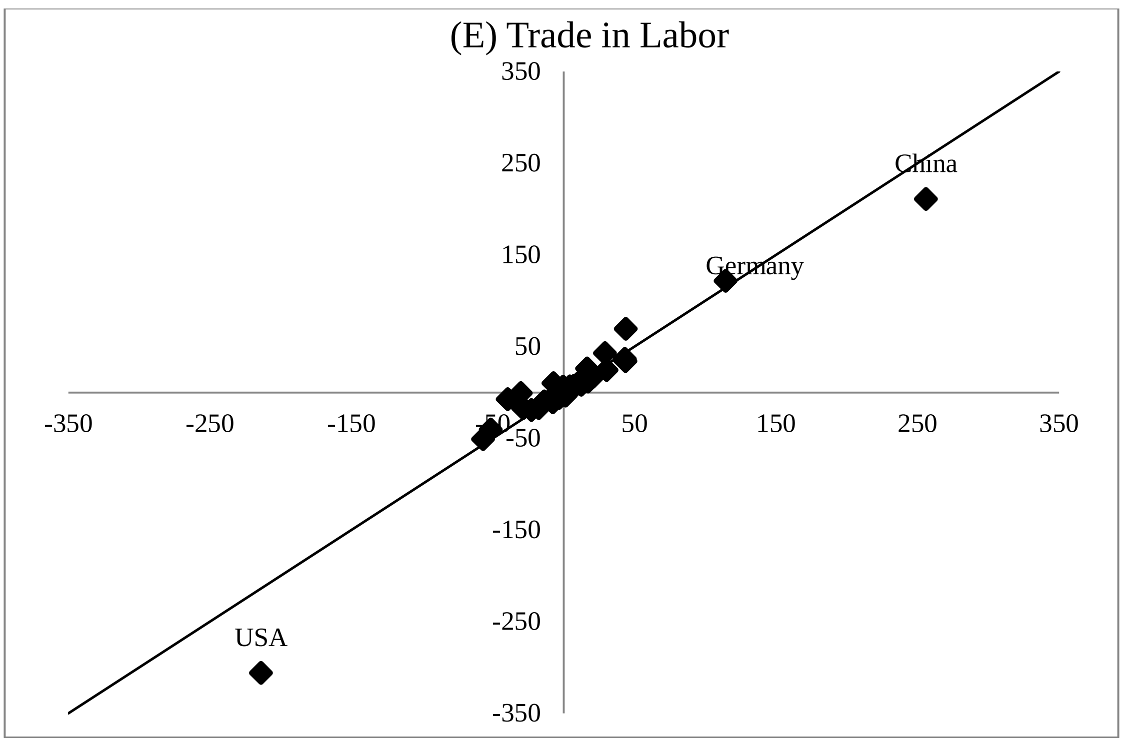


Fig. 6. Predicted factor trade is on the horizontal axis, and measured factor trade is on the vertical axis. The units are billions of 2005 international dollars.

Panel 6.C shows trade in social capital. These predictions and measures all cluster around zero, and they introduce noise into both the sign test and the regressions based on (4). This result is not surprising because local patterns of indirect taxation distort unit input requirements and factor prices in idiosyncratic ways. Panel 6.D shows that the United States is the world's largest importer of capital. *This fact is not a paradox.* The American trade deficit in 2005 was $621 billion. In spite of a large endowment of capital, it was predicted to import its services. In fact, these imports corresponded to about one quarter of the trade deficit.

Panel 6.E shows trade in labor. The two biggest exporters of labor services are China and Germany. One can now see the importance of measuring factor services. Even very careful studies of factor content like Trefler and Zhu (2010) seek a physically homogeneous quality-adjusted measure of labor. These analyses necessarily combine labor from Germany with labor from China, in spite of large differences in human capital.[13] China has about 800 million workers whose average wage is about $2800, while Germany has 41 million workers whose average wage is about $32000. Since these wages differ by an order of magnitude, there is already a significant adjustment for differences in quality. The conventional test shows that this adjustment alone is not enough to explain the volume of factor trade; one must convert factors into efficiency units. Panel 6.E shows that the paradigm explains almost all factor trade in labor.

Our provocative title was intended to focus attention on the United States as a country with high wages. Still, there is nothing special about following the literature and using the United States as the reference country. Korea is the most representative economy in the world, and the analysis with that country as reference obtains similar results. Indeed, using any

[13] According to the Barro and Lee Educational Attainment Data set (www.barrolee.com), in 2005 the average number of years of education per person as 7.6 in China and 11.8 in Germany.

reference country for the model's predictions is valid, as long as one measures the factor content of trade according to its technology.

Based in theory, the factor conversion matrices adjust well for differences in technology. Let us now look back. Tables 2 and 3 gave simplified factor conversion matrices for an artificially coarse aggregation. Tables 5 and 6 present the *actual* conversion matrices for Canada and China; they are computed from the full-blown technology matrices. Again, each column gives the factor content in the United States of the Rybczynski effects in China or Canada (assuming that output prices and thus factor prices are fixed). The entries of a column add to unity because an extra dollar's worth of any local factor creates an extra dollar of world GDP. Each row gives the Stolper-Samuelson effects in Canada or China of exogenous changes in American factor prices.

Almost all the off-diagonal elements in Table 5 are small, indicating that the United States and Canada have a similar technology. This matrix is closer to the identity matrix than the simplified version. Hence Canada's endowment in American efficiency units is not changed much. The coarser level of aggregation in the simplified case gave a misleading impression of technological differences. The technology matrix with factor uses in 26 sectors is much richer in detail, and the concomitant factor conversion matrix is correspondingly more accurate.

Table 5: Actual Factor Conversion Matrix for Canada

	Land in Canada	Natural Resources in Canada	Capital in Canada	Labor in Canada	Social Capital in Canada
Land in the US	1.64	0.00	-0.03	0.00	0.10
Natural Resources in the US	-0.01	0.62	0.04	-0.04	-0.07
Capital in the US	-0.37	0.11	0.46	0.20	1.97
Labor in the US	0.02	0.19	0.43	0.81	-1.37
Social Capital in the US	-0.27	0.07	0.10	0.03	0.37

Since these technology matrices are measured as cost shares, each factor conversion matrix is a linear mapping from a space of distributions into itself. Figure 7 shows Canada's endowment and also its endowment converted to American efficiency units. These bar graphs are both distributions, when normalized by Canada's GDP. Because the two distributions are so close, this figure illustrates the similarity of the Canadian and American technologies.

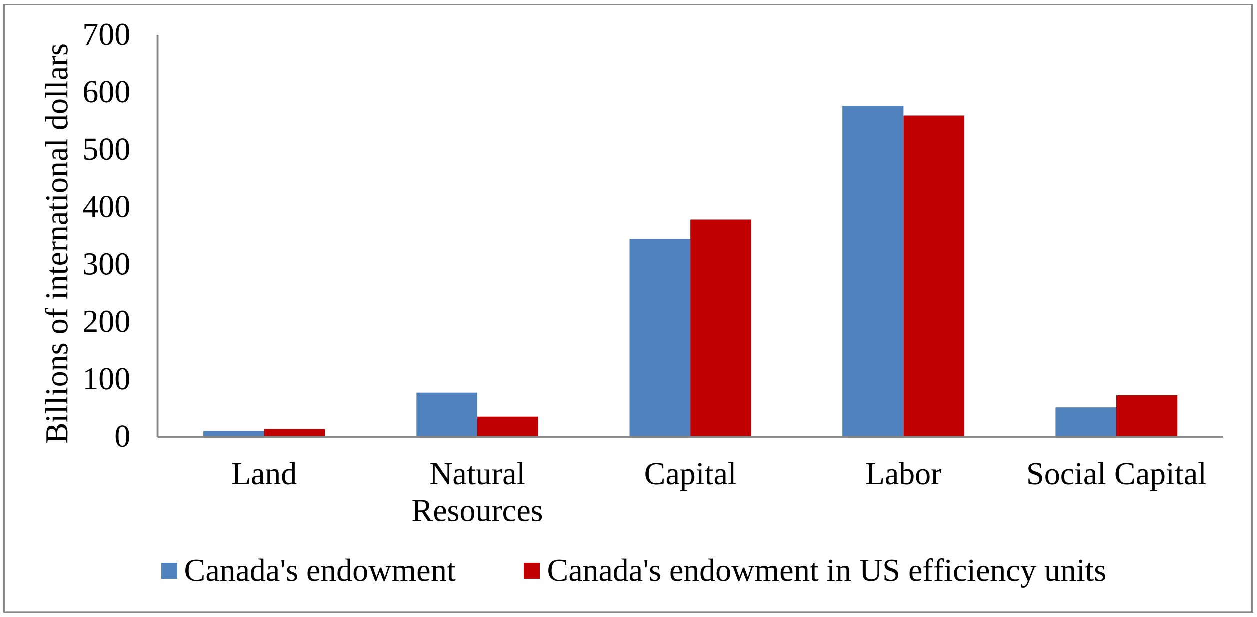


Fig. 7. The factor conversion matrix changes Canada's endowment into American efficiency units.

Now consider the factor conversion matrix for China in Table 6. It is quite different from the identity, indicating that China and the United States have different technologies, even when one accounts for unequal factor prices.[14] If one focused only on the leading diagonal element, one would conclude that Chinese land is 6.66 times more productive than America land. But that conclusion is misleading in an important way. Fix factor prices, and consider the first *column* of Table 6. The large negative element shows that an increase of one unit of Chinese land corresponds to a *decrease* of 7.79 units of American labor; in other words, China uses land in

[14] Marshall (2012) examines how sector-specific technological differences help explain the difference between factor prices in developed and developing countries.

sectors that have low labor cost shares in the United States. Now fix endowments, and consider the fourth *row* of Table 6. It shows that American labor is a strong enemy of the owners of land in China. An exogenous increase in the American wage will change world prices in such a way that the best estimates of the Stolper-Samuelson effects in China indicate higher wages at the expense of land rents.

Table 6: Actual Factor Conversion Matrix for China

	Land in China	Natural Resources in China	Capital in China	Labor in China	Social Capital in China
Land in the US	6.66	0.08	0.01	-0.02	-0.18
Natural Resources in the US	0.69	1.52	0.00	-0.04	-0.23
Capital in the US	1.50	-0.08	0.77	-0.04	0.04
Labor in the US	-7.79	-0.52	0.13	1.16	1.05
Social Capital in the US	-0.05	0.00	0.09	-0.07	0.33

Figure 8 shows the overall effects of the factor conversion matrix on China's endowment. Land and labor in China are more productive than in America, and natural resources and capital are less productive. Because the data have already been adjusted for factor price differences, these results are not so surprising. The use of the Moore-Penrose inverse and the full technology matrix give sharper factor productivity comparisons than the simplified case in Table 3.

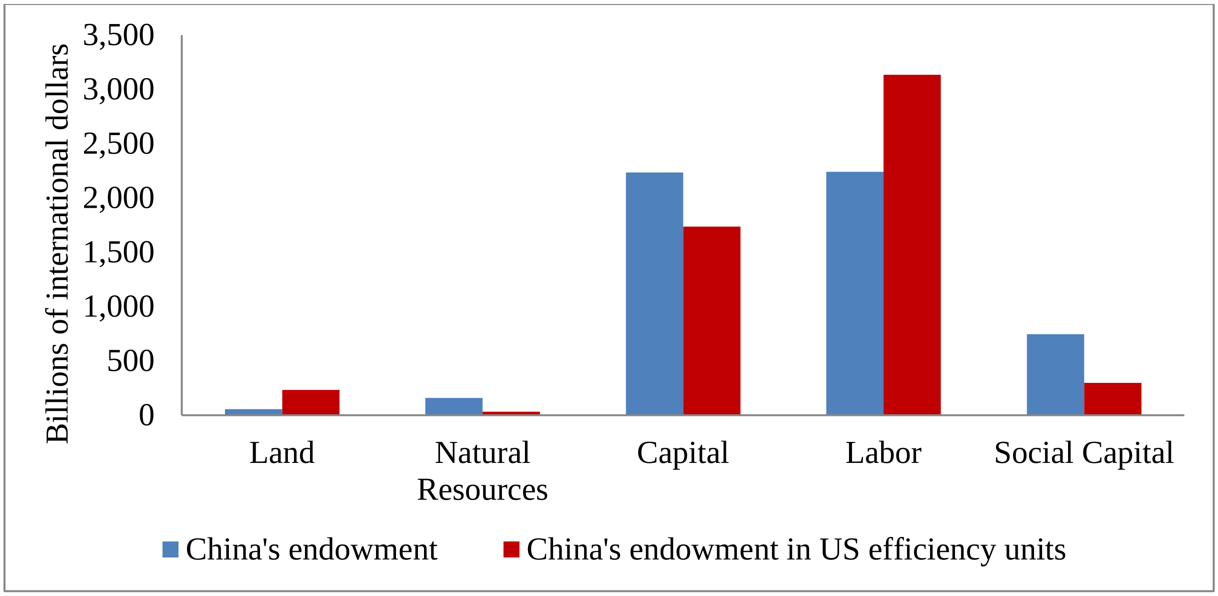


Fig. 8. The factor conversion matrix changes China's endowment into American efficiency units.

It is possible to have too fine a level of disaggregation in practice. Many countries record no economic activity in some sectors. If a row or column of an input-output matrix consists of zeros, then the factor conversion matrix will record attenuated factor content when the reference country's zeros occur in different sectors from those for its trading partner. That consideration led us to use the finest level of aggregation in which every country had positive outputs and inputs in each sector. It also explains why the results for the factor conversion test are almost as accurate as the benchmark, where we imposed that every country had America's technology.

F. The *Local* Factor Content of Trade in Labor

So far the factor content of net trade has always been measured with America's technology matrix. Consider now the factor content of trade *according to each country's local technology* $\Theta_c(x_c - m_c)$. This vector shows how trade saves local resources. We can also evaluate factor trade relative to local endowments. An elegant aspect of measuring technology as costs shares by industry is that the sum of factor trade equals the country's trade balance. This simple and strong link between the standard macroeconomic measure of the trade balance and factor trade is obscured by measures of factor endowments in physical units.

Is there truth in the widespread concern that a vast reservoir of cheap foreign labor is displacing American workers? Table 7 shows global factor trade in labor. Again, consistent measures lend an advantage. These are not anthropomorphic Chinese workers and their German counterparts; they are instead local factor services measured in international dollars per year and can thus be aggregated across countries easily. The United States is the world's largest importer of labor services, accounting for more than half of total labor imports. The six largest exporters of labor services are the rest of the world,[15] China, Germany, Japan, and Brazil. India, Indonesia, South Africa, Mexico, and Thailand are insignificant exporters of local labor services, if they export them at all.

These local measures of factor content have two salient features. The first is that trade in the services of labor is not an alarmingly large share of any local endowment. Net labor imports into the United States represent only four percent of its endowment. Imports substitute for the labor of about six million workers; the decline in the labor force participation rate in the last five years has consisted of about seven million workers. The second feature is that *factor trade is inextricably linked to the trade balance*. The correlation between the third and fourth columns of Table 7 is 0.87. Countries that import a substantial share of labor services, such as Greece and Romania, do so because they run trade deficits, not because they face an abundance of cheap foreign labor. A trade deficit can even push a country towards importing all factors, as is the

[15] The rest of the world accounts for 17% of world GDP; it is the second biggest "country" after the United States.

case for the United States. It should come as no surprise that the United States, with a budget deficit to GDP ratio of 6%, is the world's largest importer of labor services.

Here's the bottom line. Any scholar who wants to explain factor trade must recognize that trade—both in goods and the underlying factors that produce them--reflects both endowment differences and macroeconomic imbalances. Hence one has to measure factor trade in a way that is consistent with balance of payments accounts. Appendix A shows that measuring factor trade in physical units does not make sense if it violates simple macroeconomic identities.

Table 7. Global trade in the services of labor ($ billions)

Country	Net labor exports	Labor endowment	First column divided by second column	Trade balance (% of GDP)
Rest of World	137,708	4,875,754	3%	2%
China	105,794	2,240,490	5%	5%
Germany	96,939	1,303,840	7%	7%
Japan	50,832	2,054,536	2%	1%
Brazil	28,829	680,018	4%	4%
Netherlands	24,530	290,813	8%	9%
Taiwan	22,225	326,006	7%	6%
Sweden	16,326	171,079	10%	9%
Korea	14,636	503,370	3%	1%
Thailand	9,400	167,610	6%	6%
Belgium	8,177	174,617	5%	5%
Canada	7,756	576,119	1%	4%
Indonesia	5,459	224,240	2%	5%
Ireland	3,654	66,514	5%	13%
Austria	3,478	140,683	2%	2%
Denmark	2,981	101,008	3%	6%
Finland	2,976	81,412	4%	4%
Czech Republic	2,696	92,642	3%	3%
Luxembourg	1,763	15,436	11%	17%
New Zealand	423	38,815	1%	3%
Slovenia	-974	24,567	-4%	-4%
Chile	-1,038	73,888	-1%	2%
Estonia	-1,308	10,208	-13%	-12%
South Africa	-1,615	136,245	-1%	1%
Slovak Rep.	-1,731	33,874	-5%	-5%
Italy	-1,979	686,611	0%	-1%
Norway	-2,279	94,520	-2%	18%
Hungary	-2,639	82,725	-3%	-4%
India	-7,072	583,242	-1%	-2%
Poland	-7,650	192,431	-4%	-1%
Portugal	-12,254	111,617	-11%	-13%
Romania	-13,035	84,402	-15%	-11%
Mexico	-13,613	433,973	-3%	-2%
France	-15,519	1,003,300	-2%	-1%
Australia	-16,448	315,564	-5%	-3%
Greece	-18,464	101,262	-18%	-14%
Turkey	-20,843	210,101	-10%	-6%
United Kingdom	-45,936	1,099,409	-4%	-4%
Spain	-56,027	573,577	-10%	-9%
United States	-306,156	7,116,744	-4%	-5%

7. Conclusion

The Heckscher-Ohlin-Vanek paradigm offers an elegant explanation for the pattern of world trade. Earlier studies have shown conclusively that countries have different factor prices and also different unit input requirements by sector. The immediate conclusion is that it is no longer appropriate to measure factor content in physically homogeneous units, even when one adjusts for differences in efficiency units. *One must measure the value of factor services, and one must predict accordingly*. Indeed, Vanek's predictions were never delineated in quantities but always in values; his empirical work was as cogent as his theory. In sum, once the profession knew that factor prices mattered, the literature never tested the theory properly, and its rejections of the conventional test were spurious.

Modern researchers have a huge advantage: consistent input-output matrices for a wide sample of countries. Every prediction in this paper satisfies basic economic accounting identities; for example, whenever the factor content of trade is predicted or measured, the sum across factors for any country is identically equal to its balance of payments. In fact, this work has been an extended exercise in careful measurement and prediction. The technology matrices are costs shares by sector, a pure measure that has no units. The factor conversion matrices that adjust for differences in technology are also pure measures because they are based on technology matrices and merely shift factor shares of GDP between countries.

The validity of the Heckscher-Ohlin-Vanek extends beyond the simple textbook examples, where every country is assumed to have identical technology and factor prices. This research has highlighted several distinctive patterns in global factor trade. Factor trade in natural resources is perfectly in line world endowments, while land shows substantial missing trade. A few large players dominate trade in labor services. The direction and magnitude of global factor trade can be predicted using a few simple techniques and consistent input-output data.

The measure of factor trade in labor does not distinguish between skilled and unskilled labor, even though it does aggregate all types of labor in an economically meaningful way. As increasingly detailed data on factor usage by sector become available, these techniques can be readily extended. Still, even the most detailed breakdown of factor must be measured in values and must be consistent with national income accounts. We are optimistic that future research will confirm the importance of focusing on trade in factor services—not quantities—in a world where wages or rents can vary by an order of magnitude.

The factor conversion matrices developed here are novel and may have wider application in empirical trade. They are the best linear mapping between factor uses in a reference country and those in a local country. Such a matrix has two interpretations: (1) the factor content in the reference country of the local country's Rybczynski effects; or (2) the local Stolper-Samuelson effects of exogenous changes in the reference country's factor prices that are passed through to world prices. Measuring and predicting factor trade appropriately, using factor conversion matrices to account for differences in technology, and without invoking any demand-side adjustments, we have found broad empirical support for the Heckscher-Ohlin-Vanek paradigm.

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Appendix A: Why Factor Content Predictions in Physical Units Do Not Make Sense

We give the simplest example of why Trefler and Zhu's (2010) theorems are logically correct but economically misleading. Consider a Ricardian model with two goods. There are no intermediate inputs for simplicity. The technology matrix (of direct and indirect factor requirements) in physical units for Country 1 is

$$A_1 = [1 \quad 2]$$

and that for Country 2 is

$$A_2 = [2 \quad 1].$$

The home country has a comparative and absolute advantage in good 1. Each country is endowed with two physical units of labor, and agents have this utility function:

$$u(x_1, x_2) = \min\{x_1, x_2\}.$$

Since preferences are identical and homothetic, Trefler and Zhu's consumption similarity assumption is satisfied trivially. Since the goods are perfect complements, there are multiple equilibria parameterized by the terms of trade.

We use the normalization $p_1 + p_2 = 1$. Let the terms of trade be $\alpha = p_1$, and consider any $1/3 < \alpha < 2/3$. Country 1 specializes in good 1, and Country 2 specializes in good 2. The world supply of each good is 2, the wage in Country 1 is $w_1 = \alpha$, and that in Country 2 is $w_2 = 1 - \alpha$. Hence, Country 1's share of world GDP is $s_1 = \alpha$, and Country 2's share is $s_2 = 1 - \alpha$. Country 1's production vector is $y_1 = [2 \quad 0]^T$, and its equilibrium allocation is $a_1 = [2\alpha \quad 2\alpha]^T$. It exports $2 - 2\alpha$ of good 1 and imports 2α of good 2. The factor content of trade--measured according to local production techniques--is $2-4\alpha$, just as Deardorff (1982) described. Trefler and Zhu's predicted factor content of trade for Country 1 is:

$$v_1 - s_1 v = 2 - 4\alpha.$$

This quantity is exactly the measured factor content of trade, but it is different from zero if $\alpha \neq 1/2$. Country 1 runs a trade deficit if $\alpha > 1/2$.

What's wrong? How does Country 1 run a trade deficit, measured in units of labor, if the terms of trade favor it? There is no borrowing or lending in this economy, and both countries must run balanced trade. The key insight is that *the factor content of trade is the value of labor services exported!* The value of Country 1's exports is $w_1(2-2\alpha) = \alpha(2-2\alpha)$, and the value of its imports is $w_2 2\alpha = (1-\alpha)2\alpha$. *So factor trade in labor services is balanced.*

In a deeper sense, Country 1 and Country 2 labor are just not comparable. They may be physically homogenous units, but in no way are they equally productive by sector. The econometrician would measure physical output per worker as one unit of good 1 in Country 1 and also one unit of good 2 in Country 2, but local real wages depend upon world prices. In no sense is the shadow value of an additional unit of labor in Country 1 identical to that in Country 2 if the price of good 1 is different from that of good 2.

Nothing has to do with intermediate inputs. We could just as easily have defined good 1 as the consumption good, and good 2 as an intermediate input. Then the utility function would be a production function dictating that one unit of intermediate input is needed to make the good for final demand. Everything would go through as before. Although we are calling the endowment in each country "physically homogeneous labor", we could just as easily call the resource in Country 1 "labor" and the resource in Country 2 "capital." Trefler and Zhu's prediction would be that Country 1's factor content of trade would be $2 - 2\alpha$ exports of "labor" and 2α imports of "capital". These predictions would again be technically correct and again be economic nonsense, since there is no guarantee that the international wage-rentals ratio is unity.

What's the remedy? Vanek actually defined the predicted factor content of trade in values. In this example, we have:

$$v_1 - s_1 v = 2\alpha - \alpha\big(2\alpha + 2(1-\alpha)\big) = 0$$

for every possible terms of trade, exactly as it should be.

Indeed, we have shown that Deardorff's (1982, p. 687) definition of the "actual factor content of trade" is either misleading or vacuous. It is misleading if he intended empiricists to add units of physically homogeneous factors whose shadow values differ, depending upon their location. It is vacuous if he wants to keep track of factors by location that cannot be aggregated. Let $\alpha = 1/2$, and consider Country 1's factor content of trade. It is misleading to say that it is zero, because Country 1 achieves a strictly higher level of utility under trade than under autarky, violating Deardorff's Assumption 11 (1982, p.686). It is tautological if one says, "You can't add labor across countries." Under this interpretation, the factor content of trade is exports of one unit of Country 1 labor, imports of one unit of Country 2 labor, and never the twain shall meet. This is certainly not the interpretation implemented in Trefler and Zhu, and it is not an approach followed by any empiricist studying the implications of Heckscher-Ohlin-Vanek theory.

Appendix B: An Introduction into the General Theory of Factor Conversion Matrices

There are *n* goods and *f* factors. The full employment condition is:

$$v_c = \Theta_c y_c.$$

The set of all output vectors that is consistent with full employment is:

$$y_c = \Theta_c^+ v_c + (I - \Theta_c^+ \Theta_c)z, \tag{A1}$$

where Θ_c^+ is the Moore-Penrose pseudo-inverse of the technology matrix and $z \in \mathbb{R}^n$ is arbitrary. If there are more sectors than factors of production or if the technology matrix does not have full rank, then the second term on the right in (A1) is different from zero, but it captures all the flats on the production possibility frontier. Any endowment vector in the data must lie in the column space of the technology matrix; hence the full employment condition is a consistent system of linear equations in empirical applications.

Consider the goods pricing equation:

$$\hat{p} = \Theta_c^T \widehat{w_c}.$$

This equation is quite general; it is true for any technology and any small changes in factor prices. This system of equations follows from the envelope theorem and the assumption that producers choose inputs to minimize unit costs.

Now consider an exogenous change in output prices $\hat{p}$ *in the row space* of Θ_c. The *complete set* of factor price changes that are consistent with these goods price changes is:

$$\widehat{w_c} = (\Theta_c^T)^+ \hat{p} + (I - (\Theta_c^T)^+ \Theta_c^T)z, \tag{A2}$$

where $z \in \mathbb{R}^f$ is arbitrary. If $\hat{p}$ is *not in the row space* of the technology matrix, then the system of equations relating factor price changes and good price changes is inconsistent. Trade theory teaches us that almost every industry in the economy would shut down; both casual and serious empirical observations belie this otherwise elegant theoretical prediction. What are the best guesses for price changes that would keep all extant industries competitive?

Consider these price changes:

$$\hat{q} = \Theta_c^T (\Theta_c^T)^+ \hat{p}.$$

They are the goods price changes *in the row space* of the technology matrix that are closest to *any arbitrary price changes* $\hat{p} \in \mathbb{R}^n$. Indeed, this is the least squares projection of $\hat{p}$ onto the column space of Θ_c^{T} (the row space of Θ_c). Since these goods price changes are in the correct row space, we may solve again for *all* the corresponding factor price changes:

$$\widehat{w_c} = (\Theta_c^T)^+ \hat{q} + (I - (\Theta_c^T)^+ \Theta_c^T) z = (\Theta_c^T)^+ \hat{p} + (I - (\Theta_c^T)^+ \Theta_c^T) z,$$

where $z \in \mathbb{R}^f$ is arbitrary. We have used the property of any generalized inverse that $(\Theta_c^T)^+ = (\Theta_c^T)^+ \Theta_c^T (\Theta_c^T)^+$. Thus $(\Theta_c^T)^+$ *is the best estimate of the relationship between arbitrary goods price changes and local factor price changes.* This relationship is exact when the goods pricing equations are consistent. It is unique when the rank of Θ is at least *f*, and it is the best linear estimator when the goods pricing equations are inconsistent. In the latter case, it is the least squares estimates of arbitrary goods price changes onto the rows of the technology matrix.

If the number of goods is greater than the number of factors and the technology matrix has sufficient rank, then Stolper-Samuelson effects are unique. This means that the second term on the right side of (A2) is 0. If the reference country is large—typically it stands in for the rest of the world—then exogenous changes in factor prices in the reference country cause world price changes $\hat{p} = \Theta_0 \widehat{w_0}$. These changes may or may not be in the row space of the technology matrix of country *c*, but the factor conversion matrix always gives the best estimate of the Stolper-

Samuelson effects in that country. These are the estimates that allow all extant local industries to stay competitive when trade costs are as low as possible.

Appendix C: Aggregating from Thirty-Seven to Twenty-Six Sectors

We aggregated the 37 OECD sectors into 26 to eliminate local industries reporting no economic activity. This is the finest level of aggregation that has all countries producing all goods.

OECD input-output sector	Aggregation
C01T05 Agriculture, hunting, forestry and fishing	1
C10T14 Mining and quarrying	2
C15T16 Food products, beverages and tobacco	3
C17T19 Textiles, textile products, leather and footwear	4
C20 Wood and products of wood and cork	5
C21T22 Pulp, paper, paper products, printing and publishing	6
C23 Coke, refined petroleum products and nuclear fuel	6
C24 Chemicals and chemical products	7
C25 Rubber and plastics products	7
C26 Other non-metallic natural products	8
C27 Basic metals	9
C28 Fabricated metal products except machinery and equipment	10
C29 Machinery and equipment n.e.c	11
C30 Office, accounting and computing machinery	11
C31 Electrical machinery and apparatus n.e.c	11
C32 Radio, television and communication equipment	11
C33 Medical, precision and optical instruments	11
C34 Motor vehicles, trailers and semi-trailers	12
C35 Other transport equipment	13
C36T37 Manufacturing n.e.c; recycling	13
C40T41 Electricity, gas and water supply	14
C45 Construction	15
C50T52 Wholesale and retail trade; repairs	16
C55 Hotels and restaurants	17
C60T63 Transport and storage	18
C64 Post and telecommunications	19
C65T67 Finance and insurance	20

OECD input-output sector	Aggregation
C70 Real estate activities	21
C71 Renting of machinery and equipment	22
C72 Computer and related activities	22
C73 Research and development	22
C74 Other Business Activities	22
C75 Public admin. and defense; compulsory social security	23
C80 Education	24
C85 Health and social work	25
C90T93 Other community, social and personal services	26
C95 Private households with employed persons	26