European technology policy

Research efforts in Europe matter

SUMMARY

European countries do less research than Japan and the United States. But their lower level of research effort has more to do with the smaller markets facing European inventors than with lower research productivity. Europe has substantial research potential, in that increasing research effort in most European countries generates bigger income benefits there than increasing research effort in the United States and Japan by equivalent amounts. Research subsidies, enhanced patent protection, support for public research, higher educational achievement and increased integration are alternative routes towards exploiting this potential. These policies increase productivity not only in Europe, but also elsewhere. One problem with implementing such policies at the national level is the potential for free riding. A second possible problem with policies to promote research concerns their distributional consequences. While all countries within the European Union would benefit from increased research output, the countries that are already best at doing research, which tend to be the richer members, do best. The benefits of policies that facilitate the adoption of innovations are more evenly spread among richer and poorer countries.

— Jonathan Eaton, Eva Gutierrez and Samuel Kortum

Economic Policy October 1998 Printed in Great Britain

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Jonathan Eaton, Eva Gutierrez and Samuel Kortum
Boston University

1. INTRODUCTION

By a number of measures the recent economic performance of Europe has been sluggish. Average GDP per capita in the European Union (EU) is only about two-thirds that in the United States, and is below that in Japan, as shown in Table 1. The generally lower level of per capita employment in Europe explains some of the problem, but output per active worker in the EU is still only 83% of the US level and just higher than Japan's. While productivity in some individual EU members is impressive, a perception remains that Europe has been falling behind. Associated with the sense of relatively poor aggregate performance is Europe's apparent failure to be a player in such burgeoning 'high-tech' industries as electronics, computer software and biotechnology.[1]

A possible culprit is Europe's research performance. European firms, on average, employ a substantially smaller fraction of their workers as researchers, as Table 1 reports. Measures of research output are also not flattering to Europe. In 1993, the average worker in Japan applied for over twice as many US patents as the average worker in the EU. Even on its home turf, European patent activity has not been impressive. The average US and Japanese worker sought more German patents than the average non-German worker in the EU.

We thank Philippe Aghion, Katharine Rockett, Klaus F. Zimmermann and other participants in the twenty-seventh Economic Policy Panel meeting for their excellent comments.

[1] See, e.g., the European Commission's 'Green Paper on Innovation' (1995), henceforth EC 1995. On the last point, Zucker and Darby (1995) document that star US bioscientists are much more likely to have a tie with a business enterprise than are their European counterparts.

Table 1. Is the European Union technologically backward?

Country	GDP per capita (1)	GDP per worker (2)	Researchers in business (no. of persons) (3)	Research intensity (%) (4)	Patenting intensity in Germany (1/1000) (5)	Patenting intensity in the USA (1/1000) (6)
USA	27 821	58 329	764 500	0.635	0.197	–
Japan	23 235	45 049	257 094	0.398	0.204	0.567
EU	19 318	48 958	375 775	0.257	0.177	0.250
Austria	21 395	50 496	4 010	0.122	0.295	0.225
Belgium	21 856	60 031	8 750	0.232	0.200	0.220
Denmark	22 418	46 303	5 883	0.237	0.250	0.320
Finland	18 871	46 102	5 453	0.267	0.405	0.534
France	20 533	53 508	66 455	0.299	0.237	0.256
Germany, W.	21 200	50 376	128 956	0.366	–	0.387
Greece	12 743	34 462	1 319	0.035	0.011	0.011
Ireland	18 988	51 799	2 576	0.218	0.101	0.143
Italy	19 974	57 173	27 932	0.136	0.115	0.110
Netherlands	20 905	52 479	11 370	0.192	0.384	0.312
Portugal	13 100	30 868	481	0.011	0.004	0.004
Spain	14 954	47 302	11 256	0.092	0.032	0.031
Sweden	19 258	43 327	15 334	0.386	0.365	0.527
UK	18 636	41 416	86 000	0.336	0.179	0.272
Australia	20 376	44 472	13 976	0.188	0.094	0.191
Canada	21 529	47 159	35 484	0.273	0.061	0.320
New Zealand	17 473	37 682	1 508	0.101	0.095	0.143
Norway	24 364	50 077	7 141	0.356	0.125	0.182
Switzerland	25 402	47 537	8 600	0.225	0.808	0.580

Notes: Columns (1) and (2) are for 1996, while the rest of the data are for 1993. GDP is translated to current dollars by the OECD using their PPPs. The number of workers is OECD employment. Researchers are R & D research scientists and engineers employed in business enterprises. Missing observations for 1993 were filled in with the latest year available. Research intensity is the researchers expressed as a percentage of total employment. Patenting intensity is the number of patent applications in either Germany or the USA per thousand workers in the inventor's country. We do not report domestic patent applications, since they are not comparable due to the large home bias in patenting.

As Table 1 also indicates, the figures for the EU overall mask considerable variability within its membership. Some European countries, such as Germany and Sweden, appear to be leading innovators as measured by either research intensity or patenting intensity. But the question remains as to how innovative effort translates into productivity advantage.[2]

For Europe's low research output to explain poor performance in other arenas

[2] Concern about Europe's 'research gap' with the USA and Japan is not new. Citing work from the 1960s lamenting Europe's technological backwardness, Patel and Pavitt (1987) provide a detailed comparison of the research achievements of Japan, the USA and Europe between 1963 and 1983. They conclude that concern about Europe's research situation was overblown. What we find here is that, while a few European countries are rather uncompetitive as research centres, others are very innovative. But the smaller market size facing their inventors keeps them from fully exploiting their research potential.

implies that impediments exist to the flow of ideas from the rest of the world. If Europe could exploit inventions from the USA and Japan as readily as the innovators themselves, its own lack of inventiveness would convey no overall productivity disadvantage. To the extent that barriers to diffusion do limit the amount of productive knowledge that flows between countries, however, innovative lethargy can explain economic doldrums.

If a stagnant research sector is the problem, why has Europe been less innovative than the USA and Japan? There are two possible answers. One is that research is not rewarded in Europe to the extent that it is elsewhere. Low rewards could be the consequence of fragmented markets, weak patent protection or the absence of subsidies. Another answer is that Europe is just not very good at doing research, either because it has fallen too far behind the technological frontier, or because it lacks the necessary research infrastructure.[3]

The two explanations suggest different policy responses. Market integration, more effective and cheaper patent protection, and government subsidies increase the rewards to innovative activity, while enhanced access to foreign technology and improved infrastructure increase research productivity. In fact, as a visit to the Web page of the European Union (http://europa.eu.int) reveals, proposals along all of these lines are under discussion.

Missing from the discussion is any assessment of the role of incentives versus productivity in determining why Europe is not more innovative, or any quantification of how much various policies would help. Two questions need to be answered in assessing benefits relative to costs. First, how effective is a policy in stimulating research effort and, more importantly, innovative output? Second, which countries, if any, are the ultimate winners in terms of productivity and income? Increased innovation might improve Europe's economic performance relative to countries elsewhere, confer improvements globally, or achieve some combination of the two. Alternatively, increased innovation might have no discernible effect, either because Europe's potential contribution is so small or because it displaces innovation elsewhere.

A further set of questions concern the implications of various policies for the individual European states. What are the gains, if any, from co-ordinating or centralizing policy? Are some countries much better at research than others? How might research be reallocated within Europe? What is the impact on the distribution of income in Europe?

Different approaches to promoting innovation have very different impacts, especially in an international context. Government subsidies typically support activities carried out domestically, regardless of where the results get used, while

[3] Schmookler (1966) emphasizes the importance of market size, in contrast to research productivity, as a determinant of innovative activity. König and Zimmermann (1986), in examining firm-level data on innovation, find an important role for the size of a firm's market in influencing its research effort.

patents reward research that ends up being used domestically, regardless of where it took place. A government research lab may promote innovation locally, or may spur inventive activity worldwide. On the cost side, government subsidies and spending on infrastructure use up tax revenue, while tougher patent protection inhibits competition.

Eaton and Kortum (1996, 1998) model the determinants of productivity, research activity and innovation in a world economy in which ideas diffuse imperfectly across borders. Eaton *et al.* (1998) extend the model and estimate it using data on productivity, research effort and patenting from 21 OECD countries in the period 1988–90. What we do here is to use this framework and the parameter estimates to provide some quantitative insight into the European situation and to examine what various alternative policies might do.[4]

We find that Europe does indeed suffer relative to the USA from having smaller and more fragmented markets for its innovations. With a few exceptions, however, we do not find European countries as a whole lacking in intrinsic capacity to do research or in research infrastructure, although our model suggests that Europe might suffer from a lower knowledge base. When we ask, for example, where would more research effort do Europe the most good (in terms of raising EU average income), our answer is in Germany. Moreover, more research anywhere in Europe would make a larger contribution to average European income than more research in the USA or Japan.

In terms of various policies, the basic picture that emerges is that research in Europe is very responsive to various types of research policy. Direct research subsidies have a substantial effect on research inputs, with an elasticity of about 4, although our framework does not incorporate the many problems with implementing such policies. But we also find that improved patent protection, if pursued at a continental level, also raises research effort substantially.

Moreover, increasing research effort yields a pay-off. It takes less than a 5% research subsidy to raise average per capita income levels in the European Union to a higher steady-state level of 10%. But the benefits are not confined to the EU. Non-EU members in Europe benefit by about as much, while Australia, Canada, Japan and the USA benefit to a lesser extent. Stronger patent protection in the EU provides another means of achieving higher productivity levels, but here the spillover effects are even greater.

Hence a potential problem is that, since the benefits of such research promotion policies are largely shared, only the largest European economies, such as Germany, have much incentive to pursue them on their own. The rest have little incentive to

[4] To justify our reliance on this framework, we quote two experts on the European research scene: 'In principle, any discussion of the policy implications of technology should be based on a fully worked out theory of the role of technology in international trade, investment, growth, and welfare; and of the role of government in dealing with "market imperfections"' (Patel and Pavitt, 1987).

engage in these policies unilaterally. Our results therefore suggest a role for a co-ordinated technology policy in Europe.

In section 2, we take a look at some measures of productivity performance, national research activity and innovation. We then, in section 3, describe our methodology. In section 4 we discuss what our model says about why the situation in Europe is as it is. Then, in section 5, we examine some implications of various policy alternatives. Section 6 concludes.

2. RESEARCH IN EUROPE: A CLOSER LOOK

What do the data tell us about research in Europe? In this section we give a statistical overview of research effort at the national level, the sectoral composition of research, and patenting activity in Europe and in other developed countries.

2.1. Aggregate research effort

The OECD reports expenditure on R & D by country broken down by sector of performance and by source of funding. Of particular relevance are: (1) R & D performed and funded by business enterprises, (2) R & D performed by business enterprises but not necessarily funded by them, and (3) total R & D spending. The first measure might be called private sector research, while the latter two include a narrow and a broad measure, respectively, of government research support. The OECD also reports employment of R & D scientists and engineers by sector of employment. To obtain a measure of researchers analogous to private sector research expenditure, we multiply research employment in the business sector by the fraction of business sector R & D that is financed by the business sector.

The scale of a region's research effort is relevant to gauge its influence on technological change. For example, the third column of Table 1 shows that the EU is between Japan and the United States in terms of its overall number of researchers. More telling about research effort, however, is a measure that corrects for size. Hence in column (4) of Table 1 we report, as a measure of research intensity, employment of researchers divided by total employment. Here the EU comes in third.

Europe's third-place ranking is not a consequence of this particular definition. Figure 1 presents four different measures of research intensity for Europe, Japan and the USA during 1988–90. For both the expenditure-based and the employment-based measures, one version incorporates research in all sectors and one includes only private sector research. While Japan is actually ahead of the USA according to the expenditure-based measures, Europe is consistently third.

Figure 2 focuses on the employment-based measures of research intensity, across all of the 21 countries. The shaded bars portray total research scientists and engineers as a fraction of the labour force, while the white bars represent only those

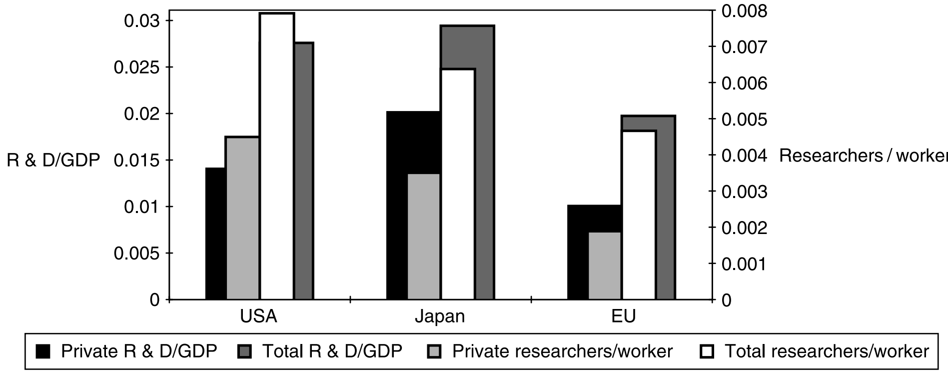

Figure 1. Indicators of research intensity

who both work in and are funded by the business sector. The picture is one of a Europe that on average devotes a smaller share of its resources to R & D than do the USA and Japan. But note also the tremendous variation in research effort within Europe, especially in the private sector. Some individual European countries, such as Germany, Sweden and Switzerland, are highly research intensive. On the other hand, Greece and Portugal devote only a tiny fraction of their resources to research. The disparity in the absolute scale of research between the large and small countries of Europe is even greater.

2.2. Industry composition

One possible reason for cross-country variation in research effort is cross-country variation in industry composition. Industries vary widely in their reliance on research, and research may occur close to production. A country's high research

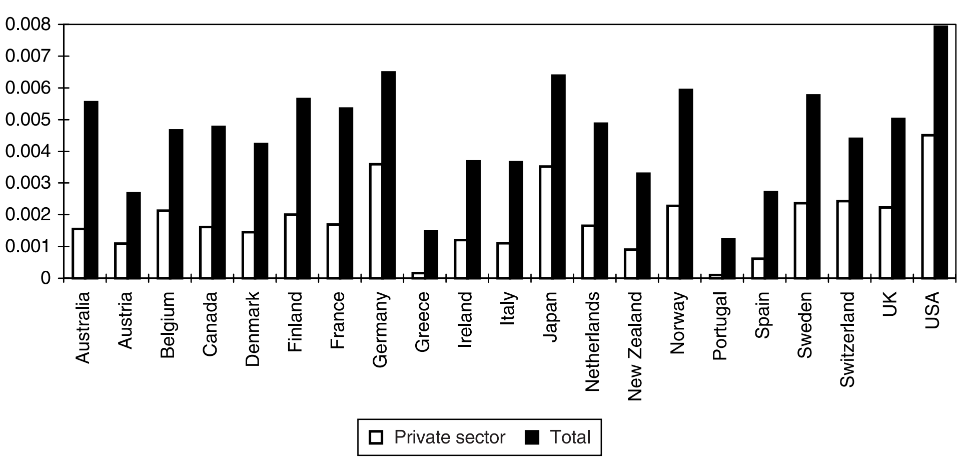

Figure 2. Researchers as a fraction of the workforce

intensity might thus reflect its specialization in research-intensive industries. Alternatively, research-intensive countries may have roughly the same industry composition as others, but simply do more research overall.

To get a handle on the role of overall level effects versus industry-composition effects, we decompose total research intensity (business enterprise research scientists and engineers as a fraction of employment) in country c, denoted r_c, as

$$r_c - r_w = \sum_{i=1}^{I} (s_{ic} - s_{iW}) r_{iW} + \sum_{i=1}^{I} (r_{ic} - r_{iW}) s_{iW} + \sum_{i=1}^{I} (r_{ic} - r_{iW})(s_{ic} - s_{iW}) \quad (1)$$

where r_W is research intensity across all countries, s_{ic} is the employment share of industry i in country c, s_{iW} is the share of industry i in the employment of all countries, r_{ic} is research intensity in industry i in country c, and r_{iW} is research intensity in industry i over all countries. (I is the number of industries.) We thus divide the difference between country c research intensity and the world average into three components: (1) the composition effect, how much employment in country c is weighted toward research-intensive activities, (2) the intensity effect, how much country c is relatively research intensive across all industries, and (3) the interaction effect, measuring how much c's industry composition is tilted towards industries in which it is unusually research intensive.

Figure 3 reports this decomposition for fifteen countries across seven industries in the period 1988–90.[5] Each country has four bars. On the left is the country's overall research intensity relative to the average. Following (from left to right) are the contributions of (1) composition, (2) intensity and (3) interaction, respectively, to the total. In general, the cross-country pattern of overall research intensity is explained by the intensity effect: major research economies tend to do more research across industries. The composition and interaction effect explain very little of the variation in research intensity. Thus understanding why some countries emerge as research centres requires knowing why they do more research overall, not why they are attractive to high-tech sectors.

2.3. Research and patenting

Patenting in the USA provides a measure of the effectiveness of research performed in different countries. If patents reflect research output, while expenditure or personnel data reflect inputs, we should see a tight relationship between the two. The expected relationship between research effort and patenting in the USA comes

[5] Data limitations forced us to reduce the number of countries from 21 to 15. (Switzerland, for example, does not provide any industry breakdown of research activity.) The seven industries are Chemical-linked (food, textiles and plastics), Earth-linked (wood and furniture, paper and printing, non-metallic minerals and miscellaneous), Chemicals, Metals, Machinery, Electrical and Transportation.

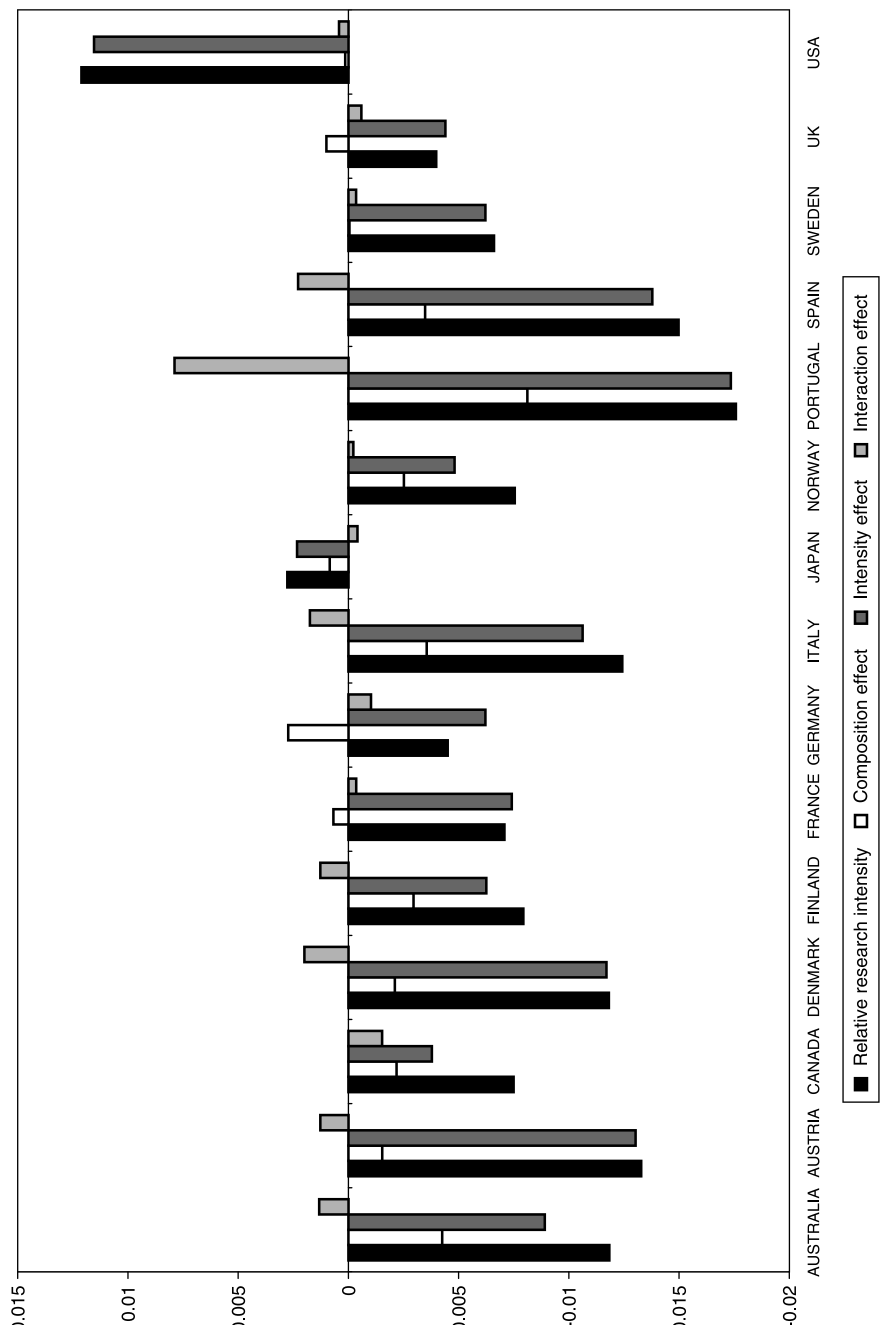

Figure 3. The effect of industry composition on research intensity

through clearly in Table 1. The relationship is not simply driven by variation in country scale, since we have divided both patenting and private sector R & D by each country's workforce. Note that Switzerland, Japan, Finland and Sweden are the leaders in terms of patenting per worker, with Portugal, Greece and Spain at the other extreme. Although Japan is known to be aggressive in seeking US patent protection, the top European countries do not look too bad in comparison.

3. A FRAMEWORK FOR ASSESSING INTERNATIONAL TECHNOLOGY POLICY

We now turn to an analytic framework that can account for these various figures. It needs to explain: (1) how domestic and foreign markets provide incentives to do research, (2) how this research generates ideas that advance technology, and (3) how these ideas are reflected in productivity around the world. Eaton *et al.* (1998) provide a framework that integrates these three relationships into a general equilibrium model of growth in the world economy. In the sections that follow, we examine Europe's current situation and assess the implications of various European technology policies, using an estimated version of this model. But first we describe the bare bones of how the model incorporates the three key ingredients, taking them in reverse order.[6]

3.1. Productivity and ideas

Non-tradable intermediate inputs combine to produce tradable output Y through the production function

$$\ln(Y/J) = J^{-1}\int_0^J \ln[Z(j)K(j)^{\phi}L(j)^{1-\phi}]\,dj \tag{2}$$

Here $K(j)$ is the amount of capital used in making input j, $L(j)$ the amount of labour, and ϕ the capital elasticity. The term $Z(j)$ represents productivity in making input j (or, equivalently for our purposes, the quality of that input in producing output). The range of inputs and, except for $Z(j)$, the technologies for producing them are the same across inputs, countries and time.

The average quality of inputs will generally differ across countries and over time depending on patterns of innovation and adoption. A natural measure of the average level of technology at any place and time is simply the geometric average of the $Z(j)$s, which we call A. Indeed, if factors were allocated efficiently across sectors,

[6] This theoretical framework extends the quality ladders model of Grossman and Helpman (1991a, b) and Aghion and Howitt (1992) to a setting in which multiple countries are innovating and making use of each other's innovations. Aghion and Howitt (1998) provide a recent survey of the closed-economy endogenous growth literature, which was pioneered by Phelps (1966), Shell (1966) and Nordhaus (1969).

A would correspond to total factor productivity. As discussed below, however, associated with innovation are monopoly mark-ups that lead to an inefficient allocation of labour.

An invention is an idea for making a particular input more cheaply, or for improving its quality: if adopted at home, an invention of size q makes the quality of a specific input e^q times better. We interpret q as the inventive step and assume that for each invention it is drawn from an exponential distribution with parameter θ. The average inventive step of a domestic invention is thus $1/\theta$, but ideas can differ in size.

Since a given idea might provide a larger percentage contribution in a more backward country, we allow an idea from country i that constitutes an improvement q at home to provide country n with an improvement of $q(A_i/A_n)^{\omega}$, where ω relates the step size of inventions to the technology gap between source and destination.

Ideas differ in their universality as well as in their size. Some inventions might be adopted widely, while others might find use in only a small number of countries. Important for our analysis are the fractions of inventions from each country that are used in each country. We use ε_{ni} to denote the fraction of ideas from country i that are used in country n. If some country n is particularly good at adopting ideas, then its ε_{ni}s will be high compared with other countries as destinations. If ideas are more likely to be used at home than abroad, we would expect the ε_{ii}s to exceed the ε_{ni}s for which $n \neq i$. Countries differ in their ability to generate ideas. We use the parameter α_i to represent the flow of ideas generated in country i.

Putting these concepts together gives us a fundamental relationship between the growth of technology g_n in each country n and the generation of ideas around the world:

$$g_n = \frac{1}{j\theta} \sum_{i=1}^{N} \varepsilon_{ni} \alpha_i \left(\frac{A_i}{A_n} \right)^{\omega}. \quad n = 1, \ldots, N \tag{3}$$

Here N is the number of countries.

Note that, as a destination country gets further behind, ideas that arrive have a larger percentage effect on productivity (as long as $\omega > 0$). 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.[7] In the steady state of the model, the αs and εs are constant, technology grows at the same rate in all countries, and the system of equations (3) determines levels of technology in each country relative to country N as well as a common technology growth rate g.

This relationship points to how a country's productivity depends both on the flow

[7] This force can be interpreted as Gerschenkron's (1962) 'advantages of backwardness'. See Eaton and Kortum (1996).

of ideas generated around the world and on its ability to make use of those ideas. National policies to promote technology include: (1) measures to stimulate innovative output at home, (2) measures to stimulate innovative output in other countries whose ideas feed domestic technology, and (3) measures to enhance the adoption of ideas.

We relate ε_{ni} to the distance between i and n, imports of n from i, the level of education in country n, and whether n and i are the same country. In particular:

$$\ln \varepsilon_{ni} = \varepsilon_D DH_{ni} + \varepsilon_{KM} KM_{ni} + \varepsilon_{KM^2} (KM_{ni})^2 - \varepsilon_{HK} \frac{1}{HK_n} + \varepsilon_{IMP} \ln IM_{ni} \tag{4}$$

where DH_{ni} is a dummy variable that equals 1 if $n = 1$ 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 i's GDP (set equal to 1 if $n = 1$). We turn next to the determinants of the αs.

3.2. Generating ideas

We relate a country's inventiveness to its research effort, which involves scientists, other workers and materials.[8] Since increasing research effort may force a country to use less talented researchers, we assume that the productivity of additional researchers declines as the fraction of researchers employed relative to the total labour force rises. We also allow countries to differ fundamentally in the environments that they provide for research activity. Finally, we allow for the possibility that, as technology progresses, coming up with new ideas may become harder and harder.

Combining these effects, we specify a country's inventive output as

$$\alpha_i = \alpha_i (r_i^{\beta} L_i)^{\beta_L} M_i^{1-\beta_L} \overline{A}^{-\gamma} \tag{5}$$

Here L_i is country i's total labour force and r_i the fraction engaged in research, with β reflecting the rate at which research productivity declines as more people do research; β_L is the labour share in the innovative process; and M_i denotes materials used in innovation. The parameter α_i captures the country's research productivity or ability to provide an environment conducive to research. Finally, $\overline{A}$ is the average state of technology in the *world*, reflecting the state of world knowledge. As world technology advances, coming up with better ideas becomes harder, as governed by the parameter γ.[9] We assume that each scientist employed in innovation requires b additional workers.

[8] We estimate the share of labour as an input in innovation by its percentage of total R & D cost. Based on OECD data, for the countries in our sample, labour, capital and materials account respectively for 48%, 18% and 34% of R & D costs. We simplify by combining capital with materials used in research.

[9] A strictly positive γ yields Jones's (1995) explanation for the slowdown in US research productivity. For $\gamma = 0$ growth is endogenous, while if $\gamma = 1$ it is only 'semi-endogenous'.

We assume that the labour force of each country grows at a common rate g_L. We consider a steady state in which inventive output nonetheless remains constant as the growth of human and materials inputs in research is just offset by the 'research drag' from rising world technology.

Policies affect inventive output in two ways. One is by increasing resources devoted to R & D activities, i.e. r or M. The other is by increasing research productivity a.

3.3. Research incentives and patenting

The rewards to employing people or materials in research depend on both their marginal product in coming up with ideas and the value of those ideas to the inventor. We use V_i to denote the average value of an idea to an inventor in country i (which will not, in general, correspond to its social value).

We use aggregate output as numeraire. Hence output will be devoted to research (in the form of R & D materials) up to the point at which its marginal value product equals $1/(1+s_i)$, where s_i represents the R & D subsidy in country i. Similarly, labour will be devoted to research until $(\delta\alpha_i/\delta r_i)(V_i/L_i)$ is equal to $w_i/(1+s_i)$, where w_i is the production wage.

Solving the labour market equilibrium condition for r gives, in logarithms:

$$\ln r_i = k^r + \frac{1}{\beta_L(1-\beta)}\left[\ln(1+s_i) + \ln a_i + \ln\left(\frac{V_i}{w_i^{\beta_L}}\right)\right] + u_i^r \tag{6}$$

Here k^r is a constant common to all countries, which incorporates, among other things, the 'research drag' imposed by the existing world stock of ideas $\overline{A}$ on research productivity, and u_i^r is a multiplicative error in our measure of research intensity. (As noted in section 2, there are many alternative measures that give somewhat different readings on countries' research efforts.)

Our policy discussion considers a government's influence on three key terms entering equation (6). A government can set subsidies directly, as governments often do through the tax treatment of R & D expenditure and income.[10] A government might also enhance the productivity of private research through education and public sector research. Finally, patent policy affects the value of ideas. But lacking any comprehensive data, in fitting equation (6) to the cross-country data on research effort appearing in column (1) of Table 4, we set research subsidies to zero.

The estimating equation highlights the two systematic sources of variation in research activity posed by Schmookler (1966): (1) differences in research productivity a_i and (2) differences in the value of inventions relative to the wage $(V_i/w_i^{\beta_L})$.

[10] Bloom *et al.* (1998) discuss differences in the tax treatment of R & D across 8 of our 21 countries.

To give the equation substance, it remains to determine V_i and w_i. We assume that, as long as an idea has not been imitated or rendered obsolete by further invention, its inventor can charge a mark-up over cost equal to the inventive step of the idea over the previous state of the art.

Imitation depends on: (1) whether the innovation is patented, (2) whether the innovation is from a local or foreign inventor, and (3) the level of intellectual property protection provided by the destination country. For unpatented inventions the third factor is irrelevant. Hence an unpatented invention from country i in country n faces an imitation hazard ι_{ni}^{not} given by

$$\iota_{ni}^{not} = \begin{cases} \iota_D^{not}, & n = i \\ \iota_F^{not}, & n \neq i \end{cases} \tag{7}$$

For an invention that is patented, the hazard ι_{ni}^{not} is

$$\iota_{ni}^{pat} = \begin{cases} \iota_D^{not}(IP_n)^{\gamma_{IP}}, & n = i \\ \iota_F^{not}(IP_n)^{\gamma_{IP}}, & n \neq i \end{cases} \tag{8}$$

where IP_n is an index of the strength of intellectual property protection in country n. Once an innovation is imitated, it is generally available, so the mark-up falls to zero. While imitation rates appear in the model as parameters, the hazard o_n of obsolescence in country n depends endogenously on the flow of ideas arriving there.

Let π_{nu} (q) denote the profit generated by an invention of size q in country n at time u, and ρ the discount rate (treated as an exogenous constant). Given a patent duration of T_n years in country n, the value there at time t of an invention of quality q from country i, if it is patented, is

$$V_{nit}^{pat}(q) = \int_0^{T_n} \pi_{nt+s}(q) e^{-(\rho + \iota_{ni}^{pat} + o_n)s} ds + \int_{T_n}^{\infty} \pi_{nt+s}(q) e^{-(\rho + \iota_{ni}^{not} + o_n)s} ds \tag{9}$$

If it is not patented, the value is

$$V_{nit}^{not}(q) = \int_0^{\infty} \pi_{nt+s}(q) e^{-(\rho + \iota_{ni}^{not} + o_n)s} ds \tag{10}$$

An inventor from i decides whether to apply for a patent in country n after learning the size of her invention and whether it is applicable in that country. A patent gives the inventor the incremental benefit of a lower hazard of imitation in n, so is worth $V_{ni}^{pat}(q) - V_{ni}^{not}(q)$. Hence, if it costs the inventor C_{ni} to patent there, an application is worthwhile if $V_{ni}^{pat}(q) - V_{ni}^{not}(q)$ exceeds C_{ni}. This condition determines a threshold quality level $\overline{q}_{ni}$ such that inventions of higher quality are patented, while those of lower quality are not. The fraction of diffused ideas that are worth patenting is thus $f_{ni} \equiv \exp(-\theta_{ni}\overline{q}_{ni})$. We assume, however, that patent applications are subject to an additive error η and multiplicative error u_{ni}^P. Putting these things together, and taking logarithms, our patent equation is

$$\ln P_{ni} = \ln \alpha_i + \ln \varepsilon_{ni} + \ln[f_{ni} + \eta(1 - f_{ni})] + u_{ni}^P \tag{11}$$

We use this equation to estimate cross-country patterns of patenting.

To ascertain the expected returns to research, we first note that an invention from country i of size q has value in country n, conditional on making it there, of

$$V_{ni}(q) = \begin{cases} V_{ni}^{pat}(q) - C_{ni}, & q \geq \bar{q}_{ni} \\ (1-\eta)V_{ni}^{not}(q) + \eta(V^{pat}(q) - C_{ni}), & q < \bar{q}_{ni} \end{cases} \tag{12}$$

When deciding to do research, however, an inventor does not know how large her invention will be or how widely it will be used. Unconditional on quality or diffusion, then, the expected value of an idea is

$$V_i = \sum_{n=1}^{N} \varepsilon_{ni} \int_0^\infty V_{ni}(q)\theta_{ni} e^{-\theta_{ni} q}\, dq \tag{13}$$

which is what matters for labour market equilibrium, condition (6).

A major policy influencing the value of an idea is thus the strength of patent protection. Tougher patent protection, by reducing the hazard of imitation, increases the value of ideas not only for a local inventor, but for any foreign inventor whose idea might be used in the country. Hence tougher patent protection raises the reward to research not only at home, but in foreign countries whose ideas the domestic market draws upon. Strengthened protection comes at the cost of higher mark-ups in local markets and, when inventors are foreign, in greater royalty payments abroad.

The production wage w_i depends on the level of technology A_i and the extent of monopoly distortion. Our model implies that mark-ups in country i are a random variable U_i with a complicated distribution that depends, among other things, on the nature of i's patent protection and its ability to absorb ideas.[11] Our assumptions here imply that

$$w_i = (1-\phi)\left(\frac{\phi}{\rho}\right)^{\phi(1-\phi)} A_i^{1/(1-\phi)} \{e^{-E[U_i]}\}^{1/(1-\phi)} \tag{14}$$

Note that the wage is higher when technology A_i is more advanced, but lower when the average monopoly mark-up $E[U_i]$ is greater.

Finally, we relate countries' observed labour productivities to their technology levels. Three issues arise in this connection. First, since production uses capital, we make an adjustment to move from total factor productivity to labour productivity, assuming perfect capital mobility. Second, we need to account for the role of mark-

[11] We spare the reader its derivation here, referring the curious to Eaton *et al.* (1998).

ups in lowering the efficiency of labour allocation in the economy. Third, some workers do research but do not produce measured output.

In fitting our model to data on labour productivity y_n, we assume that it is observed with error u_n^y, and normalized by productivity in one country (N). Putting all this together, our estimated productivity equation is

$$\ln(y_n/y_N) = \ln(\Gamma_n/\Gamma_N) - \frac{1}{1-\phi}\ln(A_n/A_N) + \ln\frac{1-(1+b)r_n}{1-(1+b)r_N} + u_n^y - u_N^y \quad (15)$$

where Γ_n reflects the extent to which monopoly mark-ups reduce labour productivity.

3.4. Combining the ingredients

Given a set of parameters, we can solve for the steady-state levels of research intensity, international patenting and labour productivity given by equations (6), (11) and (15). Equation (3) determines the relative technology levels that enter equation (15) and, if $\mathcal{J}$ is appropriately calibrated, it will predict actual world TFP growth. Where possible, we used previous studies to set parameter values, as reported in Table 2. The remaining parameters were estimated to fit data on research intensity, patenting and productivity. The data are described in the appendix. We report our estimates and their standard errors in Table 3.

Assessing the general equilibrium implications of a research policy in a global context requires tracking its impact on research activity and productivity around the world. Hence numbers must be put on a large number of parameters. Any quantitative answers we provide about the effects of policy depend, of course, on the parameter values we use. A particularly critical parameter is β, the elasticity of research output with respect to research activity. We estimate it to be 0.19, suggesting that returns to research effort diminish quite rapidly. This low estimate is the model's way of reconciling the rather low variation in research effort in the face

Table 2. Calibrated parameters

Description	Symbol	Value	Source
Real interest rate	ρ	0.07	Stock returns
Capital elasticity	ϕ	0.3	Capital's share
Labour share in research	β_L	0.478	OECD average, 1989–91
Employment growth	g_L	0.0097	OECD average, 1986–96
Labour productivity growth	g_y	0.0136	OECD average, 1986–96
Total factor productivity growth	g	0.0952	$(1-\phi)g_n$
Research drag	γ	0.71	$\gamma = g_L/g + (1-\beta_L)/(1-\phi)$
Markets per country	$\mathcal{J}$	1.5 (million)	Calibrated to fit $g_y = 0.0136$
Staff per researcher	b	1.43	OECD average, 1988–90
Domestic non-patent imitation	ι_D^{not}	0.41	Mansfield
Foreign non-patent imitation	ι_F^{not}	0.25	Mansfield

Table 3. Estimated parameters

Description	Symbol	Value	Std error
Domestic patent imitation	ι_D^{pat}	0.046	(0.111)
Foreign patent imitation	ι_F^{pat}	0.237	(0.001)
Stronger IP protection	γ_{IP}	0.023	(0.006)
Fraction of mistaken patents	η	0.055	(0.007)
Home-bias of diffusion	ε_D	0.28	(0.16)
Distance effect on diffusion	ε_{KM}	−0.14	(0.02)
Squared distance effect	ε_{KM^2}	0.0054	(0.0012)
Human capital effect	ε_{HK}	4.5	(2.3)
Import effect on diffusion	ε_{IMP}	0.11	(0.03)
Technological catch-up	ω	3.3	(1.0)
Size distribution parameter	θ	5.4	(0.9)
Research skill elasticity	β	0.19	(0.04)
Research productivity, Australia	a_1	72.2	(27.6)
Research productivity, Austria	a_2	48.8	(17.1)
Research productivity, Belgium	a_3	36.0	(11.9)
Research productivity, Canada	a_4	23.3	(8.2)
Research productivity, Denmark	a_5	59.4	(22.6)
Research productivity, Finland	a_6	57.4	(18.2)
Research productivity, France	a_7	34.1	(13.0)
Research productivity, Germany	a_8	36.1	(13.4)
Research productivity, Greece	a_9	18.6	(7.5)
Research productivity, Ireland	a_{10}	31.7	(10.9)
Research productivity, Italy	a_{11}	28.1	(11.5)
Research productivity, Japan	a_{12}	25.0	(11.1)
Research productivity, Netherlands	a_{13}	47.1	(15.3)
Research productivity, New Zealand	a_{14}	53.2	(19.3)
Research productivity, Norway	a_{15}	43.3	(14.6)
Research productivity, Portugal	a_{16}	9.6	(4.5)
Research productivity, Spain	a_{17}	19.3	(7.7)
Research productivity, Sweden	a_{18}	56.2	(18.3)
Research productivity, Switzerland	a_{19}	70.4	(23.4)
Research productivity, UK	a_{20}	31.3	(12.7)
Research productivity, USA	a_{21}	15.8	(6.8)

of big differences in research output and productivity. Since this parameter is key, a particular goal of future work is to bring additional evidence to bear on its magnitude.

Note also that our parameter estimates imply that patenting abroad diminishes the hazard of imitation only modestly. While this is consistent with other evidence, we are somewhat wary of these particular magnitudes. An item for future research is obtaining alternative estimates, and examining the sensitivity of the results to these particular magnitudes.

4. UNDERSTANDING EUROPE'S SITUATION

Before turning to analyse specific policies, we first ask how our model explains why Europe is not more active in research, and what it says about whether it should be.

4.1. Why doesn't Europe do more research?

Recall that equation (6) allows us to decompose the sources of variation in research intensity into market return effects (the expected value of an invention to an inventor relative to the wage, V/w^{β_L}) and research productivity effects (a). Column (1) in Table 4 presents, for the countries of our sample, the fraction of the labour force engaged as private researchers. Note, as we discussed above, that despite concern about Europe's lack of inventiveness, three European countries are more research oriented than Japan. While the USA allocates the largest fraction towards research, Germany is close behind.

Column (2) reports what our model *predicts* about research intensity. We capture the Italian, Japanese, UK and US figures quite closely, but we substantially overpredict research in some of the smaller European countries (which patent a lot given their research effort, suggesting that their research productivity is high). On the other hand, our predictions for New Zealand, Ireland and Greece are on the low side. Overall, our model explains about 80% of the variation in research intensity across countries.

Table 4. What determines research intensity?

Country	Research intensity (actual) (%) (1)	Research intensity (estimated) (%) (2)	Research productivity (estimated) (USA = 1) (3)	Research incentive (estimated) (USA = 1) (4)
Australia	0.155	0.198	4.568	0.144
Austria	0.109	0.184	3.083	0.207
Belgium	0.212	0.165	2.277	0.269
Canada	0.161	0.094	1.473	0.335
Denmark	0.145	0.256	3.756	0.193
Finland	0.200	0.260	3.630	0.201
France	0.169	0.302	2.158	0.359
Germany	0.358	0.511	2.280	0.416
Greece	0.015	0.008	1.176	0.163
Ireland	0.120	0.070	2.006	0.219
Italy	0.110	0.125	1.775	0.311
Japan	0.351	0.324	1.578	0.504
Netherlands	0.165	0.354	2.975	0.277
New Zealand	0.090	0.045	3.367	0.111
Norway	0.227	0.140	2.736	0.210
Portugal	0.009	0.002	0.608	0.178
Spain	0.061	0.032	1.222	0.266
Sweden	0.236	0.371	3.552	0.236
Switzerland	0.242	0.692	4.451	0.240
UK	0.222	0.265	1.977	0.372
USA	0.450	0.583	1.000	1.000

Note: The research incentive, relative to the reward for production work, is defined as V/w^{β_L}.

How does our model divide its explanation of its predictions about research intensity between research productivity and incentives? Column (3) of Table 4 presents our estimates of research productivity (a), normalized with the USA at 1. We find the USA actually below average, ranking only above Portugal. Among most of the other larger countries, research productivity is around double the US level, while for some of the smaller and more distant countries, we estimate it to be substantially higher.

So why don't these countries do more research? Column (4) reports our estimates of the value of invention relative to the wage (V/w^{β_L}), again normalized by the USA. Note that these magnitudes are by far the largest for the USA and Japan. An implication is that access to a large home market for inventions, rather than research prowess *per se*, explains the extent of US and Japanese research activity.

4.2. Should Europe do more research?

Do these estimates imply, then, that Europe as a whole would benefit by shifting research activity towards countries where research productivity is higher? Not necessarily, since countries with high research productivity might not be good at transmitting innovations elsewhere. Table 5 reports the implications for total income

Table 5. Where would another researcher do the most good?

Country	Effect on EU income	Effect on US income
Australia	1.749	0.316
Austria	4.451	0.386
Belgium	5.019	0.433
Canada	1.641	0.571
Denmark	4.240	0.389
Finland	4.326	0.416
France	4.709	0.387
Germany	5.585	0.456
Greece	2.762	0.234
Ireland	3.872	0.400
Italy	4.044	0.323
Japan	0.912	0.316
Netherlands	5.025	0.450
New Zealand	1.849	0.316
Norway	3.823	0.409
Portugal	1.746	0.139
Spain	3.602	0.313
Sweden	4.647	0.436
Switzerland	4.422	0.436
UK	4.301	0.364
USA	1.000	1.000

Note: The figures are normalized relative to the effect on income of one more researcher in the United States.

in the EU and (for purposes of comparison) in the USA of adding one private researcher to each country. Since absolute magnitudes are arbitrary, for each case we normalize by the effect of increasing research activity in the USA.

Note that an additional researcher in any of the European countries has more impact on overall EU production than an additional researcher in the USA. Additional research in Germany, followed by the Netherlands and Belgium, delivers the biggest bang to EU income. While these countries are not as productive in research as Switzerland and the Scandinavians, their innovations disseminate more broadly. At the other extreme, within Europe more research in Portugal and Greece delivers the least.

Not only is German research, on the margin, most potent in Europe; it also ranks third in the USA (after the USA's own and Canada's). Even though, in related work, Eaton and Kortum (1996) find Japanese innovation the second largest source of US productivity growth (after that of the USA itself) in terms of its total contribution, here we find that increased Japanese research, at the margin, makes a relatively small contribution (behind most European countries). This finding follows from the relatively large amount of research that Japan is already doing, relative to its size, and its modest research productivity.

In summary, these results portray a Europe with unfulfilled research potential. We now ask how successful alternative policies could be in exploiting it.

5. ALTERNATIVE SCENARIOS FOR EUROPE

We examine four alternative policies that might invigorate the European research scene. The first three affect research output directly: research subsidies, strengthened patent protection and enhanced research productivity. We then compare the effects of increasing European research output with the effects of increasing Europe's ability to *adopt* technology, including technology from abroad. The absolute magnitude of intervention is in each case arbitrary. For purposes of comparison, we consider, in each case, a level of intervention sufficient to increase the average steady-state level of income among the members of the European Union by 10%.

While the policy interventions required to subsidize research and strengthen patent protection are straightforward, it is less clear what governments can do to improve research productivity and absorptive capacity. To shed some light on the first issue, we relate our estimates of the productivity of private research to measures of public research support. We find a strong positive association between government-supported research and private research productivity. We are hesitant to attribute all of the relationship to causality from public support to research productivity, however. Regarding the second issue, our estimates point to education and imports as determinants of international diffusion, suggesting how Europe might enhance its ability to adopt innovations by raising educational levels and opening markets.

An important distinction is between policies pursued collectively and by individual countries. We report the effects of changing these various features of the research environment in the EU as a whole, but have also considered what happens when individual members implement the policy changes. In many cases, the country implementing the policy benefits less than the other members of the EU, pointing to the benefits of collective action.

The changes we consider have implications for a number of magnitudes of interest. As a country absorbs more inventions, the average efficiency of its production sector, i.e. its technology level, rises. But advances in technology do not raise income one-for-one. Policies (in particular, patent policy) can alter the allocative efficiency of the economy and therefore change the wedge between the state of technology and output per worker. Furthermore, different policies affect what a country pays to foreigners and earns from foreigners in the form of patent royalties. For purposes of brevity, we report the effects of the changes that we consider on labour productivity and on income, as well as what they imply for private research activity.

5.1. Subsidizing research

We estimate that achieving a 10% rise in the average level of EU income would require a permanent research subsidy of around 4.9%. Table 6 presents the results. We find that research intensity rises within the EU by about 20% more or less across the board.[12] The effect on research elsewhere varies. Research also rises, but by lesser amounts, in countries near the EU, but falls in countries further away. The effect on nearby countries seems to be dominated by the larger European market, while the more rapid obsolescence resulting from more European innovation is the dominant effect further away.

Since there are diminishing returns to research, the effects on EU income and productivity are, of course, more modest. Evidence of the importance of diffusion is that these magnitudes outside the EU rise by 2% or more, and approach those within the EU for countries nearby, illustrating the potential for free riding.[13]

These results suggest that encouraging research is very much a world public good. In principle, one country's research subsidy could largely crowd out another's, leading to little increase in overall research activity, but simply a reallocation of the productivity benefits. We find the potential for such crowding out to be limited, however, in that the decline in research elsewhere is fairly small. Moreover, the

[12] Bloom *et al.* (1997) find that R & D is stimulated by favourable tax treatment, although their estimated long-run elasticity is considerably lower than that implied by our simulations. They also find a substantial amount of relocation of R & D in response to changes in its tax treatment, a result that is reflected somewhat in our simulations.

[13] Our experiment allows inventors to charge distortionary mark-ups over the cost of production (until imitation or obsolescence), even though they are also receiving a government subsidy. Hence we are not considering the effect of *replacing* monopoly rights with government subsidies as a means to encourage research.

Table 6. A research subsidy in the European Union

Country	Income	Productivity	Research
Australia	6.63	6.70	−0.01
*Austria	10.18	9.96	23.12
*Belgium	9.93	9.74	22.00
Canada	3.92	3.97	−5.52
*Denmark	9.82	9.51	22.03
*Finland	9.52	9.21	21.15
*France	10.20	9.89	20.36
*Germany	11.19	10.57	22.14
*Greece	9.26	9.33	20.40
*Ireland	8.98	8.95	20.37
*Italy	9.61	9.54	18.85
Japan	6.19	6.21	−0.11
*Netherlands	10.29	9.80	22.87
New Zealand	6.95	7.02	0.69
Norway	9.49	9.48	7.54
*Portugal	8.66	8.74	18.45
*Spain	8.79	8.82	17.68
*Sweden	9.55	9.10	20.52
Switzerland	9.77	9.49	7.23
*UK	9.64	9.41	18.87
USA	2.39	2.48	−6.20

*Current members of the EU.

Note: The numbers represent the percentage change in the steady-state paths of endogenous variables caused by a research subsidy in the EU of $s = 0.0488$.

productivity benefits abroad can approach or exceed those in the subsidizing country.

It is important to point out that our model does not take into account many of the problems associated with research subsidies. We do not, for example, take into account the excess burden of the taxes that finance the subsidies. Nor do we ask how the government overcomes the adverse selection problem of targeting the most productive researchers, or the moral hazard problem of eliciting serious research effort. The microeconomic literature on research incentives suggests how a patent system, despite the monopoly distortions it imposes, can overcome some of these problems.

5.2. Strengthening European patent protection

We estimate that achieving the same overall EU income objective through strengthened patent protection would require reducing the hazard of imitation of inventions patented within the EU by slightly more than 15% (thus leaving the imitation rates at 85% of their current levels). Table 7 reports the consequences.

Research effort rises by slightly more, both within and outside of the EU, than with a subsidy. In terms of income, the spillover effects are even larger in that

Table 7. Stronger patent protection in the European Union

Country	Income	Productivity	Research
Australia	7.70	7.68	6.83
*Austria	10.15	10.36	26.67
*Belgium	9.94	10.17	25.95
Canada	4.97	4.99	−0.13
*Denmark	9.74	9.85	25.36
*Finland	9.49	9.62	23.46
*France	10.22	10.35	20.52
*Germany	11.17	10.99	21.34
*Greece	9.15	9.68	23.03
*Ireland	9.15	9.44	22.91
*Italy	9.63	10.01	19.10
Japan	7.17	7.16	1.22
*Netherlands	10.33	10.23	25.84
New Zealand	7.92	7.96	10.05
Norway	10.42	10.25	23.02
*Portugal	8.55	9.08	21.47
*Spain	8.80	9.29	18.81
*Sweden	9.58	9.55	22.78
Switzerland	11.32	10.20	24.44
*UK	9.64	9.87	18.25
USA	3.48	3.52	−4.79

*Current members of the EU.

Note: The numbers represent the percentage change in the steady-state paths of endogenous variables from reducing imitation rates for inventions patented in the EU by 15.03%.

countries outside the Union benefit by more than they did with a subsidy. Indeed, the biggest beneficiary is Switzerland, which does not increase its own level of patent protection in this simulation. Note also that, compared with a research subsidy, improved patent protection has a more uneven effect on incomes within the EU, with the richer, already more research-intensive economies faring the best.

5.3. Enhancing research productivity

Another form of policy intervention might aim directly at improving research productivity. Our estimates imply that achieving a permanent 10% income gain across the EU would require a rise in research productivity of just under 3%. Table 8 reports what would happen to individual countries. The income effects are very similar to those of a research subsidy: non-EU European countries gain about as much as their EU neighbours, while the effect in the USA is a little less than a quarter of that in Europe. Germany is the biggest gainer, while, as with stronger patent protection, poorer EU members gain less. Research activity rises everywhere, but not as much as with a subsidy, except in North America and in Japan (where it barely changes).

But what sort of specific policy interventions might increase private research

Table 8. More productive research in the European Union

Country	Income	Productivity	Research
Australia	6.68	6.74	0.02
*Austria	10.20	10.05	17.50
*Belgium	9.95	9.83	16.42
Canada	3.95	4.00	−5.54
*Denmark	9.82	9.61	16.45
*Finland	9.52	9.31	15.60
*France	10.19	10.00	14.86
*Germany	11.14	10.72	16.60
*Greece	9.32	9.39	14.88
*Ireland	9.02	9.02	14.85
*Italy	9.64	9.62	13.39
Japan	6.23	6.25	−0.11
*Netherlands	10.27	9.92	17.26
New Zealand	7.00	7.07	0.73
Norway	9.55	9.54	7.63
*Portugal	8.72	8.80	13.00
*Spain	8.84	8.88	12.26
*Sweden	9.52	9.22	15.00
Switzerland	9.84	9.55	7.32
*UK	9.64	9.52	13.42
USA	2.41	2.50	−6.23

*Current members of the EU.

Note: The numbers represent the percentage change in the steady-state paths of endogenous variables from raising research productivity in the EU by 2.96%.

productivity? A possibility might be government-supported research (either in the private sector or in government laboratories or universities). Of course, any connection drawn between such public activities and the efficacy of private research is highly speculative. But to provide some idea of the possible connection, we regressed the log of our estimate of private research productivity on the log of the share of *public* research scientists and engineers in the total labour force. The results imply that a 1% increase in public researchers raises private research productivity by 0.72%. This estimate probably overstates the effect, however, since factors that make a country a good place to do private research probably also lead the government to do more public research. Nevertheless, the result leaves open the possibility of high returns to public research efforts.[14] Taking this relationship seriously, for a moment, public research effort would have to go up by 4.1% to achieve the 10% income gain in the EU.

[14] To what extent do the benefits of publicly supported research spill across borders? We related our estimates of research productivity to public research scientists and engineers in other countries, weighted by our estimates of diffusion based on patenting. We did not find a significant relationship. We also asked whether being a major destination for patenting enhances research productivity (using distance as an instrument for patenting from other countries). The relationship was positive, but not significant.

5.4. Facilitating adoption

Finally, what would happen if Europe sought to increase income with measures to increase its ability to adopt innovations, rather than to innovate? Our model points to two channels that might facilitate adoption: raising levels of education and increasing trade among EU members.

We estimate that the EU could attain a 10% permanent increase in its average income level by raising the average level of schooling among its members by a little over half a year. Table 9 reports. The effects are very similar to those of subsidizing research or raising research productivity, except that the benefits are spread more equally among the EU membership, with poorer countries such as Portugal sharing more of the gains. Research effort rises everywhere except in North America.[15]

Table 9. More technology absorption via schooling in the European Union

Country	Income	Productivity	Research
Australia	5.92	5.97	0.68
*Austria	10.35	10.23	15.58
*Belgium	9.92	9.82	13.71
Canada	3.61	3.65	−4.07
*Denmark	10.88	10.64	18.26
*Finland	9.21	9.06	11.51
*France	10.08	9.93	12.31
*Germany	10.59	10.28	12.62
*Greece	9.65	9.73	13.75
*Ireland	9.30	9.31	12.98
*Italy	9.72	9.71	11.58
Japan	5.51	5.52	0.09
*Netherlands	10.15	9.88	14.23
New Zealand	6.20	6.25	1.55
Norway	8.35	8.32	8.19
*Portugal	10.14	10.23	16.63
*Spain	8.89	8.93	9.93
*Sweden	9.47	9.23	12.10
Switzerland	8.64	8.32	8.10
*UK	10.00	9.90	12.68
USA	2.31	2.38	−4.90

*Current members of the EU.

Note: The numbers represent the percentage change in the steady-state paths of endogenous variables from more technology absorption as predicted by raising the level of schooling by 0.5357 years throughout the EU.

[15] Hence our results suggest that the returns to improving education in Europe are potentially high. This impression should be tempered by three caveats: (1) cross-country comparisons of educational attainment are notoriously problematic; (2) our estimates of the impact of educational attainment on absorption are imprecise; and (3) our calculations do not take into account the cost of education.

Table 10. More technology absorption via trade within the European Union

Country	Income	Productivity	Research
Australia	5.86	5.92	−0.90
*Austria	10.59	10.39	21.59
*Belgium	10.41	10.23	20.83
Canada	3.46	3.51	−5.46
*Denmark	10.26	9.97	20.81
*Finland	9.95	9.68	19.24
*France	10.19	10.00	13.63
*Germany	10.48	10.11	13.07
*Greece	9.71	9.80	18.63
*Ireland	9.45	9.44	19.26
*Italy	9.89	9.86	12.74
Japan	5.45	5.47	−0.26
*Netherlands	10.66	10.22	20.55
New Zealand	6.16	6.22	−0.63
Norway	8.40	8.41	5.01
*Portugal	9.07	9.16	16.56
*Spain	9.16	9.20	13.10
*Sweden	9.89	9.51	17.93
Switzerland	8.56	8.40	4.57
*UK	9.66	9.54	11.67
USA	2.11	2.20	−5.44

*Current members of the EU.

Note: The numbers represent the percentage change in the steady-state paths of endogenous variables from more technology absorption as predicted by increasing trade within the EU by 69.57%.

Increased trade provides another means of encouraging diffusion. Table 10 reports the effects of achieving a permanent 10% average income gain through increased trade within the EU. We estimate that achieving this goal would require increasing intra-EU trade volumes by about 70%. The effects are roughly similar to those of increased schooling, except that the effects outside the EU are more muted, since this policy does not have a direct impact on the absorption of technology from outside the EU.[16]

6. CONCLUSIONS

Our analysis points to several broad conclusions. (1) For the most part, research productivity in Europe is as high as or higher than in the USA or Japan. Smaller market size, rather than lower research productivity, explains Europe's lower rate of

[16] A caveat here is that we have not modelled the determinants of trade itself in order to indicate what specific policies might lead to increased trade flows. Moreover, we have not established that causality runs from trade to diffusion and not the other way around.

private research effort. (2) Increasing research activity in most European countries, particularly in Germany, could make a substantial contribution to productivity levels not only in the EU, but throughout the OECD. (3) EU policy measures to increase research output (subsidies, stronger patent protection or enhanced research productivity) can raise productivity not only in the EU, but throughout the OECD. While policies that increase research activity within the EU raise productivity both there and elsewhere, they tend to reduce research effort in countries further away. (4) A problem in implementing research policy at the national level is the enormous potential for free riding. This potential is somewhat greater with respect to patent protection than to the other policies we consider. (5) While policies to stimulate research can benefit countries throughout the EU, the wealthiest countries tend to benefit slightly more. Policies aimed at improving the ability to adopt innovations, however, tend to favour poorer countries.

All these conclusions are, of course, drawn from a particular parameterization of a particular framework, as any such conclusions must be, and at this point they must be regarded as tentative. Any theoretical framework ignores aspects of the world that are potentially important. As just one example here, lack of comprehensive data prevented us from looking at the relationship between foreign direct investment and technology flows.[17] Even in terms of the model itself, our analysis is incomplete. We have not taken into account all of the costs of some of the policies we examine, such as increasing education levels and increasing public research effort. Moreover, we look at the effect of different policies only in the long run, ignoring what happens during the transition. Confronting these issues will be difficult, but taking them into account remains an important topic for future research.

What we hope we have done is: (1) to provide a basic framework for thinking about the fundamental issues involved in European technology policy, (2) more speculatively, to combine this framework with available data to provide an answer as to why the countries of Europe specialize in research as they do, and (3) more speculatively still, to see what various European policies towards research might achieve.

Discussion

Philippe Aghion

University College London and EBRD

This paper provides a very insightful empirical account of the determinants of research activities and performance across OECD countries and in particular *within*

[17] Among the evidence that this connection might be important is Bosworth's (1984) finding of a relationship between patent flows to and from the UK and foreign direct investment positions.

Europe, with a view to explaining why most countries in Europe seem to do worse than the USA and Japan in terms of output growth and/or labour productivity growth. It also provides policy recommendations based on cross-country estimations of a multi-country Schumpeterian growth model.

The research findings are as follows:

1. While the productivity of research activities appears to be at least as large in European countries as in the USA or Japan, research incentives in European countries suffer from small market outlets for innovative products.
2. Simulations based on a multi-country Schumpeterian growth model with cross-country knowledge spillovers indicate that policies (such as direct research subsidies or patent protection) that stimulate research activities within one European country will also raise productivity growth elsewhere, although research efforts may be reduced in other countries due to the free-rider effect resulting from cross-country knowledge spillovers.
3. Education and import liberalization should enhance productivity growth in the European Union by facilitating the *diffusion* of innovations across EU countries.
4. There is a *large variance* in research intensities across Europe (Sweden and Switzerland versus Portugal and Greece).
5. Countries with a higher level of research per capita and a higher rate of patenting are the countries with a higher research intensity *across all industries*.
   (a) Cross-country variations in research intensities within Europe are mostly explained by differences in research productivities, which in turn reflect differences in the amounts devoted to public research in the various EU countries.
   (b) Lower output growth performance in Europe seems to be due to a larger downsizing of the manufacturing sector (compared to the USA or Japan) rather than to a significantly lower performance of the R & D sector.

This paper contributes to our understanding of the determinants of (and barriers to) productivity growth within a group of (small) open economies subject to technological cross-country spillovers. The following comments are meant to be constructive and they essentially reflect my positive interest and curiosity when reading the paper.

Patents may not be sufficient to measure R & D output. In particular, some countries may put more emphasis on fundamental research that creates knowledge of a more tacit nature, and for which therefore there is less need for patenting.

R & D input is measured (and also modelled) as a pure labour input. However, there is evidence that physical capital investments are an equally substantial component of R & D inputs. Now, had R & D been modelled as embodying both labour and capital, the authors would have avoided some undesirable conclusions (such as: if the UK undertakes an R & D subsidy, the UK may end up with a lower productivity gain than the other countries, because diverting labour to research is bad for output!) Also, introducing capital as R & D input would help to explain why big differences in R & D labour inputs are not reflected in differences in R & D output. (Incidentally, could it be the case that Europe would have relied more on capital input because of the higher labour costs?) Finally, introducing physical capital as an input to R & D would yield interesting policy implications as to the growth-enhancing effects of subsidies to particular types of (high-tech) capital investment.

As suggested by the recent literature on patent races, competition and growth,[18] when knowledge is tacit, research subsidies to different countries or sectors may become strategic complements, so that the crowding-out (or 'free-rider') effect pointed out in the paper might turn into a multiplier effect.

Isn't there a tension (which is not considered in the paper) between policies aimed at encouraging new innovations and policies aimed at facilitating the diffusion of existing innovations? (Typically, expected monopoly rents to successful innovators should decline as their innovations become more rapidly 'imitated' by other firms or countries.)

I would have liked to see less general equilibrium analysis and a little more of partial equilibrium microfoundations when analysing the impact of R & D policy. For example, research subsidies are shown to have a substantial impact on research inputs. What about research *outputs*? For example, in France, the R & D agency ANVAR complains about the fact that more than 50% of R & D-monitored fiscal deductions are redundant or misused! Are the underlying agency problems more serious in Europe than in the USA? More generally, what can be said about the *design* of R & D policies across various countries and their impact on R & D output and productivity growth? In particular, what are the relative costs and benefits of *different* types of subsidy policy (*ex ante* vs *ex post*, targeted vs untargeted subsidies, etc.)? Should government emphasize general education versus specialized education and research, etc.?

This being said, the paper makes a real contribution to the existing empirical literature on the cross-country determinants of R & D productivity intensity and growth, and although I am not an empiricist, I can sense that the econometric analysis and the simulations have been quite carefully performed. The underlying framework, on the other hand, is a straight cross-country extension of my growth model with Peter Howitt. The main implications of that model and of its subsequent developments are described at length in our recent book *Endogenous Growth Theory* (Aghion and Howitt, 1998).[19]

[18] See Aghion and Howitt (1998, chapter 7, and the references to that chapter).

[19] In particular, I refer the authors to chapter 12, section 12.4 of this book for a multi-country analysis that reconciles the existing cross-country evidence by Mankiw *et al.* (1992) and more recently by Evans (1996) on β-convergence with the Schumpeterian approach to endogenous growth, precisely by explicitly introducing cross-country R & D spillovers into the framework.

Katharine Rockett

Institut d'Analisi Economica, CSIC, Barcelona and CEPR

The authors start from the observation that, by some measures, European research and overall economic performance are weak compared to that of the USA and Japan, and conclude that the culprit may be smaller and more fragmented markets for innovations in Europe. Direct research subsidies, improved patent protection and more co-ordinated technology policy across Europe are found to be policies that could benefit the European economies substantially. The paper is thoughtful and careful, and should certainly be used as a benchmark for future work. My comments on the paper aim to aid readers in interpreting how far we should go in reaching policy conclusions based on this work.

A crucial factor in getting the paper's main result seems to be the lower appropriability of the benefits of innovation that European firms face in other European countries. The model's hazard rate of imitation for innovations patented outside the innovator's home country is five times higher than the rate for innovations patented inside the innovator's home country. In fact, the hazard rate of imitation with a foreign patent is barely lower than the hazard rate without a foreign patent. As the authors themselves recognize, these numbers may significantly understate the actual value of foreign patents and bear much more investigation and outside corroboration. However, even taking these numbers at face value, the policy conclusions can differ greatly depending on *why* imitation is more of a problem across the different countries of the European Union rather than in the USA. If the difficulty is the cost of defending the patents in different local legal systems, a unified European patent with a single court of appeal might solve the problem. If the problem is narrow patent breadth (or local interpretations of patent breadth), strengthening patent rights, either locally or within a unified European patent system, would be a more appropriate response.

The social cost of these two policy responses is very different: the first may involve a large fixed cost of changing the administrative structure, and the second may involve a large recurring cost of increasing the monopoly power of patent holders. Further, it is worth noting that planned changes in the European patent system already anticipate the first problem,[20] but the second might require more extensive changes than those already in process. The model's numbers on appropriability should, then, be interpreted as an indication that there might be an access problem linked to the present state of the European patent system, but further research is needed to identify the source of this problem and suggest appropriate policy action. A possible source of data in gauging the magnitude of benefits due to various policy

[20] The Community Patent Covention of 1976 would make it possible to obtain a single Europe-wide patent that would be defended in a single court system. This convention is still awaiting the ratification of some member states.

changes might be an examination of the US imitation rates before and after unification of the US Court of Appeals for patent cases.

Another factor determining market access is the 'absorption coefficients', which reflect distances between countries, trade between countries and education levels of countries that receive technologies. These factors certainly affect the ability of a country to absorb new technologies. However, it is interesting to consider how well they would have tracked the significant increase in market access that has occurred from the launch of the 'Single Market' in 1986 until the present. Moreover, since the data used in the paper date from 1988–90, this is not a completely gratuitous thought experiment. Since relative education levels and distances between countries have changed little, most of the increased access would have to be accounted for by increased trade between member states. This raises two issues. First, greater access has been exploited not only through trade, but through increased direct foreign investment. Second, from a policy perspective, trade is not a control variable. 'Increasing inter-EC trade' is not by itself an implementable policy: one should also identify what the most important trade barriers might be. In that sense, the paper's numbers indicate a potential access problem that must be investigated at a more disaggregated level before policy recommendations can be formulated.

In any case, while this second market access effect might account for a portion of the variation in research performance across European countries, it is not clear that it helps us to understand the relative performance of Europe and the USA. The paper's results reflect some bias: the USA is assumed to be a single market, so market access there *cannot* be bad. Therefore, since the US research performance in the data is better than Europe's, and market access within Europe is endogenously estimated, a fit is naturally obtained by imparting worse access to Europe. It would be interesting to see how the results would change if the USA were treated as a set of 50 states (or a smaller number of regions) with differences in education, distance and trade. This might give a more accurate idea of the magnitude of the market access effect. On the other hand, with less difference in absorption between the USA and Europe, other variables in the model would have to adjust to fit the data on observed research differences between the two. This could, for example, push the hazard rate on imitation for innovations with a foreign patent to a significantly higher level than imitation for innovations without a foreign patent. Such an estimate would clearly suggest that adjustment in the basic model would be needed, but this work might have a reward in the sense of yielding a more comprehensive overall fit of the model to observations.

This paper should be viewed as presenting some fascinating but controversial conclusions that bear further investigation. As for the way such an investigation should be conducted, the method of investigation used in this paper has considerable advantages and might be appropriate for substantial future modelling. For example, the type of model used is particularly well suited to considering international spillovers and asymmetries and to discussion of broad-based policy measures such as R & D tax credits.

On the other hand, some of the questions raised in this report might be more easily dealt with in partial equilibrium models. For example, returning to the issue of market access, barriers to participation in markets might be more easily quantifiable at the industry level using data on shipping costs, differences in standards and the like. Further, some of the costs of the policy experiments considered in the paper might be more easily modelled in a partial equilibrium framework. For example, as the authors point out, most of the costs of increased patent protection are not considered in the paper. The higher prices resulting from increased monopoly power and such secondary effects as the effects on diffusion of knowledge necessary for further innovation might be easier to handle in a partial equilibrium model. Further, technology policy lends itself to industry-specific measures (such as targeted subsidies) that can be evaluated more easily in traditional industrial organization models that can account more easily for differences in market structure and type of research performed. The diversity of effects and policies that must be considered in policy making in this area certainly suggests that a broad-based approach, integrating the results of multiple modelling techniques, would be most useful.

General discussion

Samuel Bertolila thought that the European R & D system is not properly reflected in the paper's analysis. A central message of the paper is that Europe should provide more subsidies for R & D. However, an increasing portion of R & D funding is already coming from the EU. There are actually programmes in the EU that require co-ordination with researchers in other countries. Hence, the paper should not discuss subsidies *per se*, but should embed the R & D subsidies in their institutional environment and their time dimension. A number of important issues would then arise: what part of R & D subsidies should be financed at the EU level? How will the composition of funding affect R & D intensity in Europe? And finally, should there be targeting in the EU programmes, and if so, in which areas?

To obtain a clearer picture of the effects of R & D subsidies, Michael Gasiorek suggested making use of the long history of R & D subsidies both at the national and at the European level. Paul Dobson asked why we need subsidies in Europe at all. It could be argued that R & D in Europe is lower simply because of the structure of industry. The USA and Japan are much more dependent on industries that have large opportunities for R & D, but also have the established infrastructure and the complementary industries to support this position.

Jakob de Haan argued that part of the difference in R & D spending can be explained by the higher defence spending in the USA. Correcting for this specifically US feature may change the overall picture. Furthermore, the fear of falling back in innovations is often overplayed. In the Netherlands, for instance, the public worried about a fall in R & D spending. A careful look at what really happened shows that most of the R & D spending is done by five or six large companies. These companies have reduced their R & D activities for firm-specific reasons, but the general attitude towards R & D has not changed. So one needs to be very careful when drawing conclusions about R & D intensity from temporary effects on R & D spending.

Harry Flam noted that the tax system influences the size of expenditures in R & D. In Sweden, for instance, there is generous tax treatment of R & D expenditures. To some extent, this might have influenced the data used in the paper. Hans-Werner Sinn argued that a large part of the difference between the USA and Europe can be explained by the different levels of capital market development. The US stock market is much more open to innovative firms, whereas financing of risky innovations is very difficult in Europe.

Alberto Alesina felt that the policy conclusions with regard to education policy were too vague. The authors find, for instance, that if the level of education is increased in Portugal to twelve years of schooling, production will rise by 20%. It is not so surprising that increasing the level of education in the country with the currently lowest level of education in Europe leads to higher productivity. For policy conclusions, however, it would be important to know the kind of education needed and how important the role of universities is. In particular, a general complaint in Europe is that the state universities there do not work as efficiently as the private universities in the USA.

Harry Flam stressed the complementarity between own research and the ability to adopt innovations. The paper comes to the conclusion that Germany and the UK should specialize in R & D and leave the rest of Europe to benefit from that. However, a country cannot take advantage of research in other countries unless it does some research domestically. Jakob de Haan argued that it is not so much the R & D spending stressed in the paper but the general educational level of the population that will determine the adoption of innovations.

Alberto Alesina and Samuel Bertolila criticized the paper's strong emphasis on market size effects. If market size is important for innovative activities, bigger countries should grow faster. This may be true in a world with trade restrictions, but the size of countries becomes irrelevant when the world is more and more integrated. Paul Dobson suggested an explanation of why market size is important. The paper draws on the value of innovation in the home market which is mainly determined by the sheer size of total demand. However, it could also be that a large market means that more competitors can be accommodated by the larger market size, and that this in turn stimulates R & D competition. This competitive motive may be at least as important as the pure profit motive.

Michael Waterson noted two stylized facts about patents. First, the distribution of the value of patent rights is extremely skewed. Second, the use of patents varies enormously across industries. Both stylized facts are important and should show up in the modelling of patent protection. Lucrezia Reichlin wondered whether the model allows for the possibility of patent renewal.

APPENDIX. THE DATA

Our sample is a cross-section of 21 OECD countries.[21] Data on research activity are available from them on a fairly uniform basis. The sample includes the major research economies of the world (based on international patenting activity, for instance) and it covers an overwhelming preponderance of world GDP. Our data are chosen to reflect the situation in the period 1988–90 as closely as possible.

Our endogenous variables are as follows:

- Patents P_{ni} are patent applications by reporting country n and country of residence of inventor i averaged over 1988–90 (OECD, 1995).[22]
- Productivity y_n^* is real GDP per active worker in country n, relative to the USA, averaged over 1988–90 (OECD, 1997).
- Our measure of research effort starts with business enterprise research scientists and engineers, relative to total employment (from OECD, 1995). To obtain our measure of research intensity in country i, r_i, we multiply this figure by the fraction of business enterprise R & D expenditure that is privately financed (averaged over 1988–90). In some cases, we interpolated to fill in missing years.

Our explanatory variables are as follows:

- Our labour variable L_i is total employment in country i relative to the USA (OECD, 1997).
- We measure human capital HK as average years of schooling of the labour force in 1985 (1980 for Switzerland), as reported by Kyriacou (1991).
- Import data IM are from the IMF *Direction of Trade Statistics Yearbook*, various issues.
- Distance KM is between major cities (reported in Eaton and Tamura, 1994) from Software Toolworks, version 5.0.
- We measure patenting costs $c_{ni} = (C_{ni}/Y_n)$ as the cost of applying for a patent, including agents' fees and translation fees, constructed from Helfgott (1993), scaled by GNP (from the World Bank).[23]
- To measure the strength of intellectual property protection in country n, we take the

[21] The countries are listed in Table 1.

[22] During this period, Japanese inventors applied for over 300 000 patents per year domestically. This figure compares, for example, with only around 75 000 applications by US inventors in the USA. Okada (1992) finds that Japanese patents granted to foreigners contained on average 4.9 times as many inventive claims as patents granted to domestic inventors. To account for this discrepancy, we translate 4.9 Japanese patents sought domestically to the equivalent of one application by a foreign inventor in Japan or by any inventor elsewhere. There is no evidence of any other significant international differences in the claim content of patents.

[23] 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. Pursuant to our discussion of Japanese patents in the footnote above, we scale up the cost of an application for a Japanese inventor in Japan by a factor of 4.9.

arithmetic average of four of the five sub-indices entering Ginarte and Park's (1997) overall index of the strength of patent rights by country, which we label GP_n. The four sub-indices are the coverage given to patent holders, the enforcement of patents, membership in international agreements, and possibilities for losing protection (we exclude their index of patent duration, since it enters our model directly). Our final index $IP_n = (1 - GP_n)/\max\{1 - GP_j\}$, which is decreasing in the strength of intellectual property protection and is bounded between 0 and 1.

- We use Ginarte and Park's data on patent duration T_n by country.

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