MEASURING TECHNOLOGY DIFFUSION AND THE INTERNATIONAL SOURCES OF GROWTH

Jonathan Eaton
Boston University

and

Samuel Kortum
Boston University

Growth accounting based on analysis of time-series data has established that technical change explains much of the increase in worker productivity in this century.[1] Where technical change comes from and how it spreads across countries is less well understood.

Here we review a new methodology to trace the source of technical change to its origins in the inventive activity of different countries. Eaton and Kortum [1996a;1996b] develop and apply variants of this methodology to infer the sources of growth in the world economy.[2]

The methodology requires the use of indirect evidence since we observe neither the creation nor the diffusion of inventions. Productivity growth serves as a measure of the final benefits of invention, while R&D activity reflects inputs into the inventive process. What we lack is direct evidence of the channels linking increased productivity with the inventive activity that generated it. Our solution is to use patents as an indirect indicator of inventive output and to use information about where patent protection is sought to infer where inventors expect their ideas to be used.[3]

To use these data our model incorporates a decision to patent. The incentive for an inventor from country i to seek patent protection in country n is increasing in the extent to which inventions from country i diffuse to country n. Inferring the pattern of international technology diffusion implied by the pattern of international patenting and other data requires a number of specific modeling assumptions about production technologies, market structure, and inventor behavior, none of which is easy to verify directly. As a consequence, we have employed different sets of assumptions in two distinct implementations of our basic methodology. Reassuringly, the two implementations deliver the same basic message.

Two broad conclusions emerge: (1) The United States, followed by Japan and Germany, are overwhelmingly the major sources of innovation in the world economy; well over one-half the productivity growth in the countries we consider derives from innovations originating in these three countries. The United States makes the largest contribution to every country's growth with the exception (in one study) of Germany's contribution to its own growth. (2) The extent of international technology diffusion among developed countries is substantial, but not complete; an invention is more likely to be used at home than abroad. In particular, every country makes its largest contribution to growth at home. These results depict a world in which countries are highly dependent on each other's research efforts but in which domestic research is still capable of giving one country a productivity edge over another.

We organize our paper as follows. The next section develops our basic equation relating the dynamics of aggregate productivity across countries to innovative activity and patterns of international technology diffusion. We then describe how we estimate the parameters of this productivity equation. We use data on labor productivity to infer how well countries exploit the world's inventions and data on international patents to quantify the links between research and its ultimate beneficiaries. The implications of two alternative implementations of this framework are then compared. We focus on the results that relate growth in the major research economies to the countries where the innovations generating that growth occurred. The final section concludes.

A MODEL OF GROWTH AND INTERNATIONAL TECHNOLOGY DIFFUSION

We model a world in which aggregate output of a specific country results from performing a large number of tasks. An innovation raises the productivity of a worker undertaking a particular task. The process of technological diffusion spreads innovations from one country to another.

In particular, the logarithm of a country's output is

$$lnY = \int_0^1 ln[z(j)L(j)]dj, \quad (1)$$

where $L(j)$ is the number of workers engaged in task j and $z(j)$ is their productivity at this task. At any time the state of technology in the country can be described by the distribution of productivities across tasks, which we denote by $H(z)$. A natural summary measure of aggregate productivity is the mean of this distribution, which we call A.[4]

The world consists of N countries indexed by n. Research performed anywhere in the world can generate innovations that raise labor efficiency in particular tasks. A country's distribution H_n improves as it absorbs innovations. As a consequence productivity rises. Countries' aggregate productivity will depend on their ability to absorb innovations arising at home and abroad.

Our previous work has specified two alternative theories of how innovations improve the distribution of productivities in a country. Both, however, lead to the same international productivity dynamics. Letting g_n denote productivity growth in country n

$$g_n = \sum_{i=1}^{N} \epsilon_{ni} I_i \left(\frac{Ai}{A_n}\right)^{\omega} \quad n = 1, \ldots, N, \quad (2)$$

where I_i measures country i's inventiveness, ϵ_{ni} measures country n's ability to adopt i's inventions, and $\omega > 0$ captures the extent to which innovations from advanced countries are more potent.

Note that growth in any country is potentially influenced by innovations everywhere. A particular country i's contribution to another country n's growth depends on three things: (1) country i's overall inventiveness, (2) country n's ability to tap into i's inventions, and (3) country i's technological know-how relative to country n (as measured by A_i/A_n).

This characterization of growth in the international economy captures a number of special cases. At one extreme, if $\epsilon_{ni} = 0$ for all $i \neq n$ then there is no technology diffusion. The world reduces to a set of closed economies each of whose growth is driven solely by its own inventiveness. In this special case one could infer the determinants of growth by relating growth rates to characteristics, such as research effort and scale, as they vary across countries, [Levine and Renelt, 1992; Backus and Kehoe, 1992] or over time [Kortum, 1994; Jones, 1995a; 1995b].

However, if innovations diffuse internationally, as we find that they do, this approach is not valid: Growth in any given country is determined by innovations from around the world. Opposite to the closed-economy extreme is a world in which national borders do not impede diffusion at all. In this case $\epsilon_{ni} = \epsilon$ for all i and n and international productivity differences vanish. Some other force (such as imperfect capital mobility) therefore must explain differences in productivity across countries, even though technology may be the source of growth in world productivity.[5]

A primary goal of our research is to measure where we are between these two extremes. To achieve this goal we employ equation (2) to decompose each country's growth into the contributions made by innovations from itself and from other countries. In a world of no international diffusion this growth decomposition would yield a diagonal matrix, while with no international impediments to technology diffusion the rows (each corresponding to a specific destination) would be the same, since each country would be taking advantage of research anywhere to the same extent. To perform this decomposition requires having some idea of the magnitudes of the various components of equation (2). We now turn to how we estimate these magnitudes.

QUANTIFYING THE MODEL

We infer parameters by fitting the steady state of the model to data on relative productivity levels, productivity growth, international patenting, and research activity. We discuss, in turn, how we make use of each type of data.

Relative Productivities

The model has implications for relative productivity levels across countries. If inventiveness, as reflected by each country's I_i, does not change over time then, as long as $\omega > 0$, any set of countries connected by strictly positive diffusion links (ϵ_{ni}'s) will converge to a common growth rate, with each country's relative productivity level determined by its ability to absorb innovations from home and abroad. Hence in steady state there is no cross-country relationship between domestic characteristics and growth, since all countries grow at the same rate. Consequently we cannot follow the standard procedure of estimating parameters by relating productivity *growth* to country characteristics. Instead we estimate them by relating relative productivity *levels* to country characteristics.

To derive the model's predictions about relative productivity, we rewrite equation equation (2) in matrix form as $\dot{B} = \Delta B$ where B is a Nx1 vector with representative element $B_i = A_i^{\omega}$ and Δ is a NxN matrix with representative element $\delta_{ni} = \omega\epsilon_{ni}I_i$. As long as $\omega > 0$ and enough of the ϵ_{ni}'s are strictly positive (more technically, as long as Δ is indecomposable), then Frobenius' theorem ensures that this system has a unique positive eigenvalue with an associated positive eigenvector.[6] This eigenvector, defined up to a multiplicative constant, determines relative productivity levels.[7]

What determines a country's relative position? If diffusion is greater within than between countries, as we find that it is, then a country can attain a higher relative level of productivity by being more inventive. More generally, countries that are better at making use of their own and others' inventions will have higher relative productivities, but as long as enough of the ϵ's are positive, all countries will grow at the same rate.

Growth: Exogenous or Endogenous?

What determines the common steady-state world growth rate? Depending on the specification of the determinants of inventiveness, it could either be exogenous, i.e., independent of the amount of resources devoted to invention, or endogenous, i.e., increasing in those resources.

We can illustrate this point by relating inventive output I_{it} at time t in country i to the fraction r_{it} of individuals engaged in research and the size of its labor force L_{it}. We also allow inventive output to depend on the level of world productivity $\bar{A}_t$, since as the world becomes more advanced it may be harder to innovate. In particular we could set $I_{it} = r_{it}^{\beta} L_{it} \bar{A}_t^{-\phi}$ where $0 < \beta \leq 1$ to allow for potential contemporaneous diminishing returns to current research effort as the research talent pool becomes depleted and $\phi \geq 0$ to allow advances in productivity to exhaust the pool of new ideas (for a single country, the case of $\phi > 0$ reduces to the specification in Jones [1995b] and Kortum [1994]).

As discussed before, in steady state I_i must be constant over time. A further characteristic of a steady state is that a constant fraction r_i of labor is engaged in research. A steady state is thus consistent with either of two possibilities. One is that $\phi > 0$ while L_i grows at rate $n > 0$. In this case $\bar{A}$ and each A_i all grow exogenously at rate n/ϕ. Another is that $\phi = 0$ and L_i remains constant over time. In this case the growth rate is determined by the Frobenius root of the matrix Δ. This matrix, recall, has typical element $\delta_{ni} = \omega\epsilon_{ni}I_i$. Since the Frobenius root is increasing in any element of the matrix Δ, growth increases when any country increases its research effort, or when any country becomes better at adopting inventions.[8]

In either the case of exogenous or endogenous growth, we benchmark our model to match the observed average world growth rate.

Inferring Patterns of International Diffusion from Patent Data

While the N equations (2) provide a rich description of international patterns of technology diffusion, a problem is identifying the diffusion parameters ϵ_{ni} from international data on productivity. Cross-section variability is insufficient to identify all these parameters (unless the pattern of the ϵ's is radically restricted).

Our approach is to use international patenting data to help identify diffusion. Patents taken out by inventors from country i in country n reflect, among other things, the inventor's assessment of the likelihood that the invention in question will prove useful in country n. A problem is that other factors will also affect the decision to patent. Hence we model this decision explicitly. We assume that all inventions face a hazard of imitation and that patenting reduces this hazard. The quality of inventions is random. In order to be worth patenting in country n the quality of an invention from country i must exceed a threshold level that depends: (1) on the cost of patenting in country n for inventors from country i relative to country n's market size, (c_{ni}/Y_n), (2) on the strength of patent protection for inventors from country i in country n, ι_{ni}, (3) on relative overall productivity levels A_i/A_n, and, most importantly for our use of the patent data, (4) on the diffusion parameter ϵ_{ni}. We denote the probability that an invention will exceed this quality as $f(c_{ni}/Y_n, \iota_{ni}, A_i/A_n, \epsilon_{ni})$. Thus our model predicts that the number of patents taken out by inventors from country i in country n is:

$$(3) \qquad P_{ni} = I_i f(c_{ni}/\gamma_n, \iota_{ni}, A_i/A_n, \epsilon_{ni}) \quad i, n = 1,\ldots,N.$$

The systems of equations (2) and (3) have the expressions I_i and ϵ_{ni} in common. Since the latter system has N^2 equations, the identification of the parameters underlying I_i and ϵ_{ni} is greatly facilitated by estimating the two systems jointly.

Two Alternative Implementations

In both Eaton and Kortum [1996a] and Eaton and Kortum [1996b] we have implemented the general strategy of fitting the steady state of this model to a cross section of country-level data on relative productivities, growth, patenting, and research effort from the late 1980s. In these studies we also make use of data on labor forces and patenting costs which we treat as exogenous. There are several major differences in the approaches of the two papers, however:

1. In Eaton and Kortum [1996a] we specify the inventive process along the search-theoretic lines developed by Kortum [1994]. According to this approach many ideas, even if they diffuse to a country, may not raise the state of the art there. In Eaton and Kortum [1996b] we employ a variant of the Grossman-Helpman [1991] quality ladders model in which any idea that reaches a country raises productiv-

ity there. To explain heterogeneity in international patenting decisions, we generalize the specification to allow for inventive steps of random size.

2. In both studies we restrict $\epsilon_{ni} = \epsilon(x_{ni})$ where x_{ni} is a vector of exogenous variables. In Eaton and Kortum [1996a] x_{ni} is a set of country effects (country-specific dummy variables) reflecting: (1) destination country n's overall ability to absorb innovations, (2) source country i's overall ability to disseminate innovations, and a potential home-bias for when $n = i$. In Eaton and Kortum [1996b] x_{ni} consists of the distance between n and i, n's imports from i, the level of human capital in n, and a potential home-bias when $n = i$.
3. Eaton and Kortum [1996a] relates innovation to research scientists and engineers as well as the size of the labor force. Eaton and Kortum [1996b] takes this approach but also explores a variant in which national innovativeness is captured by a set of source country effects.
4. Eaton and Kortum [1996a] endogenizes research effort by equating the return to the marginal researcher to the wage of production workers. Computing the return to research imposes a substantial computational burden. Instead, Eaton and Kortum [1996b] conditions on the observed levels of research employment, in one specification, and, in another, conditions on source country effects. The results we report below are taken from the second specification.
5. Eaton and Kortum [1996b] estimates the model using data from the 19 OECD countries for which all relevant variables were available. Because of the much greater computational burden of endogenizing research effort, Eaton and Kortum [1996a] restricts itself to the top five research economies (measured either in terms of research scientists and engineers or in terms of patenting in major destination countries): the United States, Japan, Germany, France, and the United Kingdom.
6. Eaton and Kortum [1996a] uses as its productivity measure van Ark's (1995) estimates of value added per hour in manufacturing adjusted for capital accumulation. Since this measure was not available for the wider sample Eaton and Kortum [1996b]uses GDP per worker from the Summers-Heston [1991] dataset.[9]

INTERNATIONAL SOURCES OF PRODUCTIVITY GROWTH

What does equation (2) imply about the sources of growth when we insert our estimates of the relevant parameters from these two studies? Despite the differences in implementation, the two approaches yield remarkably similar decompositions of the sources of growth. The top part of Table 1 presents these decompositions using estimates from Eaton and Kortum [1996a] and Eaton and Kortum [1996b] (in parentheses) for the five leading research economies. Since Eaton and Kortum [1996b] uses a wider sample of countries, for this case we also present the contribution of the other OECD countries, aggregated together.

Both sets of estimates imply home-bias, yet all countries except the United States obtain more growth from abroad than from domestic research. The United States is by far the major source of growth, followed by Germany and Japan. One difference is

TABLE 1
Sources of Growth

	Source					
Destination	Germany	France	United Kingdom	Japan	United States	OECD
Germany	.16	.08	.07	.27	.42	0
	(.32)	(.08)	(.07)	(.07)	(.29)	(.17)
France	.13	.11	.07	.26	.42	0
	(.19)	(.20)	(.08)	(.07)	(.30)	(.16)
United Kingdom	.15	.07	.13	.32	.33	0
	(.16)	(.08)	(.18)	(.07)	(.34)	(.17)
Japan	.14	.07	.07	.35	.36	.07
	(.10)	(.04)	(.04)	(.32)	(.40)	(.10)
United States	.10	.05	.05	.20	.60	0
	(.06)	(.03)	(.03)	(.08)	(.72)	(.08)
R&D share	.10	.04	.07	.30	.49	0

that Eaton and Kortum [1996b] attributes more growth in the European countries to Germany relative to Japan.

To relate the sources of growth with research effort we report the share of private-sector research scientists employed in each of the five source countries in the last row of the table, based on OECD (1991) data.[10] A country's research effort does appear to match up roughly with its contribution to growth. We estimate that the French and Germans contribute slightly more to growth in other countries than their research effort would suggest, while Japan and the United States contribute slightly less. Because of home bias, each country derives more of its own growth from domestic inventiveness than its share in total research would imply.

The growth decompositions in the table are just one output of the methodology we have described. Although these results provide a glimpse of the technological links among countries, they do not provide insight into important policy questions such as how promotion of research in one country affects other countries as well as itself. But, as we show in Eaton and Kortum [1996a, 1996b], we can use estimates of the structural parameters of our models to shed quantitative light onto exactly these sorts of issues.

CONCLUSION

Several prominent economists have argued that technology and technology flows are inherently not susceptible of quantitative analysis. Krugman, for example, argues that "Knowledge flows, ... , are invisible; they leave no paper trail by which they may be measured and tracked, and there is nothing to prevent the theorist from assuming anything about them that she likes" [1991, 53-54]. According to Dougherty and Jorgenson "The impact of spillovers has remained the primary focus of research in economic growth under the rubric of 'endogenous technological change'. This research has retained the national accounting framework of Kuznets [1971] and Solow [1957], but has failed to provide a quantitative determination of the contribution of spillovers to economic growth" [1996, 28]. Finally, in our cross-country context, Mankiw argues "Yet for practical macroeconomists trying to understand international differences, the payoff from endogenous growth theory is not clear. Models that emphasize unmeasurable variables such as knowledge are hard to bring to the data" [1995, 300].

Knowledge flows do indeed leave "paper trails" in the form of international patents. We have shown how to use them to quantify the contribution of technology flows to economic growth.

NOTES

1. Solow [1957] is, of course, the classic reference. Jorgenson and his collaborators, by "broadening the concept of substitution employed by Solow [1957]," find that traditional factors of production contribute more to growth [Dougherty and Jorgenson, 1996, 25]. Nonetheless, technical change remains a big contributer: From 1960 to 1989 technical change accounts for over one-fourth of per capita output growth in the United States, about one-half of per capita growth in Japan, and well over one-half in each of France, Germany, and the United Kingdom [Dougherty and Jorgenson, 1996]. Furthermore, these estimates should be considered lower bounds on the importance of technical change since they ignore the fact that technical change provides the incentive for capital deepening.
2. Other studies that have also quantified the importance of international technology diffusion to productivity growth are Coe and Helpman [1995], Benhabib and Spiegel [1994], Parente and Prescott [1994], and Keller [1996].
3. Others using patent data to chart the development of knowledge are Griliches [1990], Caballero and Jaffe [1993], and Kortum [1994]. They do not, however, consider the international diffusion of technology. Another literature fits patterns of international patenting to a "gravity" equation [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 U.K. 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 relate 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.
4. This is what aggregate output per worker would be if the same number of workers were doing each task. A benevolent social planner would choose this allocation since it maximizes output. In the market equilibrium we consider, however, producers of different inputs will typically charge different markups, so that productivity will not be this high. Productivity is nevertheless proportional to our index A.
5. Mankiw [1995] advocates this case. An implication, noted by Lichtenberg [1992], is that cross-sectional differences in national levels of productivity should then be unrelated to cross-country differences in national research expenditures. Instead Lichtenberg finds that countries that spend more on research attain higher levels of productivity.
6. McKenzie [1960] and Takayama [1974] discuss the relevant mathematics.
7. An interesting special case is that $\epsilon_{ni} = \epsilon_n \epsilon_i$, meaning that the number of new ideas available to country n depends only on its ability to adopt ϵ_n. National *growth rates* of productivity will converge if a more backward country finds that it has more to gain from a given idea (i.e., $\omega > 0$). But differences in productivity *levels* will be determined by differences in abilities to adopt technology. As with equal diffusion, this case implies that a greater national research effort confers no relative national advantage. Parente and Prescott [1994] take this approach in relating a country's level of productivity to its willingness (promoted by low tax rates) to adopt new technologies from around the world. Benhabib and Spiegel [1994] also take this approach in a model in which high levels of human capital promote adoption.
8. In the case of exogenous growth, increases in I_i or ϵ_{ni} increase the overall level of world productivity, without affecting steady-state growth.
9. Under the assumption of perfect capital mobility, output per hour raised to the power of one minus capital's share provides an index of the level of total factor productivity. Even if capital mobility is imperfect, output per hour, so adjusted, may be the best index for total factor productivity given the difficulty of measuring capital stock *levels*.
10. The last row of Table 1 represents R&D scientists and engineers employed in the business sector multiplied by the fraction of R&D performed by the business sector that is financed by the business sector or by foreign sources. The objective is to exclude researchers who are primarily engaged in government-financed defense research. We performed this calculation only for the top five research economies.

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