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Trade in ideas
Patenting and productivity in the OECD

Jonathan Eaton[a,b], Samuel Kortum[a,b]

[a]Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215, USA
[b]NBER, 1050 Massachusetts Avenue, Cambridge, MA 02138, USA

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Abstract

We develop a model of growth and technology diffusion which we fit to aggregate data from OECD countries. Our model implies that each country will eventually grow at the same rate, with its relative productivity determined by its ability to adopt new inventions. Hence productivity levels rather than growth rates better reflect a country's ability to innovate or to adopt new technology. We estimate the model to explain international patterns of productivity and patenting. We find that more than 50% of the growth in each country in our sample derives from innovation in the United States, Germany, and Japan.

Key words: Technology; International diffusion; Innovation; Patent; Productivity; Research

JEL classification: F43; O14; O31; O34; O40

1. Introduction

Growth accounting has established that technological change explains much of the increase in worker productivity in this century.[1] Where technological change originates and how it spreads across countries is less well understood. A reason is the difficulty of observing either the creation or diffusion of inventions. While we

[1]Solow (1957) is, of course, the classic reference.

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can observe inputs into the inventive process, such as R&D expenditures or R&D scientists and engineers, we have no direct measure of inventive output. Patents, however, are indirect evidence of research output, and where patent protection is sought reflects where inventors expect their ideas to be used.

We develop a model of the innovation and international diffusion of technology which we use to explain relative productivity and growth among OECD countries. Productivity growth in our model results from inventive activity in different countries. Diffusion eventually results in all countries growing at the same rate, with countries that can absorb more innovations having higher relative productivity. We use data on research scientists and engineers to learn about the location of inventive activity, and data on labor productivity to infer how well countries exploit the world's inventions. Data on international patents allow us to quantify the links between research and its ultimate beneficiaries.[2]

In order to isolate patterns of invention and technology diffusion from patent data we distinguish among various influences on the decision to patent. We relate the level of patenting by one country (the source) in another (the destination) to five factors: (1) the source's research effort; (2) the destination's market size; (3) how rigorously the destination protects intellectual property; (4) the cost of patenting in the destination, and (5) the likelihood that inventions from the source can be adopted into the destination's technologies.

We estimate the parameters of the model in order to fit international patterns of productivity and patenting. Our estimates of the impediments to diffusion account for observed differences in productivity across OECD countries. In spite of these impediments, our results imply that international trade in ideas is a major factor in world growth: every OECD country other than the United States obtains more than 50% of its productivity growth from ideas that originated abroad, and for all but the five leading research economies (the United States, Japan, Germany, France, and the United Kingdom) the figure is more than 90%. As for the source of these innovations, the United States, Japan, and Germany together drive more than half of the growth of every country in our sample.

Distance appears to inhibit the flow of ideas between countries while trade

[2]Others making use of patent data to chart the development of knowledge are Caballero and Jaffe (1993) and Kortum (1995). They do not, however, consider the international diffusion of technology. Another literature fits patterns of international patenting to a 'gravity' equation. See, for example, Slama (1981). Bosworth (1984) argues for using international patent data as an indicator of technology transfer (noting the relatively sparse data on royalty payments). He finds, in UK data, a strong association between patenting and direct foreign investment. Dosi et al. (1990) estimate trade and patent flows among OECD countries. None of these papers relates patenting and technology flows to productivity. Nor do they explicitly model the patenting decision. Putnam (1995) does model this decision. Using data on individual inventions and where they are patented, he finds that international patent rights are quite valuable.

relationships enhance it. We estimate that a country's level of education significantly facilitates its ability to adopt technology.[3]

Other studies have also quantified the importance of international technology diffusion to productivity growth. Significant examples are Coe and Helpman (1995), Benhabib and Spiegel (1994), and Parente and Prescott (1994). Closest to the analysis here is Eaton and Kortum (1994), who also use data on patenting to infer the extent of technology diffusion among the five leading research economies.[4]

Our paper proceeds as follows. In the next section we review the international patent system. Section 3 presents a model of world innovation and growth. We discuss our data, estimation procedures, and estimates in Section 4. Section 5 explores some implications of our estimates. Section 6 concludes.

2. The international patenting system

While a single patent does not protect an invention worldwide, a single invention may be patented in any number of countries.[5] A patent in a specific country provides protection (subject to enforcement) in two ways: (i) it protects the inventor from imitators producing in that country and (ii) it protects the inventor from outside imitators selling in that country.

If patent protection were costless, an inventor might as well apply for patents in all countries offering patent protection. In fact, there are two types of costs associated with obtaining a patent. First, patenting requires the publication of the specification of the invention in the local language in the country granting protection, thus divulging information to potential imitators. Second, a patentee

[3]This result supports the finding of Benhabib and Spiegel (1994) that human capital contributes to productivity by facilitating the adoption of new technology rather than by serving as a standard factor of production. Our finding on trade supports the assumption of Coe and Helpman (1995) that technology diffusion relates to trade patterns. In particular, they assume that technology diffuses as better inputs, developed and produced in the inventing country, are exported for use in production in other countries. Their specification of the contribution of R&D to growth differs substantially from ours. In particular they assume that productivity is a Cobb–Douglas function of foreign and domestic R&D stocks. A strictly positive level of each stock is essential for any output at all. In contrast, in our analysis, conditional on their adoption, ideas from any country affect productivity symmetrically.

[4]Since they also model the decision to undertake research, their model is more complicated. As a consequence its empirical implementation is more limited in geographical scope than ours. Moreover, they do not attempt to relate the rate of diffusion to other measures of economic interaction, as we do here.

[5]Penrose (1951) provides a thorough discussion of the history and operation of the international patenting system. Evenson (1984) provides an overview of international patenting data.

must pay filing fees, agents' fees, and translation fees on the order of $1000–5000 in 1992 (Helfgott, 1993).

Because patenting is costly, inventions are typically protected in only a small fraction of the countries of the world. This is the case even among large and technologically advanced countries. Over 70% of patent families (the set of patents in different countries protecting the same invention) consist of only one patent, while only 2% of patent families consist of 10 or more patents (Putnam, 1993). From aggregate data on patents it is clear that most inventions are only protected at home. For example, in 1988 US inventors applied for patent protection in the United States on 75 000 inventions, but applied for protection in France on only 15 000 and in Ireland on only 1200. Because foreign patenting is not undertaken carelessly, we believe that it may convey considerable information about patterns of technology diffusion.

In deciding on where to patent, the head of General Electric's foreign patenting operations makes the following suggestions:

> By covering the competitor's home or major manufacturing country, the applicant has a better chance of preventing the competitor from entering into markets regardless of where such markets might develop.

But he continues:

> Where only a limited investment is needed to manufacture the product, greater focus should be given to covering the major market countries rather than the manufacturing countries, since it would be easy for competitors to shift manufacture in order to avoid a patent (Helfgott, 1986, p. 3).

Here we model the market-covering justification for patenting. Hence, patent protection is sought in countries with large markets and in countries where the invention is likely to prove useful.

3. The model

We adopt the quality ladders model of innovation developed by Grossman and Helpman (1991). In any country, output Y is produced by combining intermediate inputs subject to a constant returns to scale Cobb–Douglas production function,

$$\ln(Y/J) = J^{-1}\int_0^J \ln[Z(j)X(j)]\mathrm{d}j, \tag{1}$$

where $X(j)$ is the quantity of input j. The range of inputs is fixed over time and the same across countries.[6] Output is homogeneous and tradable across countries, while inputs are nontraded.[7] We choose units so that to produce any input at rate x requires local labor services at rate x.[8]

Output expands over time as the quality of inputs (Z) improves. To keep track of this process, we define an aggregate index of technology in country n as:

$$\ln A = J^{-1}\int_0^J \ln Z(j)\mathrm{d}j, \tag{2}$$

which is output per worker when labor is allocated efficiently across sectors.[9]

3.1. Inventions

The quality of inputs rises as a result of inventions. An invention, if adopted, improves the quality of a specific input by a percentage amount, the step size of the invention. We assume that the step size of an invention that is invented and adopted domestically is a random variable Q drawn from the exponential distribution, so that $\Pr[Q<q]=1-e^{-\theta q}$. The average inventive step of domestic inventions is therefore $1/\theta$. The type of input to which the invention applies is drawn from the uniform distribution on $[0,J]$. If adopted, an invention of size q applicable to input j raises the quality of that input from $Z(j)$ to $Z'(j)=e^{q}Z(j)$.

We make the size of an invention stochastic to introduce heterogeneity into the patenting decision. Inventions that are large steps may be patented widely while small ones may not be worth protecting anywhere.

The same invention may be adopted in a wide set of countries. However, some inventions will only be applicable to the technologies of one or two. We let ϵ_{ni} be the marginal probability that an invention that occurred in country i is applicable in country n. In the empirical work we explore various parameterizations of these

[6]Grossman and Helpman (1991) assume that the range of inputs is the interval [0,1]. Our slight generalization serves to parameterize the extent to which a given improvement in an individual input contributes to total output. A larger value of J means that a given improvement has less aggregate effect.

[7]By assuming a single, homogeneous tradable output we prevent inventions from having any effect on the terms of trade between countries. While it would be interesting to consider the implications of inventions for the terms of trade, we preclude the possibility here in order to focus purely on the implications of innovation for productivity.

[8]The model could easily be modified to accommodate multiple factors. If capital is perfectly mobile between countries (which might be a reasonable approximation for the OECD) then its introduction has no implications for the analysis here. High productivity countries would have more capital seeking to exploit the higher return there, although these countries would not be more productive because they had more capital.

[9]Since our assumptions about market structure imply different markups in different sectors, labor is not allocated efficiently in equilibrium. We relate the more complicated expression for actual output per worker to this productivity index below.

probabilities. We interpret these parameters as indicators of international technology diffusion.

Motivated by the theory of technological catch-up and results from Eaton and Kortum (1994), we assume that a given invention is generally a larger inventive step in a technologically less advanced country.[10] Furthermore, we expect that an invention from a technologically more advanced country is, on average, bigger and better. To capture this effect in a simple way, we assume that the step size of an invention from country i, adopted in country n, is drawn from the exponential distribution with parameter $\theta_{ni} = \theta(A_i/A_n)^{-\omega}$, where $\omega > 0$. One interpretation is that the step size Q is drawn from the exponential distribution in the home country and that the step is simply scaled up or down according to the relative productivity in the adopting country, $Q_{ni} = (A_i/A_n)^{\omega} Q$. Our theory does not require that we make any assumption about the cross-country correlation of the step size of a given invention.

We denote the flow of inventions from country i by α_i. Ideas thus flow into country n from country i at rate $\epsilon_{ni}\alpha_i$, and the mean step size of these inventions is $1/\theta_{ni}$.

3.2. World growth

Given the rates at which ideas from around the world bombard country n, and the average inventive step of these ideas, the country's growth rate g_n is:

$$g_n = \frac{\dot{A}_n}{A_n} = \frac{1}{J\theta} \sum_{i=1}^{N} \epsilon_{ni} \alpha_i \left(\frac{A_i}{A_n} \right)^{\omega}, n = 1, \ldots, N, \tag{3}$$

where N is the number of countries. This equation relates productivity growth in each country to the level of inventiveness around the world. The weight applied to each source country's inventiveness depends both on the diffusion parameter as well as its relative productivity. Note that as a destination country gets farther behind, ideas that arrive have a larger percentage effect on productivity. If ϵ_{ni} and α_i are strictly positive and constant over time for all countries, this force eventually brings countries to a common steady-state growth rate, although their relative productivity levels may remain permanently different, depending on their abilities to adopt inventions.

To calculate the steady-state growth rate and relative productivity levels, we define the variable $\mu_n = A_n^{\omega}$. We can then state the dynamics of productivity growth among the set of N countries in terms of the system of linear differential equations:

[10] The notion of technological catch-up plays an important role in economic history. Gerschenkron (1962) interprets the spread of the industrial revolution throughout Europe and Japan in this light. Fagerberg (1994) surveys analytic and empirical work on the topic.

$$\dot{\mu} = \Delta\mu \tag{4}$$

where μ is an $N \times 1$ vector with representative element μ_n and where Δ is an $N \times N$ matrix with typical element:

$$\delta_{ni} = \frac{\omega}{J\theta}\epsilon_{ni}\alpha_i.$$

Under a wide range of parameter values this system has a single, strictly positive eigenvalue λ^F with a corresponding positive eigenvector (defined up to a scalar multiple) μ^F satisfying $\lambda^F\mu^F = \Delta\mu^F$. In this case the system will converge to a steady state in which productivity in each country grows at rate $g = \lambda^F/\omega$, with country n's productivity relative to country N given by $(\mu_n^F/\mu_N^F)^{1/\omega}$.[11]

Some characteristics of the steady state are as follows. First, more research in any particular country raises the world growth rate, rather than the growth rate of that country relative to others. Second, as long as more ideas are adopted locally than abroad then countries that do more research will have higher relative productivity. Third, greater flows of information, as reflected in higher values of ϵ_{ni}, imply higher world growth.[12]

A basic objective of our empirical work is to quantify the system of equations (Eq. (3)) in order to identify the sources of growth in the world economy. A problem is that, with only N relationships, the parameters of the system are difficult to identify, since productivity levels are growing at the same rate. To address this problem we model the decision by inventors in any country to patent in any country. The consequent system of N^2 patenting equations embodies many of the same terms as Eq. (3). Estimating the cross-country patenting equations in conjunction with the steady-state productivity relationships thus gives us a better handle on the international diffusion probabilities central to Eq. (3). We now describe how we model market structure and patenting.

3.3. Market structure

Bertrand competition between the producers of inputs within a country allows the owner of an invention to charge the highest price at which production without

[11]Frobenius' theorem ensures that, as long as Δ is indecomposable, meaning that there is no ordering of countries such that Δ can be written

$$\begin{pmatrix} \Delta_{11} & \Delta_{12} \\ 0 & \Delta_{22} \end{pmatrix},$$

then there exists a unique strictly positive eigenvector that has a corresponding nonnegative eigen value. See McKenzie (1960) or Takayama (1974, theorem 4.B.1). Indecomposability here means that there is no isolated block of countries, i.e. countries not receiving ideas from outside the block, which on its own grows more slowly than countries outside the block.

[12]The first and third implications follow from the fact that if the conditions of Frobenius' Theorem are satisfied, then λ^f is increasing in each element of Δ. See McKenzie (1960) or Takayama (1974, theorem 4.B.1).

that invention is unprofitable.[13] We use the price of final output as numeraire. If w_n is the wage in country n a firm producing an input with an invention of size q will charge $p_n = e^q w_n$ and produce $X = Y_n / Jpn = Yn/Je^{-q} w_n$. The profit flowing from country n to this invention is thus

$$\pi_n(q) = (1 - e^{-q}) Y_n / J.$$

3.4. Productivity

Incorporating Eq. (2) into production function Eq. (1) gives, for any country,

$$\ln(Y/J) = \ln A + \frac{1}{J}\int_0^J \ln X(j)\mathrm{d}j.$$

Since inputs are produced with a unit labor requirement

$$X(j) = L(j) = L^P \exp[-q(j)] / \int_0^J \exp[-q(i)]\mathrm{d}i,$$

where $L(j)$ is the number of workers making input j, and $\int_0^J L(j)\mathrm{d}j = L^P$, total production workers. Substituting $X(j)$ into the relationship above gives, for country n,

$$y_n \equiv \frac{Y_n}{L_n^P} = \Gamma_n A_n,$$

where, since $q(i)$ has an exponential distribution,

$$\Gamma_n = \frac{-\exp\left(\sum_{i=1}^{N} \phi_{ni}/\theta_{ni}\right)}{\sum_{i=1}^{N} \phi_{ni}\theta_{ni}/(1 + \theta_{ni})},$$

where $\phi_{ni} \equiv \epsilon_{ni}\alpha_i\left[\sum_{j=1}^{N} \epsilon_{nj}\alpha_j\right]^{-1}$, the fraction of usable ideas flowing into country n that originates in country i.

[13]The production technology implies a unit elastic demand for an individual input given the prices of all other inputs. Hence to maximize profit the owner of the invention charges the highest price at which it remains the only seller.

3.5. The decision to patent

An inventor earns the profit generated by his or her invention in a country as long as it is adopted there and has not been imitated or rendered obsolete by a more advanced technology. We assume that inventions are imitated at a rate that depends on whether or not the inventor has a patent in that country. The profits from an imitated invention pass to a local monopolist. We denote the hazard of imitation of an idea from country i in any country n as ι_{ni}^{pat} if it was patented there and as ι_{ni}^{not} if it was not.[14] For a patent in country n to have any value to an inventor from country i requires, of course, that $\iota_{ni}^{pat} < \iota_{ni}^{not}$.

The hazard of obsolescence depends on the rate at which ideas flow into a country and the probability with which they apply to a particular industry. The steady-state rate of obsolescence in country n is thus

$$o_n = \frac{1}{J}\sum_{i=1}^{N} \epsilon_{ni}\alpha_i.$$

In steady state, the hazard of obsolescence is lower in countries with a lower level of technology since these countries obtain fewer inventions, although those that they do obtain come in bigger steps.

Consider, then, the expected value at time t of an invention from country i of size q that is applicable in country n, $V_{nit}(q)$. The probability of its not having become obsolete by time $s > t$ is $e^{-o_n(s-t)}$, while the probability of its not having been copied by then is $e^{-\iota_{ni}^{k}(s-t)}$, where $k \in \{pat, not\}$ depending upon whether or not the invention was patented. Therefore,

$$V_{nit}^{k}(q) = \int_0^\infty \pi_{nt+s}(q) e^{-(r+\iota_{ni}^{k}+o_n)s}\,\mathrm{d}s.$$

Here again $k = pat$ if the idea was patented and $k = not$ otherwise, and r is the discount rate, which we treat as constant over time. To obtain a solution to this integral, we henceforth assume that the system is in steady state, so that Y_n grows at a constant rate g. In this case,

$$V_{ni}^{k}(q) = \frac{(1-e^{-q})Y_n}{J(r+\iota_{ni}^{k}+o_n-g)}.$$

We assume that an inventor chooses whether to seek patent protection in country n after learning both the size of his or her invention and whether it is

[14] We allow imitation rates to vary depending upon whether or not the idea originated domestically.

applicable in that country. A patent gives the inventor the incremental benefit of a lower hazard of imitation, so is worth $V_{ni}^{pat}(q)-V_{ni}^{not}(q)$. Hence, if it costs an inventor from country i C_{ni} to patent in country n, then the inventor will seek patent protection in that country if $V_{ni}^{pat}(q)-V_{ni}^{not}(q)$ exceeds C_{ni} and not otherwise.[15] The return to patenting rises with the quality of the invention q. Hence the condition

$$V_{ni}^{pat}(q) - V_{ni}^{not}(q) = C_{ni} \tag{5}$$

determines a threshold quality level $\bar{q}_{ni}$ such that inventions of higher quality are patented while those of lower quality are not. A possibility, of course, is that the cost of patenting would exceed the benefit for any invention regardless of its quality, in which case patenting would be zero, and $\bar{q}_{ni}$ infinite. Otherwise, with constant output growth and a constant rate of arrival of inventions, the equation for the quality threshold is

$$\bar{q}_{ni} = -\ln(1-\gamma_{ni}c_{ni}),$$

where $\gamma_{ni} \equiv J(r+\iota_{ni}^{pat}+o_n-g)(r+\iota_{ni}^{not}+o_n-g)/(\iota_{ni}^{not}-\iota_{ni}^{pat})$ and $c_{ni} \equiv C_{ni}/Y_n$. (We treat c_{ni} as a constant over time, assuming that patenting costs rise at the same rate g as income.)

Inventions flow from country i at rate α_i, a fraction ϵ_{ni} of which is applicable to country n. Given the quality threshold for patenting and the distribution function for the inventive step, inventors from country i choose to seek protection in country n on a fraction of these inventions. This fraction has a lower bound of zero, corresponding to an infinite $\bar{q}_{ni}$. Hence the fraction of diffused ideas that are patented is:

$$f_{ni} \equiv e^{-\theta_{ni}\bar{q}_{ni}} = [\max\{1-\gamma_{ni}c_{ni},0\}]^{\theta_{ni}}. \tag{6}$$

It is well known that some important inventions have not been patented while many patents represent inconsequential innovations. We capture such factors that vary across source and destination countries in a multiplicative i.i.d. error $e^{u_{ni}}$ in the patenting decision. Our specification of a multiplicative error implies that, when the predicted fraction of patentable ideas hits zero, the model should fit perfectly. To explain errors in patenting in countries where our model predicts that patenting is unprofitable, we allow for systematic bias in the patenting decision. Specifically, we posit that a fraction η of inventions that are not worth patenting is

[15] Since translating patent documents is costly, the cost of applying for a patent may depend on the source country as well as the destination country.

patented by mistake.[16] Therefore, the number of patent applications from country i for protection in country n, P_{ni}, is:

$$P_{ni} = \epsilon_{ni}\alpha_i[f_{ni} + (1 - f_{ni})\eta]e^{u_{ni}} \quad i,n = 1, \ldots, N. \tag{7}$$

This system of equations, along with the dynamics of productivity, is the basis of our empirical work.

3.6. Specification of inventiveness and diffusion

In much of what follows, we relate inventiveness and diffusion probabilities to underlying observable characteristics. We relate a country's inventiveness to the number of researchers R_i in that country. We assume that research workers are drawn from the same Pareto distribution of talent in each country. The most talented researchers engage in R&D activity. These assumptions imply that if R_i workers are doing research out of a total workforce of $L_i = L_i^P + R_i$ in country i then the country produces inventions at rate $\alpha R_i^{\beta} L_i^{1-\beta}$, where α and β are parameters.[17]

We specify technology diffusion, ϵ_{ni}, the probability that an invention from country i will be adopted in country n, as depending on: (1) whether n and i are the same country or not, (2) the distance between n and i, (3) the level of human capital in n (the adopting country), and (4) the level of country n's imports from i relative to n's GNP. The first factor allows ideas to flow more freely within than between countries (Lichtenberg, 1992). The second factor, distance, reflects possible geographical impediments to the free flow of ideas. The third factor tests whether a country's level of human capital increases its ability to absorb ideas from either domestic or foreign sources (Benhabib and Spiegel, 1994). The fourth factor examines whether imported goods are a vehicle for the diffusion of technology (Coe and Helpman, 1995). Our specification of technology diffusion is thus

[16]Our model also allows for the symmetric possibility that inventors fail to patent a fraction η' of inventions that should be patented. The parameter η' is not identified separately from the average level of innovation α_i and the number of markets J. We explored the alternative strategy of setting η to zero and specifying patenting as a Poisson process with a mean given by our model. The problem is that between most countries the extent of patenting is so large that the randomness introduced by such a specification is trivial relative to the level of patenting.

[17]Under these assumptions, a steady state requires that R_i and L_i remain constant over time. If either grows over time then an offsetting fall in α is needed to attain a steady state. Jones (1995) and Kortum (1995) provide models with this feature.

$$\ln \epsilon_{ni} = \epsilon_{HOM}DH_{ni} + \epsilon_{KM}KM_{ni} + \epsilon_{KM^2}KM_{ni}^2 - \epsilon_{HK}\frac{1}{HK_n} + \epsilon_{IMP}\ln IM_{ni}, \quad (8)$$

where DH_{ni} is a dummy variable that equals one if $n=i$ and zero otherwise, KM_{ni} is the distance from n to i, KM^2 is the square of distance, HK_n is the average years of schooling in country n, and IM_{ni} is n's imports from i relative to n's GDP (set equal to one if $n=i$). If ϵ_{HK} is positive, then our specification implies that the human capital effect has a theoretical maximum of one (in levels) corresponding to infinite years of schooling.

4. Estimation

We fit the systems of Eq. (4) and Eq. (7) to a cross-section of data from OECD countries. We first discuss the data and our specification of diffusion parameters. We then present ordinary (OLS) and two-stage least squares estimates of a linearization of the patent equation. We conclude with nonlinear least squares (NLLS) estimates of the complete system of patent and productivity equations.

4.1. Data

Our sample is a cross-section of 19 OECD countries.[18] Table 1 provides a list of countries, along with summary tabulations of the data.

Our endogenous variables are patents taken out in each country by inventors from each country in the sample and, in our NLLS estimation, relative productivities.[19] The patents variable is patent applications by reporting country and country of residence of the inventor in 1988 (WIPO, 1990). Table 1 summarizes the full matrix of patent data, reporting patenting in the country by residents (domestic patents), patenting in the country by nonresidents (foreign patents), and patenting in foreign countries by residents (patents abroad). This last measure reports multiple patents on the same invention. The data reveal significant levels of cross-country patenting; foreign patenting exceeds domestic patenting in all countries except in Japan and the United States, while patents abroad exceed domestic patents for all countries except Greece. Nevertheless, given that the number of foreign countries is in each case 18, domestic patenting is far more

[18] We use this sample since data on research activity are available from them on a fairly uniform basis. Data limitations forced us to drop Iceland, Luxembourg, New Zealand, Switzerland, Turkey, and Yugoslavia, however.

[19] The patent data, as well as the cost of patenting discussed below, were adjusted for Japanese domestic applications. The Japanese apply for over 300 000 patents domestically each year. Okada (1992) finds that Japanese patents granted to foreigners contain on average 4.9 times as many inventive claims as those granted to Japanese inventors. Thus we translate 4.9 Japanese domestic patent applications into the equivalent of one application elsewhere. This adjustment is reflected in Table 1.

Table 1
Selected data

Country	GDP per worker[a]	Domestic patents[b]	Foreign patents[c]	Patents abroad[d]	Research S&Es[e]	Research intensity[f]	Years of schooling[g]
Australia (AL)	30.61	6.57	14.49	8.66	9.86	0.13	8.7
Austria (AS)	25.50	2.23	27.90	5.79	3.47	0.10	8.6
Belgium (BE)	30.24	0.64	30.70	4.73	8.18	0.20	9.4
Canada (CA)	34.33	2.77	27.31	8.09	26.73	0.21	10.0
Denmark (DN)	24.56	1.33	9.13	5.06	3.90	0.14	6.9
Finland (FI)	26.30	2.04	6.79	5.38	13.51	0.53	10.8
France (FR)	29.14	12.44	49.65	42.36	48.80	0.19	9.5
Germany (GE)	28.02	31.98	47.79	103.25	107.11	0.36	10.3
Greece (GR)	16.83	0.37	12.34	0.17	0.63	0.02	8.4
Ireland (IR)	20.82	0.73	2.92	0.76	1.32	0.10	8.8
Italy (IT)	29.76	2.29	39.72	19.80	28.06	0.12	9.1
Japan (JP)	21.43	63.05	33.20	86.97	278.12	0.36	9.5
Netherlands (NE)	29.69	2.16	35.80	16.58	10.73	0.18	9.5
Norway (NR)	29.63	0.93	8.02	2.25	10.66	0.51	9.2
Portugal (PR)	13.26	0.05	2.19	0.09	0.63	0.01	6.5
Spain (SP)	24.45	1.82	22.57	2.21	6.50	0.05	9.7
Sweden (SW)	27.60	3.41	32.38	15.05	12.24	0.28	9.6
United Kingdom (UK)	25.51	20.90	55.34	41.18	87.33	0.31	8.5
United States (US)	36.42	75.63	65.45	155.30	701.33	0.58	12.1

[a]Averaged from 1986–1988 in $1000s, from Summers and Heston (1991).
[b]Patent applications by residents of each country (for 1988) in 1000s, from WIPO (1990).
[c]Applications from residents of one of the other 18 countries.
[d]Total applications by residents of the given country for patent protection in one of the other 18 countries.
[e]Business enterprise research scientists and engineers (averaged from 1986–1988) in 1000s, from OECD (1991). In some cases we interpolated to fill in missing years.
[f]Researchers per worker in %.
[g]From Kyriacou (1991).

frequent than would be the case if there was no greater propensity to patent in the home country.

The productivity variable is real GDP per worker, averaged over 1986–1988, from Summers and Heston (1991). If capital is imperfectly mobile across countries, total factor productivity would provide a better measure of a country's level of technology than output per worker. Given problems of capital stock measurement, however, we have chosen to focus on our simpler measure.

Our explanatory variables can be divided among the factors determining: (1) each country's productivity as a source of innovation (α_i), (2) diffusion of technology between each country pair (ϵ_{ni}), and (3) the returns to patenting an invention from country i in country n, conditional on diffusion (f_{ni}).

Our measure of research effort R_i is business enterprise research scientists and engineers, averaged over 1986–1988, from OECD (1991). In some cases we interpolated to fill in missing years. Our measure of the total labor force, L_i, is from Summers and Heston (1991). The United States accounts for about half of the research scientists and engineers in the sample, and Japan for about half of what remains. The United States is also the most research intensive, followed by the Scandinavian countries, Germany, Japan, and the United Kingdom.

Our data on human capital are from Kyriacou (1991).[20] Import data are from the IMF *Direction of Trade Statistics Yearbook*, various issues. Distance is from Software Toolworks, version 5.0.

Our measure of C_{ni}/Y_n is the cost of applying for a patent, including agents' fees and translation fees, constructed from Helfgott (1986), scaled by GNP (from the World Bank).[21] We allow the hazard of imitation of patented inventions to vary with an index of the strength of intellectual property protection (Rapp and Rozek, 1990), as reported by Maskus and Penubarti (1995). This index rates countries according to the strength of protection that they provide on a scale from 1 to 5, with 5 serving as the highest level. Our OECD countries all score 4 or 5, with the exception of Portugal, which scores 3. Hence we pool those scoring 3 and 4.[22]

4.2. Estimates of the patent equation

We can estimate an approximation to the patent Eq. (7) without solving for the model's implications for growth and technology levels. The patent equation is of

[20]We thank Mark Spiegel for providing these data to us.

[21]For the reason discussed above, we scale up the cost of an application for a Japanese inventor in Japan by a factor of 4.9. We ignore the more complicated fee structure applying to patents through the European Patent Office, except to the extent that it reduces translation costs. We also ignore complications introduced by patent renewal fees.

[22]We thank Keith Maskus for providing us with these data.

interest in its own right, and the parameter estimates can be used as starting values for estimation of the complete system.

In order to obtain an equation that is linear in logs, we approximate $[f_{ni}+(1-f_{ni})\eta]$ by setting $\eta=0$ and then taking a first-order approximation to $\ln f_{ni}$ around the points $\ln(A_i/A_n)=0$ and $C_{ni}/Y_n=0$. We obtain $\ln f_{ni} \approx -\psi_{ni}(C_{ni}/Y_n)$, where $\psi_{ni} \equiv \gamma_{ni}\theta$. Applying the approximation to Eq. (7) we get

$$\ln \frac{P_{ni}}{L_i} = \ln \alpha + \ln \epsilon_{ni} + \beta \ln \frac{R_i}{L_i} - \psi_{ni} \frac{C_{ni}}{Y_n} + \omega^* \ln \frac{y_i}{y_n} + u_{ni}, \tag{9}$$

where we have added a term in relative productivity levels, y_i/y_n.[23] The equation relates patenting per country i worker in country n positively to the probability of diffusion, to country i's research intensity, and to country i's productivity relative to country n. The cost of patenting in country n by inventors from country i relative to country n's market size has a negative effect.

The term Ψ_{ni} incorporates a number of parameters, most importantly the imitation hazards ι_{ni}^{pat} and ι_{ni}^{not}, reflecting the advantages of patenting. Thus we allow Ψ_{ni} to take on four values depending on whether $n=i$ and depending on whether destination country n provides strong intellectual property protection. This specification amounts to

$$\psi_{ni} = \psi_{H5}DH_{ni}D5_n + \psi_{H4}DH_{ni}(1-D5_n) + \psi_{F5}(1-DH_{ni})D5_n + \psi_{F4}(1-DH_{ni})(1-D5_n),$$

where $D5_n$ is a dummy variable that equals one if country n provides the highest level of intellectual property protection. To complete the specification of our linear patent equation we incorporate the expression for ϵ_{ni} above, i.e.

$$\ln \epsilon_{ni} = \epsilon_{HOM}DH_{ni} + \epsilon_{KM}KM_{ni} + \epsilon_{KM^2}KM_{ni}^2 - \epsilon_{HK}\frac{1}{HK_n} + \epsilon_{IMP}\ln IM_{ni}.$$

Table 2 reports the OLS estimates of the parameters. The equation explains over 75% of the percentage variation in international patenting per source country worker. These coefficients imply that imports are not an important vehicle for technology diffusion but that ideas diffuse more within countries than between them.[24] Technology diffusion between countries falls as the distance between them grows. The quadratic term in distance implies that diffusion attains a minimum at about 10 000 km, at which point it is about one fifth of the value at a zero distance. Human capital has the predicted effect of raising the ability of a country to absorb technology. The magnitude of the coefficient implies that, due solely to

[23]In this equation P_{ni} is actual patent application plus one. In this way we avoid the problem of zero patent applications (which occur between a few of our country pairs).

[24]The import variable is arbitrarily normalized to unity for home countries. The estimated parameter on the home dummy thus captures both the role of home trade and any additional factors increasing domestic diffusion.

Table 2
OLS estimate of the patent equation (dependent variable: $\ln(P_{ni}/L_i)$)

Independent variable	Parameter	Estimate[a]
Constant	$\ln \alpha$	6.4 (0.5)
DH_{ni}	ϵ_{HOM}	0.73 (0.35)
KM_{ni}	ϵ_{KM}	−0.31 (0.04)
KM_{ni}^2	ϵ_{KM}^2	0.016 (0.002)
$-1/HK_n$	ϵ_{HK}	23 (4)
$\ln IM_{ni}$	ϵ_{IMP}	0.008 (0.041)
$\ln(R_i/L_i)$	β	0.90 (0.06)
$-DH_{ni}D5_{ni}(c_{ni}/Y_n)$	ψ_{H5}^{b}	−0.023 (0.021)
$-DH_{ni}(1-D5_{ni})(c_{ni}/Y_n)$	ψ_{H4}	−0.007 (0.010)
$-(1-DH_{ni})D5_{ni}(c_{ni}/Y_n)$	ψ_{F5}	0.020 (0.006)
$-(1-DH_{ni})(1-D5_{ni})(c_{ni}/Y_n)$	ψ_{F4}	0.035 (0.002)
$\ln(y_i/y_n)$	ω^*	1.2 (0.22)

Note: total sum of squares = 1131; residual sum of squares = 250; number of observations = 361.
[a]Estimated standard errors are in parentheses.
[b]The estimates of the ψ parameters should be multiplied by one million.

its higher level of schooling, the US absorbs about five times as much technology as does Portugal. The ψ parameters for foreign patenting are of the correct sign and precisely estimated. Furthermore, $\psi_{F5} < \psi_{F4}$ as theory predicts, i.e. countries providing strong protection are more attractive destinations for foreign patents. The ψ parameters for home patenting are insignificant and of the wrong sign. Finally, the productivity of the source country relative to the destination country does have a positive effect on patenting. The elasticity of idea production with respect to research employment is precisely estimated to be close to unity.[25]

This last estimate is notably different from the estimate (nearer zero) that we obtained in Eaton and Kortum (1994). This other study focused on only the five countries doing the most research, however, so that a much smaller range of variation was observed. Furthermore, it treated research effort as endogenous. A potential source of upward bias in our current estimate of β is unobserved variation in α across countries that raises both the productivity of research and research effort. To correct for this we also estimated Eq. (9) instrumenting for

[25]We also estimated the equation without the term $\ln(y_i/y_n)$, since it falls out of a first-order expansion. The coefficients on other variables were broadly similar, although somewhat closer to those estimated by NLLS.

[26]We also considered two alternative instruments: (1) country size as measured by the total labor force, to capture the role of a large home market in encouraging research and (2) government expenditure on R&D per worker, to capture non-market incentives to do R&D. The first instrument explained almost none of the variation in research intensity, however. Hence it failed the 'relevance' criterion for a good instrument. The second instrument, while highly correlated with research intensity, yielded an even larger estimate of β than OLS, suggesting that it failed the 'validity' criterion. A possible explanation is that government support raises research productivity as well as the incentive to do research.

research intensity $\ln(R_i/L_i)$ with our measure of human capital.[26] Doing so lowers the estimate of β to 0.61, with a standard error of 0.15. There was essentially no impact on other parameter estimates.

4.3. *Simultaneous estimation of the patent and productivity equations*

Our estimate of the patent equation suggests that our model captures some of the major determinants in the international patenting decision. There is a large role for factors that we interpret as determinants of diffusion between countries. These diffusion parameters should have important consequences for the behavior of productivity across countries. To examine these consequences and to sharpen our estimates of the diffusion parameters we now estimate the patent equation simultaneously with the equation for productivity dynamics (Eq. (3)). We impose the restriction that the system is in steady state. Hence innovation and diffusion have no implications for differences in growth rates of productivity across countries, but determine relative levels of productivity instead. Hence we set $g=g_n$ in Eq. (3), yielding Eq. (4).

4.3.1. *Specification of the nonlinear system*

In estimating the system of equations we introduce error into the productivity relationship by assuming that true productivity y_n is measured with a multiplicative error. Observed productivity $y_n{}^*$ is thus $y_n^* = y_n e^{\nu_n}$, where ν_n, $n=1,\ldots,N$ is i.i.d. with variance $\sigma_\nu{}^2$. Since our model only has implications for relative productivities, we normalize productivity relative to country N's.

We estimate the system of equations:

$$\begin{aligned} g &= \frac{1}{J\theta}\sum_{i=1}^{N}\epsilon_{ni}\alpha_i\left(\frac{A_i}{A_n}\right)^{\omega} \quad n=1,\ldots,N, \\ \frac{y_n^*}{y_N^*} &= \frac{A_n\Gamma_n}{A_N\Gamma_N}e^{v_n - v_N} \quad n=1,\ldots,N-1, \\ P_{ni} &= \epsilon_{ni}\alpha_i[f_{ni} + (1-f_{ni})\eta]e^{u_{ni}} \quad i,n=1,\ldots,N, \end{aligned} \tag{10}$$

where, by way of review,

$$\alpha_i = \alpha R_i^{\beta} L_i^{1-\beta},$$

$$\epsilon_{ni} = \exp\left[\epsilon_{HOM}DH_{ni} + \epsilon_{KM}KM_{ni} + \epsilon_{KM^2}KM_{ni}^2 - \epsilon_{HK}\frac{1}{HK_n}\right]IM_{ni}^{\epsilon_{IMP}},$$

$$f_{ni} = [\max\{1-\gamma_{ni}c_{ni},0\}]^{\theta_{ni}},$$

$$\Gamma_n = \exp\left(-\sum_{i=1}^{N}\phi_{ni}/\theta_{ni}\right)\left[\sum_{i=1}^{N}\phi_{ni}\theta_{ni}/(1+\theta_{ni})\right]^{-1},$$

$$\phi_{ni} = \frac{\epsilon_{ni}\alpha_i}{\sum_{i=1}^{N}\epsilon_{ni}\alpha_i},$$

$$\theta_{ni} = \theta\left(\frac{A_i}{A_n}\right)^{-\omega},$$

$$\gamma_{ni} = \frac{J(r + \iota_{ni}^{pat} + o_n - g)(r + \iota_{ni}^{not} + o_n - g)}{(\iota_{ni}^{not} - \iota_{ni}^{pat})},$$

$$o_n = \frac{1}{J}\sum_{i=1}^{N}\epsilon_{ni}\alpha_i.$$

In principle γ_{ni} contains 50 imitation parameters $\iota_{ni}^{\ k}$. Since we have no hope of identifying all of them we impose the following restrictions: (1) $\iota_{ni}^{\ not} = \iota^{nf}(1 - DH_{ni}) + \iota^{nh}DH_{ni}$, where ι^{nf} is the rate of imitation of foreign non-patented ideas and ι^{nh} is the imitation rate for domestic non-patented ideas; (2) $\iota_{ni}^{\ pat} = \iota^{p5}D5_n + \iota^{p4}(1 - D5_n)$, where ι^{p5} is the rate of imitation for patented ideas in countries with the strongest patent protection and ι^{p4} is the imitation rate for patented ideas in other countries. Hence we allow for differences in the hazard of imitation of non-patented inventions according to whether they originated locally or abroad and in the hazard of imitation of patented ideas according to the strength of patent protection in the destination. Because of the difficulty of separately identifying all of these imitation hazards, we set $\iota^{nf} = 0.25$ based on the estimate of the rate at which technology 'leaks out' from US firms to non-US competitors (Mansfield and Romeo, 1980). Furthermore, since estimates of ι^{nh} tend to be arbitrarily large (to explain the large amount of patenting at home), we simply fixed $\iota^{nh} = 1000$.

To reduce the computational burden in the estimation routine we calibrate the parameter J, conditional on all the other parameter estimates, to predict the average rate of growth of GDP per worker in our countries during 1985–1990 (0.02501). Hence our model predicts $g = 0.02501$ exactly. The real interest rate is set at $r = 0.07$.

The parameter vector that we estimate is thus

$$\boldsymbol{\Theta} = [\iota^{p5}, i^{p4}, \eta, \alpha, \beta, \omega, \theta, \epsilon_{HOM}, \epsilon_{KM}, \epsilon_{KM^2}, \epsilon_{HK}, \epsilon_{IMP}].$$

The exogenous variables for source i and destination n are given by the vector $\boldsymbol{x}_{ni} = [R_i, L_i, DH_{ni}, KM_{ni}, HK_n, IM_{ni}, c_{ni}, D5_n]$ $i, n = 1, \ldots, N$. The endogenous variables are patents P_{ni} and relative productivity levels y_n^* / y_N^*.

Estimation of the nonlinear system. In order to estimate the system we express it in vector form with additive errors. To this end we define the log of measured productivity in country n relative to N as

$$\tilde{y}_n \equiv \ln y_n^* - \ln y_N^* = \ln y_n - \ln y_N + v_n,$$

where $v_n \equiv \nu_n - \nu_N$ for $n=1,\ldots,N-1$. The resulting covariance matrix of the disturbance vector $\boldsymbol{v}$ is $\sigma_v^2 \Omega_v$ where $\Omega_v \equiv [\boldsymbol{I}_{N-1} + \boldsymbol{e}_{N-1}\boldsymbol{e}'_{N-1}]$ where $\boldsymbol{I}_{N-1}$ is the $N-1$ by $N-1$ identity matrix and $\boldsymbol{e}_{N-1}$ is an $N-1$ vector of ones. We define $\tilde{\boldsymbol{y}}$ as the $N-1$ vector of relative productivity levels with representative element $\tilde{y}_n$. Similarly we define $\tilde{p}$ as an $N^2 \times 1$ vector with representative element $\tilde{p}_{N(i-1)+n} \equiv \ln(P_{ni}/L_i)$. The corresponding mean-zero i.i.d. error is u_{ni}, as defined earlier. We define its variance as $\sigma_u{}^2$. We can now write the system (Eq. (10)) as

$$\begin{bmatrix} \tilde{p} \\ \tilde{y} \end{bmatrix} = G(\Theta,x) + \cdot,$$

where Θ is the vector of parameters, $\boldsymbol{x}$ is the matrix of exogenous variables, and $\varepsilon \equiv [u',v']'$ is an N^2+N-1 vector of disturbances with covariance matrix

$$\boldsymbol{\Omega} = \begin{bmatrix} \sigma_u^2 I_{N^2} & 0 \\ 0 & \sigma_v^2 \Omega_v \end{bmatrix}.$$

We assume that $E[\varepsilon|\boldsymbol{x}]=0$.

We estimate the parameters using a two-step feasible generalized nonlinear least squares procedure. First, we impose the value of the ratio $\sigma_u{}^2/\sigma_v{}^2=100$, which allows us to construct $\hat{\boldsymbol{\Omega}}$ up to a scalar multiple.[27] We then use a numerical minimization routine to find the value of $\hat{\boldsymbol{\Theta}}$ that minimizes

$$\left[\begin{pmatrix} \tilde{p} \\ \tilde{y} \end{pmatrix} - G(\hat{\Theta},x)\right]' \hat{\Omega}^{-1} \left[\begin{pmatrix} \tilde{p} \\ \tilde{y} \end{pmatrix} - G(\hat{\Theta},x)\right]. \tag{11}$$

From the residuals $\hat{\cdot} \equiv [\hat{u}',\hat{v}']'$ we calculate $\hat{\sigma}_u^2 = \hat{u}'\hat{u}/N^2$ and $\hat{\sigma}_v^2 = \hat{v}'\Omega_v^{-1}\hat{v}/(N-1)$. From these estimates of the variances of the patent and productivity errors, we construct a new estimate of Ω and perform the minimization in Eq. (11) once again to obtain our parameter estimates.

The estimates are shown in the first column of Table 3, based on the estimate $\hat{\sigma}_u^2/\hat{\sigma}_v^2 = 35.3$ obtained from our first stage estimates, in which we imposed $\sigma_u{}^2/\sigma_v{}^2=100$. In the second column we show the first-step estimates themselves. The third column shows estimates obtained by setting $\sigma_u{}^2/\sigma_v{}^2=10$, thus putting relatively more weight on the residuals from the patent equation.[28] Table 4 shows actual and fitted levels of productivity relative to the United States based on the estimates in the first column of Table 3.

[27]This starting value reflects our prior beliefthat there is more randomness in the patenting decision than in productivity measurement.

[28]We solve the model using a program written in GAUSS. Starting with an initial parameter vector Θ_0 we solve Eq. (4) to obtain the model's implication for relative productivity levels. The results are then fed into the patenting equation. Next we calculate the implied vector of errors in productivity and patenting. Calculating one solution requires less than a second on a Pentium PC with a corrected microprocessor. Then, within a minimization routine, the model is solved repeatedly to find a parameter vector $\hat{\Theta}$ that minimizes Eq. (11). Convergence typically requires about half an hour.

Table 3
NLLS estimates of the patent and productivity equations

Parameter	Feasible GLS $\hat{\sigma}_u^2/\hat{\sigma}_v^2 = 35.3$	$\sigma_u^2/\sigma_v^2 = 100$	$\sigma_u^2/\sigma_v^2 = 10$	Feasible GLS $\hat{\sigma}_u^2/\hat{\sigma}_v^2 = 15.8$
$\ln \alpha$	5.9 (0.3)	6.2 (0.3)	5.8 (0.3)	
ϵ_{HOM}	−0.6 (0.2)	−0.5 (0.1)	−0.3 (0.2)	−0.3 (0.2)
ϵ_{KM}	−0.27 (0.04)	−0.32 (0.03)	−0.27 (0.04)	−0.06 (0.03)
ϵ_{KM^2}	0.015 (0.002)	0.018 (0.002)	0.015 (0.002)	0.003 (0.002)
ϵ_{HK}	9.5 (2.1)	13 (1)	8.7 (1.9)	8.3 (2.1)
ϵ_{IMP}	0.13 (0.04)	0.10 (0.03)	0.10 (0.04)	0.27 (0.04)
β	0.93 (0.05)	0.95 (0.05)	0.96 (0.05)	
ω	3.6 (2.2)	71 (437)	6.9 (11)	1.5 (0.4)
θ	1.9 (0.2)	1.8 (0.2)	1.8 (0.2)	4.8 (0.9)
ι^{p4}	0.240 (0.001)	0.239 (0.001)	0.239 (0.001)	0.243 (0.0005)
ι^{p5}	0.238 (0.001)	0.238 (0.001)	0.237 (0.001)	0.241 (0.001)
η	0.047 (0.008)	0.055 (0.009)	0.054 (0.010)	0.035 (0.005)
Source dummies	no	no	no	yes
$\hat{u}'\hat{u}$	267	268	266	93
$\hat{v}'\Omega_v^{-1}\hat{v}$	0.47	0.40	0.49	0.57
Number of observations	380	380	380	380

Note: estimated standard errors are in parentheses. Estimated source country dummy coefficients are (see Fig. 1 and Fig. 2): AL 9.7 (0.4), AS 9.0 (0.4), BE 8.4 (0.3), CA 9.0 (0.3), DN 9.2 (0.4), FI 9.0 (0.3), FR 10.6 (0.3), GE 11.0 (0.3), GR 6.0 (0.4), IR 7.1 (0.4), IT 9.9 (0.3), JP 11.0 (0.3), NE 9.6 (0.3), NR 8.1 (0.4), PR 5.5 (0.4), SP 8.1 (0.3), SW 9.7 (0.3), UK 10.5 (0.3), US 11.7 (0.3).

4.3.2. An alternative specification of inventiveness

As with our OLS estimation of the patent equation, a potential concern is the endogeneity of research effort, i.e. unobserved factors may raise both the productivity and return to research activity, leading to a spuriously high estimate of the parameter β. One approach would be to estimate the system using instruments for research intensity. Instead we pursue a less restrictive specification, and allow inventiveness to vary freely across countries. Specifically we replace the research effort measure $\alpha R_i^{\beta} L_i^{1-\beta}$ with a set of source country dummy variables $s_i = \ln(\alpha_i)$. The results based on a first-stage estimate of $\hat{\sigma}_u^2/\hat{\sigma}_v^2 = 15.83$ appear in the fourth column of Table 3.

4.3.3. Results

The estimates of the diffusion parameters do not differ enormously from the OLS estimates. One difference, however, is that the coefficient on imports is now significant in the diffusion equation. A second difference is that the human capital parameter is smaller by a factor of two. Nonetheless, the effect remains large: due to more schooling, the US absorbs twice as much technology as does Portugal.

Most of the parameter estimates do not vary enormously as we change the weight that we place on fitting productivity relative to patenting, or introduce

Table 4
Productivity levels relative to the United States

Country	Source country			
	Actual	Fitted	Simulated (double US RS&Es)	Simulated (12 years of school)
Australia	0.84	0.70	0.65	0.85
Austria	0.70	0.58	0.46	0.74
Belgium	0.83	0.71	0.60	0.82
Canada	0.94	0.99	0.99	1.06
Denmark	0.67	0.49	0.38	0.78
Finland	0.72	0.67	0.57	0.73
France	0.80	0.65	0.54	0.76
Germany	0.77	0.69	0.59	0.77
Greece	0.46	0.50	0.40	0.68
Ireland	0.57	0.69	0.60	0.84
Italy	0.82	0.59	0.49	0.72
Japan	0.59	0.64	0.55	0.75
Netherlands	0.82	0.69	0.59	0.81
Norway	0.81	0.65	0.54	0.78
Portugal	0.36	0.47	0.36	0.80
Spain	0.67	0.67	0.56	0.77
Sweden	0.76	0.66	0.57	0.77
UK	0.70	0.61	0.51	0.78
US	1.00	1.00	1.00	1.00

source country dummies. An exception is the catch-up parameter ω which is unstable across specifications and imprecisely estimated, except when source country dummies are included. Another difference is that, when we introduce source country dummies, distance matters less and imports more in determining diffusion.

The imitation rates and patenting error were not estimated in our linear patent equation. The estimates indicate that patenting abroad lowers the hazard of imitation by only about one percentage point, and slightly more where intellectual property protection is strongest. The estimated η imply that at most 6% of ideas not worth patenting were patented anyway.

Introducing source country dummies increases substantially the fit of the patenting equation at some cost to the fit of productivity. The estimated source country effects $\hat{s}_i$ are of interest in themselves. They give a reading on the inventiveness of a country independent of the standard research input measures commonly used. The coefficients themselves vary between 5.5 for Greece to 11.7 for the United States, with standard errors of less than 0.4. A country's total inventive output is proportional to the exponent of these coefficients, so the range of variation is much greater. The estimates imply that the United States is about twice as innovative as Germany and Japan, which are very similar. We plot our estimates of source country effects against research scientists and engineers (Fig.

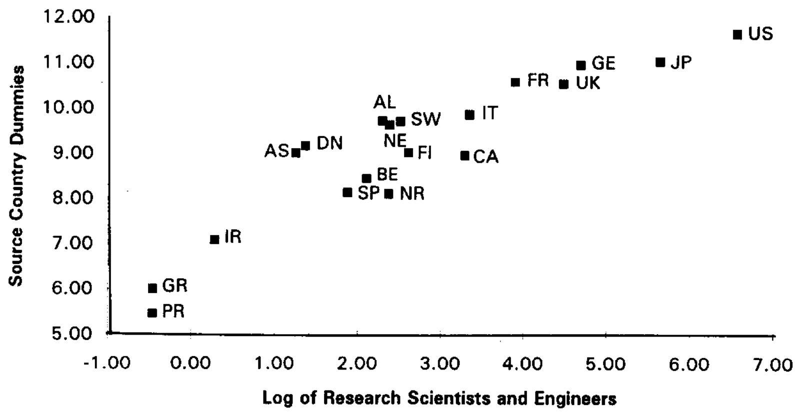

Fig. 1. Estimated inventiveness vs. research scientists and engineers.

1) and total labor force (Fig. 2). In both figures the relationship is striking but is somewhat tighter with research scientists and engineers.

5. Implications

We now examine some implications of our results. We first discuss diffusion and its determinants. We then turn to sources of growth in the world economy. Our estimates also have implications for the value of ideas, which we then turn to. We conclude with two counterfactual experiments. Except where we indicate otherwise, our analysis is based on the parameter estimates from the GLS estimation using research effort as a measure of inventiveness.

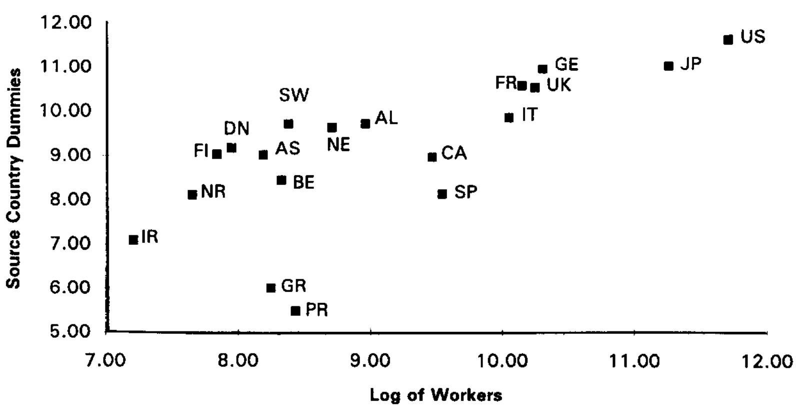

Fig. 2. Estimated inventivenessvs. labor force.

5.1. Diffusion

What do our estimates imply about where technologies flow? We can calculate, for each pair of countries, the values of the diffusion rates ϵ_{ni} implied by our parameter estimates and data on trade and distance. We normalize these estimates by the implied diffusion rate within a hypothetical home country with an infinite amount of human capital. Internal diffusion rates vary (depending on the country's level of human capital) from 0.23 (Portugal) to 0.45 (United States). Cross-border diffusion rates vary from 0.07 (Greece to Canada) to 0.48 (France to Belgium). The results suggest that, while there is a tendency for ideas to stay at home, the tendency is not overwhelming. International diffusion rates average roughly half those of domestic diffusion rates.

5.2. Sources of growth

What do our estimates imply about the sources of growth in the world economy? Combining our estimates of diffusion rates with our estimates of inventiveness allows us to ascribe the share of each country's productivity growth emanating from each country. Specifically, our estimate of the productivity growth in country n that derives from ideas from country i is:

$$g_{ni} = \frac{\hat{\epsilon}_{ni}\hat{\alpha}_i}{\hat{\theta}_{ni}\hat{J}}.$$

Table 5 and Table 6 report these magnitudes as a percentage of total growth for each destination country n, where the reported source countries are just the destination country itself, Germany, Japan, and the United States. Table 5 reports the growth decomposition based on estimates using research effort as a measure of inventiveness and Table 6 is based on the estimates using source country effects. Both sets of estimates imply that the United States, followed by Japan and Germany, is the major source of growth in the world economy. Germany's influence is usually greater in Europe while Japan's is greater elsewhere. The primary effect of shifting from research effort to source country effects is to reduce the role of the United States and raise that of the home country. Nevertheless, even in the second set of results the United States contributes the most of any foreign country, and more than the home country everywhere but Germany, while countries other than the five major researchers (the United States, Japan, Germany, France, and the United Kingdom) contribute less than 10% to their own growth.

5.3. The value of ideas

Our parameter estimates also allow us to infer how much inventors earn at home

Table 5
Sources of growth based on national research

Country	Percentage of growth from			
	Home country	Germany	Japan	United States
Australia	0.94	5.28	7.74	72.14
Austria	0.33	14.82	7.78	55.64
Belgium	0.82	12.27	7.08	56.31
Canada	2.83	1.58	10.02	82.23
Denmark	0.28	12.90	8.20	56.91
Finland	1.44	11.04	8.24	59.73
France	4.95	11.23	7.61	57.81
Germany	11.25	11.25	7.73	58.54
Greece	0.07	10.81	8.35	61.49
Ireland	0.13	9.31	7.51	60.44
Italy	2.81	11.03	7.97	59.62
Japan	27.02	3.38	27.02	61.61
Netherlands	1.09	12.96	6.85	56.03
Norway	0.98	12.12	7.52	57.70
Portugal	0.05	7.87	16.42	56.67
Spain	0.74	8.10	17.13	55.35
Sweden	1.22	11.05	7.54	60.72
UK	7.62	10.04	7.35	60.36
US	81.86	1.63	10.47	81.86

Table 6
Sources of growth based on country effects

Country	Percentage of growth from			
	Home country	Germany	Japan	United States
Australia	7.93	12.17	15.82	40.13
Austria	3.86	27.25	7.10	28.63
Belgium	2.36	22.07	6.55	30.48
Canada	4.21	7.57	10.85	62.16
Denmark	3.58	21.06	8.86	31.31
Finland	4.75	19.18	7.71	31.86
France	20.25	18.81	7.01	29.88
Germany	31.71	31.71	6.64	29.00
Greece	0.18	22.72	7.50	34.24
Ireland	0.57	18.27	8.09	34.44
Italy	9.55	19.63	7.20	33.25
Japan	32.05	9.90	32.05	39.64
Netherlands	7.87	23.29	5.98	29.18
Norway	1.66	20.29	7.48	32.06
Portugal	0.08	19.60	7.74	33.59
Spain	1.79	18.34	8.71	34.82
Sweden	8.62	18.13	7.01	34.63
UK	17.55	16.46	7.11	34.06
US	71.72	6.23	8.03	71.72

and abroad from both unpatented and patented inventions.[29] Our estimates imply that the average value of an idea patented domestically varies roughly with market size, ranging from 18 000 1988 US dollars for Portugal to $2.2m for the United States. Our estimates indicate that only a handful of countries earn much income from patented ideas. While all but the smallest countries earn most of their income from patented ideas at home, only the United States derives more than half of its total return to ideas at home.

5.4. Counterfactuals

We can make use of our estimates to consider the consequences for world growth and relative productivity of varying any number of the exogenous variables. We report the results of two such experiments.

5.4.1. US researchers

What would happen if the United States were to double the number of its researchers? Since they represent a major share of researchers throughout the OECD the impact on steady-state growth is significant, rising from 2.5 to 4.3%. Moreover, US productivity would increase relative to every country except Australia and Canada by about 10% (see Table 4).

5.4.2. World education

What would happen if every country brought its labor force up to an education level such as that of the United States (12 years)? The effect on world growth is less dramatic, rising to 2.6%. Countries with low levels of education would find their relative productivity much higher, however (see the last column in Table 4). Our results imply, for example, that Portugal, whose labor force averages only 6.5 years of schooling, would find that its relative productivity level would rise from an initial estimate 0.47 of the US level to 0.80 of the US level. (Actually its productivity is only 0.36 of the US level.)

6. Conclusion

We have developed a model of technology diffusion and growth which we fit to OECD data on patenting and productivity. Our model implies that, under a wide

[29] We are much more uncertain about the implications for these magnitudes than for productivity and growth. They rest on our rather arbitrary assumption that the hazard of imitation abroad differs from that at home on unpatented ideas but not on patented ones. Ideally we would have allowed the imitation hazard to have varied for both types of ideas but our model would not have identified additional imitation parameters with any precision.

range of parameter values, countries will eventually grow at the same rate, with a country's relative productivity determined by its ability to make use of new inventions. An implication is that relative levels of productivity rather than growth rates of productivity better reflect a country's ability to innovate or to make use of new technology. We have shown how to infer a country's inventive capacity and ability to make use of its own and others' inventions from observations on aggregate growth, relative productivity levels, and patterns of international patenting.

The sheer scale of a country's economy, and of its research community, is highly correlated with its total inventive output. A country's ability to tap into these sources of invention depends on its level of human capital, its trade relationships, and its proximity to the sources of innovation. We find that each of the 19 countries we examine relies on innovations from just three, the United States, Germany and Japan, for over 50% of its total growth. Only these three countries, plus France and the United Kingdom, derive more than 10% of their growth from research done at home. Nevertheless, while we find the extent of technology diffusion to be significant, impediments to diffusion are sufficient to generate large differences in productivity across countries.

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