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The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called 'European Paradox'

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Abstract

This paper discusses, first, the properties of scientific and technological knowledge and the institutions supporting its generation and its economic applications. The evidence supports the broad interpretation that we call the 'Stanford–Yale–Sussex' synthesis. Second, such patterns yield important implications with respect to the so-called 'European Paradox', i.e. the conjecture that EU countries play a leading global role in terms of top-level scientific output, but lag behind in the ability of converting this strength into wealth-generating innovations. Some descriptive evidence shows that, contrary to the 'paradox' conjecture, Europe's weaknesses reside both in its system of scientific research and in a relatively weak industry. The final part of the paper identifies a few normative implications: much less emphasis should be put on various types of 'networking', and much more on policy measures aimed at strengthening both frontier research and European corporate actors.

JEL classification: D80; O33; O38

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1. Introduction

The present paper is intended to reappraise the tangled relationships between science, technologies and their industrial exploitation with reference to a popular interpretation concerning European weaknesses in industrial innovation known as the 'European Paradox'. Such a paradox – which sounds quite similar to an earlier 'UK paradox' fashionable around 30 years ago – refers to the conjecture that EU countries play a leading global role in terms of top-level scientific output, but lag behind in the ability to convert this strength into wealth-generating innovations. We shall argue, first, that the paradox mostly appears just in the flourishing business of reporting to and by the European Commission itself rather than in the data. Second, both the identification of the purported paradox, and the many proposed recipes for eliminating it, seem to be loaded with several, often questionable, assumptions regarding the relationship between scientific and technological knowledge, and between both of these and the search and production activities of business enterprises.

We begin by setting the scene and recalling what we consider to be the main properties of scientific and technological knowledge and of the institutions supporting its generation (Section 2). The proposed framework, we suggest, fits quite well with a series of robust 'stylized facts' (Section 3). Having spelled out the interpretative

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tools, we turn to the evidence supporting the existence of a 'European Paradox' (or the lack of it) (Section 4) and discuss European comparative performance in terms of scientific output, higher education characteristics, proxies for technological innovation, and actual production and exports in those lines of business that draw more directly on scientific advances. Here, one does not find much of a paradox. Certainly one observes significant differences across scientific and technological fields, but the notion of overall 'European excellence' finds little support. At the same time, one does find ample evidence of widespread European corporate weakness, notwithstanding certain success stories.

This interpretation also has far-reaching normative implications (Section 5). If we are right, much less emphasis should be put on various types of 'networking', 'interactions with the local environment', or 'attention to user needs' – current obsessions of European policy makers – and much more on policy measures aimed at strengthening 'frontier' research and, at the opposite end, at strengthening European corporate actors.

2. Science and technology: some interpretative yardsticks

Our interpretative framework stems from what might be called the *Stanford–Yale–Sussex* (SYS) *synthesis*, a phrase sure to displease almost everyone, but a convenient shorthand for the confluence between works on the economics of information (including Arrow (1962), David (1993, 2004), and Nelson (1959))[1] and works focusing on the specific features of technological knowledge (including Freeman (1982, 1994), Freeman and Soete (1997), Nelson and Winter (1982), Pavitt (1987, 1999), Rosenberg (1976, 1982), Winter (1982, 1987), and also Dosi (1982, 1988)). In such a *synthesis*, first, one fully acknowledges some common features of information and knowledge—in general, and with reference to scientific and technological knowledge in particular. Second, one distinguishes the specific features of technological knowledge and the ways it is generated and exploited in contemporary economies.

As to the former point, both information and knowledge share the following properties:

- *Some general features of public goods*: (i) non-rival access (i.e. the fact that one holds an idea does not constrain others from holding it too); (ii) low marginal cost of reproduction and distribution, which *in principle* makes it difficult to exclude others from having access to newly generated information (except through legal devices such as copyright and patents), as compared to high fixed costs of original production. (The latter point applies primarily to *information, stricto sensu*.)
- A fundamental uncertainty concerning the mapping between whatever one expects from search activities and their outcomes.
- (Relatedly) serendipity in the ultimate economic and social impact of search itself (Nelson, 2004).
- Quite often, very long lags between original discoveries and 'useful' applications.
  However, scientific and even more so technological knowledge share, to a different extent, some degrees of *tacitness*. This applies to the pre-existing knowledge leading to any discovery and also to the knowledge required to interpret and apply whatever codified information is generated. As Pavitt puts it with regards to technological knowledge,
- "most technology is specific, complex . . . [and] cumulative in its development . . .. It is specific to firms where most technological activity is carried out, and it is specific to products and processes, since most of the expenditures is not on research, but on development and production engineering, after which knowledge is also accumulated through experience in production and use on what has come to be known as 'learning-by-doing' and 'learning-by-using"' (Pavitt, 1987, p. 9).
- Moreover, "the combination of activities reflects the essentially pragmatic nature of most technological knowledge. Although a useful input, theory is rarely sufficiently robust to predict the performance of a technological artefact under operating conditions and with a high enough degree of certainty, to eliminate costly and time-consuming construction and testing of prototype and pilot plant" (Pavitt, 1987, p. 9).

A distinct issue regards the relations between scientific knowledge, technological innovation, and their economic exploitation. In this respect, note that the *SYS synthesis* is far from claiming any linear relation going from the former to the latter. On the contrary, many contributors to the *SYS* view have been in the forefront of arguing that the relationships go both ways (see Freeman (1982, 1994), Kline and Rosenberg (1986), Pavitt (1999), and Rosenberg (1982), among others).

In particular, it has been shown that, first, technological innovations have sometimes preceded science in that practical inventions came about *before* the scientific

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[1] Note that Richard Nelson was at Yale when he produced the seminal contribution to which we refer.

understanding of why they worked (the steam engine is a good case in point, and another example is the airplane, the aerodynamic properties of which have been mathematically elaborated only after the actual development of the artefact).

Second, it is quite common for scientific advances to have been made possible by technological ones, especially in the fields of instruments (think of the importance of the microscope or, in the field of theoretical physics, of accelerators).

Third, one typically observes some complementarity between science and technology, which however "varies considerably amongst sectors of application, in terms of the direct usefulness of academic research results, and of the relative importance attached to such results and to training" (Pavitt, 1987, p. 7).

Having said that, it is also the case that since the Industrial Revolution, the relative contribution of science to technology has been increasing and its impact has become more and more pervasive, while the rates of innovation have often been shaped by the strength of the science base from which they draw (Nelson, 1993; Mowery and Nelson, 1999; Mokyr, 2002). In turn, "this science base largely is the product of publicly funded research and the knowledge produced by that research is largely open and available for potential innovations to use. That is, the market part of the Capitalist Engine [of technological progress] rests on a publicly supported scientific commons" (Nelson, 2004, p. 455).

Together, the fundamental vision underlying and supporting such a view of publicly supported *open science* throughout a good part of the 20th century entailed (i) a sociology of the scientists community largely relying on self-governance and peer evaluation, (ii) a shared culture of scientists emphasizing the importance of motivational factors other than economic ones, and (iii) an ethos of disclosure of search results driven by 'winner takes all' precedence rules.[2]

3. Some persistent 'stylized facts'

Both the factual implications of the *SYS synthesis* and the normative implications of the *Open Science* institutional arrangements are supported by a broad set of persistent 'stylized facts'. Consider the following pieces of evidence partly drawn from Pavitt (2001, 2003):

1. Contrary to the claim that scientific and technological *knowledge* can be increasingly reduced to sheer 'information', the distinction between the two continues to be highly relevant. *A good deal of knowledge is, and is likely to continue to be, rather 'sticky', organization- and people-embodied, and often also spatially clustered.* Related to this is the persistence of widespread agglomeration phenomena driven by top-level research (see Jaffe et al. (1993) among many others, and Breschi and Lissoni (2001) for a critical review).
2. *Useful academic research is good academic research.* "Systematic evidence from the US shows that the academic research that corporate practitioners find most useful is publicly funded, performed in research universities, published in prestigious referred journals" (Pavitt, 2001, p. 90) and frequently cited by academics themselves (on these points see Mansfield (1995), Narin et al. (1997) and Hicks et al. (2000)).
3. *Government funding of basic research is responsible, especially in the US, for most major scientific advances*, including in the fields of information sciences and bio-sciences (see Pavitt (2001) and the references cited therein).
4. The proportion of *university research that is business financed is very low everywhere* (typically less than 10%) and *lower in the US than in Europe* (see Table 10 and the discussion below).
5. *The expansion of US university patenting has resulted in a rapid decline of the patent quality and value* (Henderson et al., 1998).
6. *Increases in licensing income in leading US universities are concentrated in biotech and software*, and have preceded the Bayh–Dole Act. Moreover, income flows from licensing are quite small as compared to the overall university budget; in most cases, they are unable to cover even the administrative costs of the 'technology-transfer office' in charge of them! At the same time, anecdotal evidence begins to hint at the ways the new appropriation regimes for public research tend to corrupt the ethos of researchers and to twist their research agendas, and in the US even "[s]ome of the nation's largest and most technology-intensive firms are beginning to worry aloud that increased industrial support for research is disrupting, distorting, and damaging the underlying educational and research missions of the university, retarding advances in basic science that underlie these firms' long-term future" (Florida, 2000, p. 367). (On many of the foregoing points see also Nelson (2004).)
7. Interestingly, *only very rarely has a critique of the Open Science System and the public funding of*

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[2] On those points, following the classic statements in Bush (1945), Polanyi (1962) and Merton (1973), see the more recent appraisals in Dasgupta and David (1994), David (2004), Nelson (2004) and the conflicting views in Geuna et al. (2003).

> *basic research come from corporate users*, except for peripheral countries and peripheral entrepreneurs (such as Italian ones, hoping to transform universities into some sort of free training subsidiaries). On the contrary, notably, "in the UK, where critical rhetoric is among the strongest, it comes mainly from government sources... In the US, companies like IBM have complained recently about the potentially harmful effects on future competitiveness of reduction in public support to academic research in the physical sciences" (Pavitt, 1999, p. 90). Together, there is an increasing perception also *among business firms* that 'too much appropriability' hurts firms themselves. In fact, as noted by Florida (2000, p. 367), "[l]arge firms are most upset that even though they fund research up front, universities and their lawyers are forcing them into unfavorable negotiations over intellectual property when something of value emerges. Angered executives at a number of companies are taking the position that they will not fund research at universities that are too aggressive on intellectual property issues... One corporate vice president for industrial R&D recently summed up the sentiment of large companies, saying, "The university takes this money, then guts the relationship". [But also] [s]maller companies are concerned about the time delays in getting research results, which occur because of protracted negotiations by university technology-transfer offices or attorneys over intellectual property rights. The deliberations slow the process of getting new technology to highly competitive markets, where success rests on commercializing innovations and products as soon as possible".

More generally, both upstream researchers and downstream product developers begin to perceive what Heller and Eisenberg (1998) have called the *anticommons* tragedy: the excessive fragmentation of Intellectual Property Rights among too many owners can slow down research activities and product development because all owners can block each other.

With this general background in mind, let us turn to the comparative assessment of the mechanisms for the generation and economic exploitation of scientific and technological knowledge in the EU.

4. In search of the purported 'European Paradox'

The central point of the 'paradox', to repeat, is the claim that EU scientific performance is 'excellent' compared with that of its principal competitors, while Europe's major weakness lies in its difficulties in transforming the results of research into innovations and competitive advantage.

One of the first official documents that popularized the 'paradox' was the Green Paper on Innovation (European Commission, 1995). The two pieces of evidence provided therein in support of it, and thereafter too often taken for granted, were, first, the (slightly) higher number of EU publications per euro spent on non-business enterprise R&D (non-BERD) and, second, the lower number of granted patents per euro spent on BERD *vis-à-vis* the US and Japan. Those phenomena, as important as they are, do not shed much light on the substance of the 'paradox' and, as a matter of fact, even the European Commission seems to admit in its Third Report on Science and Technology Indicators (European Commission, 2003) that the "paradox is vanishing".[3]

What does indeed the overall evidence tell us? In what follows, we shall illustrate some of the strengths and weaknesses of European Science and Technology (S&T) system, arguing that the paradox is nowhere to be seen. First, let us briefly consider the claim regarding 'scientific excellence'.

4.1. The pieces of evidence and myths on European scientific leadership

A central part of the 'Paradox' regards the width, depth and originality of European science. Discerning whether the data support the claims of a purported European leadership[4] is not an easy task. Bibliometric analysis offers important insights, but also has various drawbacks and biases, which we discuss at somewhat greater length in Dosi et al. (2005). That notwithstanding, measuring the *Scientific Impact of Nations* continues to be a revealing exercise. And indeed, as we show below, the picture that emerges from the data on publications and citations is far from that of European leadership in science.

Advocates of the 'paradox' notion have emphasized that, during the second half of the nineties, Europe has overtaken the US in terms of the *total* number of

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[3] One of the documents published by the commission that presents the results has the revealing title: "From the 'European Paradox' to declining competitiveness". (ftp://ftp.cordis.europa.eu/pub/indicators/docs/pckfbd_snap4.pdf).

[4] A view again forcefully endorsed by most of the EU Commission: for example, the chapter of the Third Report devoted to measuring European performance in knowledge production is titled 'Scientific output and impact: Europe's leading role in world science' (European Commission, 2003).

Table 1
Publications and citations weighted by population and university researchers

	Publications / *Population*	=	Publications / Researchers	x	*Researchers* / *Population*
UK	5.84		6.99		0.84
Germany	3.88		4.77		0.81
France	3.96		4.09		0.97
Italy	2.58		5.83		0.44
US	**4.64**		**6.80**		**0.68**
EU15	**3.60**		**4.30**		**0.84**
	Citations / *Population*	=	Citations / Researchers	x	*Researchers* / *Population*
UK	42.60		51.00		0.84
Germany	26.82		32.98		0.81
France	25.81		26.68		0.97
Italy	16.89		38.25		0.44
US	**39.75**		**58.33**		**0.68**
EU15	**23.03**		**27.52**		**0.84**
	Top1%publications / *Population*	=	Top1%publications / Researchers	x	*Researchers* / *Population*
UK	0.08		0.10		0.84
Germany	0.05		0.06		0.81
France	0.04		0.05		0.97
Italy	0.03		0.06		0.44
US	**0.09**		**0.13**		**0.68**
EU15	**0.04**		**0.04**		**0.84**

Note. Our calculations are based on numbers reported by King (2004) and OECD (2004a). Number of publications, citations and top1%publications refer to the period 1997–2001. Population (in thousands) and number of university researchers (measured in full-time equivalents) refer to 1999.

published research papers. However, the latter indicator needs to be adjusted by a scaling factor due to sheer size: otherwise, one could claim that the Italian science base is better than the Swiss one, given the higher total number of papers published! The first column of Table 1 shows that, if one adjusts for population, Europe's claimed leadership in terms of number of publications disappears.[5]

Moreover, in science, together with the numbers of publications, at least equally important, are the originality and the impact of scientific output upon the relevant research communities. Two of the most widely used proxies of such an impact are citations to articles[6] and shares of the top 1% most cited publications.

As shown in Table 1, the US is well ahead with respect to both indicators. In particular, after controlling for population, the *outstanding* EU scientific output is still less than half that of the US.

In the second and third column of the same table, we disaggregate output (i.e. number of publications, citations, and top 1% publications) per unit of population into two components: a measure of scientific productivity of university researchers (i.e. output per university researcher), and the ratio of university researchers to total population. The table clearly shows that US leadership is due to the quality of research published rather than to the sheer number of researchers.

In line with the above is the evidence concerning Nobel Prize winners from Europe. After the Second World War, the gap between the US and Europe has been growing at an impressive rate.

Irrespective of the differences associated with different specialization across scientific disciplines, there is clearly a high inter-disciplinary variation in the revealed quality of European research. According to European Commission (2003), NAFTA (the US plus Canada and Mexico) performs better than the EU-15 countries in clinical medicine and biomedicine, and does especially well in chemistry and the basic life sciences. Using a different and more aggregate classification and comparing citations shares, King (2004) also finds evidence of US superiority in life and medical sciences, while

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[5] Normalization by population is admittedly a very rough proxy when used to average across very different entities, ranging from Sweden, Germany and the UK all the way to Italy, Greece and Portugal (just sticking to EU-15). However, the US average also involves averaging over not only Massachusetts and California but also Mississippi and Idaho.

[6] Typically, these are very skewed: only a few publications are highly cited, while the overwhelming majority of articles receive zero citations.

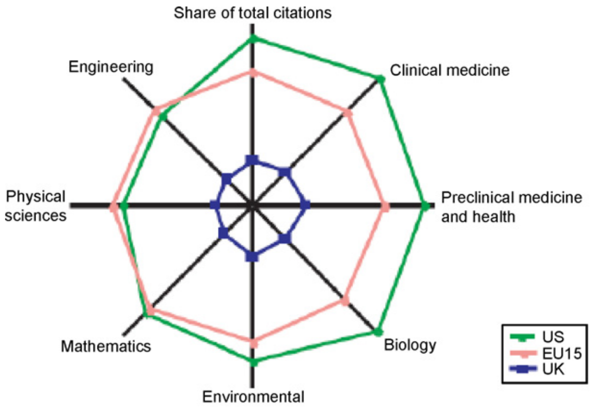

Fig. 1. Strengths in different disciplines. *Note*. Plot shows citation shares measured by distance from the origin. *Source*. King (2004) elaborating ISI Thomson data.

Europe performs slightly better in physical sciences and engineering (see Fig. 1). Incidentally, a few important distinctive patterns within the EU also emerge: for example France is strong in mathematics, while Germany and UK do relatively well in physical and life sciences, respectively.[7]

The general conclusion from the bibliometric data is therefore far from supporting any claim to European leadership in science. On the contrary, one observes a structural lag in top-level science *vis-à-vis* the US, together with (i) a few sectoral outliers in physical sciences and engineering, and (ii) a few single institutional outliers (such as Cambridge in computer science and a number of other disciplines).

The first fact on which the 'paradox' is supposedly based is simply not there. Rather a major EU challenge is how to catch up with the US in terms of scientific excellence.

4.2. US–EU differences in their higher education systems

A natural candidate for explaining the US leadership in scientific productivity is the excellence of its research universities. Important insights for cross-national comparison are offered by the huge case-study literature together with few quantitative indicators (Mowery and Sampat, 2005).

First, although historically research universities emerged for the first time in mid-19th century Prussia, with what has become known as the Humboldt model, today universities seem to occupy a more significant position as basic research performers within the United States than in any other industrialized country (Mowery and Rosenberg, 1993). For instance, in France public *non-university* institutions such CNRS (National Center for Scientific Research), INSERM (National Institute for Health and Medical Research), CEA (the Atomic Energy Commission), and the Institute Pasteur play a central role as basic research performers. Similarly, much German basic research is concentrated in the Max Plank Institutes. In contrast, after the Second World War, in line with the influential Vannevar Bush (1945) report, US universities have been selected as the most appropriate institutional locus for basic research. This difference is likely to be important, given the strong complementarities between basic research and teaching activities.

Second, the available data on enrolment reveal that, since the beginning of the 20th century, US higher education institutions have consistently absorbed larger shares of the relevant cohorts of population than European ones. For instance, enrollment in European universities exceeded 10% only in the 60s, when US rates by that time were reaching 50% (Burn et al., 1971). This has probably been due also to a sharp US distinction between research-cum-graduate teaching universities, undergraduate liberal art colleges, and technical colleges. Conversely, Europe (especially Continental Europe) often offers in most universities a confused mix of the three. Anecdotal evidence suggests that this is neither good for research nor for mass-level training.

Third, an interesting exercise is to break down R&D carried out by the academic sector (HERD) according to the field of performance.[8] Table 2 shows that, in a selected number of EU countries, a larger proportion of Higher Education R&D is allocated to engineering, social sciences, and humanities than in the US. Conversely, the US academic R&D effort is concentrated on the medical and natural sciences. The latter is consistent with the evidence on scientific output presented in the previous section.

Fourth, detailed survey-based studies have shown that, with the possible exception of the pharmaceuticals sector, US industrial firms report that they benefit more from 'public research' accessed through conferences, publications and the mobility of PhD's than from university prototypes, patents and licences (Cohen et al., 2002).

Finally, at a complementary level, as we shall show more extensively below, the evidence that university–

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[7] See King (2004) for further details on this point.

[8] Coincidentally, US and EU-25 investments in HERD as a percentage of GDP are very similar (0.40 and 0.39, respectively, in 2001).

Table 2
Shares of HERD by country and S&E field (1998 or 1999)

	NS&E	Natural sciences	Engineering	Medical sciences	Agricultural sciences	Social sciences & humanities
Germany	78.4	29.2	20.3	24.7	4.2	20.6
Spain	77.9	39.4	18.7	14.2	5.6	22.1
Sweden	76.3	21.0	21.9	27.4	6.1	17.6
US	93.7	41.8	15.5	29.1	7.4	6.3

Note. NS&E stands for Natural Sciences and Engineering. *Source*. OECD, Science and Technology Statistics database (2003).

industry links are stronger in the US than in Europe is at least mixed. On the one hand, qualitative evidence on labour mobility between university and industry supports to some extent the conventional wisdom; on the other, data concerning industry support to higher education R&D points in the opposite direction (see Table 10).

4.3. *Poorer technological performances: R&D inputs and innovative outputs of the EU*

In order to explore in detail the European performance in technology and innovation, one also needs to match European investments in science and technology (i.e. inputs for which education and R&D expenditures are the usual proxies) with outputs (where patents are the normal proxy).

First, as shown in Fig. 2, at aggregate levels the EU under-invests in R&D with respect to both the US and Japan and, notwithstanding the wide variation within the EU itself, the gap is not shrinking.

Second, the usual claim concerning the higher share of government-funded R&D in the EU as compared to the US is simply groundless.[9] On the contrary, if one compares the shares of government-financed R&D as a percentage of GDP (Table 3), the EU is still lagging behind.

Publicly supported R&D may be categorized into several components. As shown in Table 4, the US government, compared to European ones, spends more both on R&D carried out by firms (business enterprise R&D (BERD)) and on other forms of R&D (i.e. higher education, government, etc.). However, the bulk of the difference is in publicly financed BERD.

However, the latter underestimates the full amount of public support for industrial technology, because it does not include (i) fiscal incentives and loans and (ii) R&D

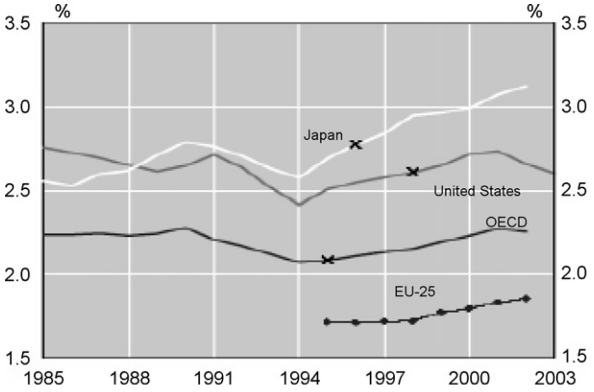

Fig. 2. Gross domestic expenditure on R&D as a percentage of GDP. *Source*. OECD (2004a).

Table 3
Government-financed GERD as a percentage of GDP

	1998	1999	2000	2001
Finland	0.87	0.94	0.89	0.87
France	0.81	0.80	0.84	0.82
Germany	0.81	0.78	0.78	0.79
Italy	0.51	–	–	–
Spain	0.35	0.36	0.36	0.38
Sweden	–	0.89	–	0.90
United Kingdom	0.55	0.55	0.53	0.53
EU-15	0.65	0.65	0.65	0.66
EU-25	0.63	0.63	0.63	0.63
US	0.79	0.76	0.71	0.76

Note. Italian percentage refers to 1996. *Source*. OECD (2004a).

Table 4
Breakdown of government-funded R&D (2001): BERD and non-BERD

	Government financed BERD	On GDP (%)	Government financed non-BERD	On GDP (%)
EU-15	9,369	0.10	53,352	0.56
EU-25	9,868	0.09	55,073	0.52
US	18,849	0.19	57,533	0.57

Note. Our calculations are based on OECD (2004a). Gross expenditures are expressed in 2000 dollars (millions)—i.e. based on constant prices and purchasing power parities (PPP).

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[9] The misunderstanding is usually based on the use of the share of publicly funded R&D on total R&D expenditures, which does not carry much economic sense. More meaningful figures are those which relate government funded R&D with the economic size of each country or area.

financed by the government in support to industry, but carried outside the firms themselves.

More generally, three broad categories of public support for industrial technology can be identified: first, all those programmes designed to encourage industrial firms to carry out R&D by reducing its costs through grants, loans, and fiscal measures; second, government payments to industrial firms financing R&D as part of procurement programs, notably for defence or space objectives; and third, public support to 'research infrastructures' specifically aimed at industrial development but not involving any direct financial transfer to private firms (e.g. applied research undertaken in public institutes and universities).

Unfortunately, hardly any international statistics on the above are available, even for industrialized countries. However, Young (2001), exploiting the data from a Pilot Study run by OECD using such categories, finds that the pattern of support varies considerably across countries. In particular, in the US federal support for industrial technology is almost entirely paid to firms (public institutes and universities do not seem to receive public funds for industrial technology!), with the largest share in the form of mission-oriented contracts and procurement. This fact, to a considerable extent, stems from the large US military and space programs. As far as EU countries are concerned, in France and the United Kingdom mission-oriented contracts are also relatively important, although clearly of a much smaller size than in the US. On the other hand, in Germany and the Netherlands funds are distributed evenly across the three categories.

Third, one observes a wide gap in industry-financed R&D as a percentage of GDP (see Table 5). Again, although there are diverse patterns across countries, there is no sign of overall European catching up. Part of this apparent gap is due to inter-sectoral differences (which tend to hold worldwide) in the propensity to undertake R&D. This, in turn, is partly due to inter-sectoral differences in technological opportunities and partly due to differences in the way the latter are tapped—in some industries this involves formal R&D activities and in others more informal processes of learning-by-doing, learning-by-using and learning-by-interacting with suppliers and customers.[10] It happens that Europe is largely penalized by a composition effect, in that it is relatively strong in technologies (such as mechanical engineering) where a good deal of search is not recorded under the 'R&D' heading. However, even after controlling for inter-sectoral differences, the European gap does not entirely disappear.[11]

Table 5
Breakdown of industry-financed GERD as a percentage of GDP

	1998	1999	2000	2001
Finland	1.84	2.16	2.39	2.41
France	1.16	1.18	1.14	1.21
Germany	1.44	1.59	1.65	1.65
Italy	0.43	–	–	–
Spain	0.44	0.43	0.47	0.45
Sweden	–	2.47	–	3.07
United Kingdom	0.86	0.91	0.91	0.88
EU-15	0.98	1.04	1.06	1.08
EU-25	0.93	0.98	1.00	1.02
US	1.70	1.77	1.88	1.84

Note. Italian percentage refers to 1996. *Source*. European Commission (2004).

Moreover, one also observes a lower ratio of 'knowledge workers' in the total workforce in Europe as compared with the US: see Table 6 depicting the numbers of tertiary level graduates and researchers as a percentage of the population and the labour force, respectively.[12] Note, however, that Europe has a higher ratio of Science & Engineering graduates.

Complementary to proxies for the intensities of innovative search efforts and for the skills of workforce involved, patent-based indicators are generally used to shed light on the *Technological Output of Nations*. Needless to say, institutional differences, distinct corporate appropriability strategies, and differing propensities to patent across sectors may bias the international comparisons. Moreover, these indicators are generally constructed on the basis of patent applications issued by national patent offices having a 'home advantage' bias. However, the OECD has developed 'patent families' (i.e. patents filed in different countries to protect the same invention) that try to mitigate this latter bias and which generally capture patents of relatively high economic value.[13] In Table 7 we report EU-25 and US shares in 'triadic' patent families (i.e. inventions filed with the European Patent Office (EPO), the Japanese Patent Office (JPO), and the US Patent and Trademark Office (USPTO)). The shares are relatively stable with signs of a slight European decline.

Again, EU performance varies significantly in distinct technology fields. The upper part of Table 8 depicts

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[10] Within an extensive literature, on these points see Dosi (1988), Klevorick et al. (1995) and Malerba (2004).

[11] See European Commission (2003) on page 116 for data and discussion.

[12] These data should, however, be taken with some care, given the uneven state of secondary education across different countries.

[13] The downside is that triadic patents are usually owned by big corporations and therefore small firms innovation activity is likely to be underestimated (Dernis et al., 2001).

Table 6
Breakdown of population with tertiary education (% of 25–64 years age cohort), new science & engineering graduates (per 1000 population aged 20–29), and total researchers (per thousand of total employment)

	Tertiary education			S&E graduates			Researchers		
	1999	2001	2003	1999	2001	2003	1999	2001	2002
France	20.9	22.6	23.1	19.0	20.2	22.2	6.8	7.2	7.5
Germany	23.0	23.5	24.3	8.6	8.0	8.4	6.7	6.8	6.9
Italy	9.5	10.0	10.8	5.5	6.1	7.4	2.9	2.8	–
Spain	21.1	23.6	25.2	9.6	11.3	12.6	4.0	5.0	5.1
Sweden	28.5	25.5	27.2	9.7	12.4	13.9	9.6	10.6	–
UK	27.5	28.7	30.6	15.6	19.5	21.0	5.5	–	–
EU-15	20.5	21.5	22.5	10.2	11.9	–	5.6	5.9	–
EU-25	19.4	20.1	21.2	9.4	11.0	–	5.3	5.6	5.8
US	35.8	37.3	38.1	9.3	9.9	10.9	8.6	–	–

Note. US indicator for tertiary education in 2003 refers to 2002; the Italian number for S&E graduates in 2003 also refers to 2002, and EU-25 to 2000. The UK number of researchers refers to 1998. *Source*. European Innovation Scoreboard 2005 indicators and OECD.

Table 7
Shares in ‘triadic’ patent families

	1994	1996	1998	2000
EU-25	34	32	33	32
US	35	37	35	35

Source. OECD (2004a).

the shares of US and EU patents filed at the European Patent Office in five main fields. It shows that EU has a relative strength in Processes and Mechanics and, conversely, major weaknesses in Electricity/Electronics, Instruments, and Chemistry. At a more disaggregated level, the lower part of the same table focuses on six selected subfields where the technological dynamism (as revealed by total patent growth) has been particularly high. It suggests that in Information Technologies, Pharmaceutical and Biotech the US is well ahead, while Europe has comparable shares of patents in Telecommunication and does particularly well in Material Technologies (especially due to Germany).

To sum up, both R&D expenditures and patent indicators pinpoint a *European lag in terms of* both *lower search investments and lower innovative output*. This is largely the consequence of weaknesses in technological fields that are considered as the ‘engine’ of the contemporary ‘knowledge economy’. On the other hand, the data show a few points of strength related to mechanical technologies and new materials.

4.4. *Structural weaknesses of European corporations and science–industry interaction*

The third aspect to explore the *paradox conjecture* concerns the limits and weaknesses that European business enterprises display in innovating and competing in the world economy. The evidence, in our view, suggests that the fundamental factors underlying the worsening European performance centre, first, as discussed earlier, on the commitment of European firms to research and international patenting and, secondly and relatedly in several sectors, on their relatively weak participation in the core international oligopolies. All this, at least in first approximation, is quite independent from any imagined weaknesses in the industry–university links.

Let us focus in particular on those industries where the consequences of European lags in science and technological innovation are likely to be more severe.

Table 8
Breakdown of shares of patents filed with EPO for different fields

	Electricity	Instruments	Chemistry	Processes	Mechanics	All fields
EU-15	36.3	36.5	37.5	50	54.1	42.6
US	35.2	39.7	39.9	27.1	22.1	33.1
	Telecom	**IT**	**Semiconductor**	**Pharmaceutics**	**Biotech**	**Materials**
EU-15	37.9	26.9	29.2	35.7	28.3	55.1
US	35.7	49.3	36.2	43.5	51.3	19

Source. European Commission (2003).

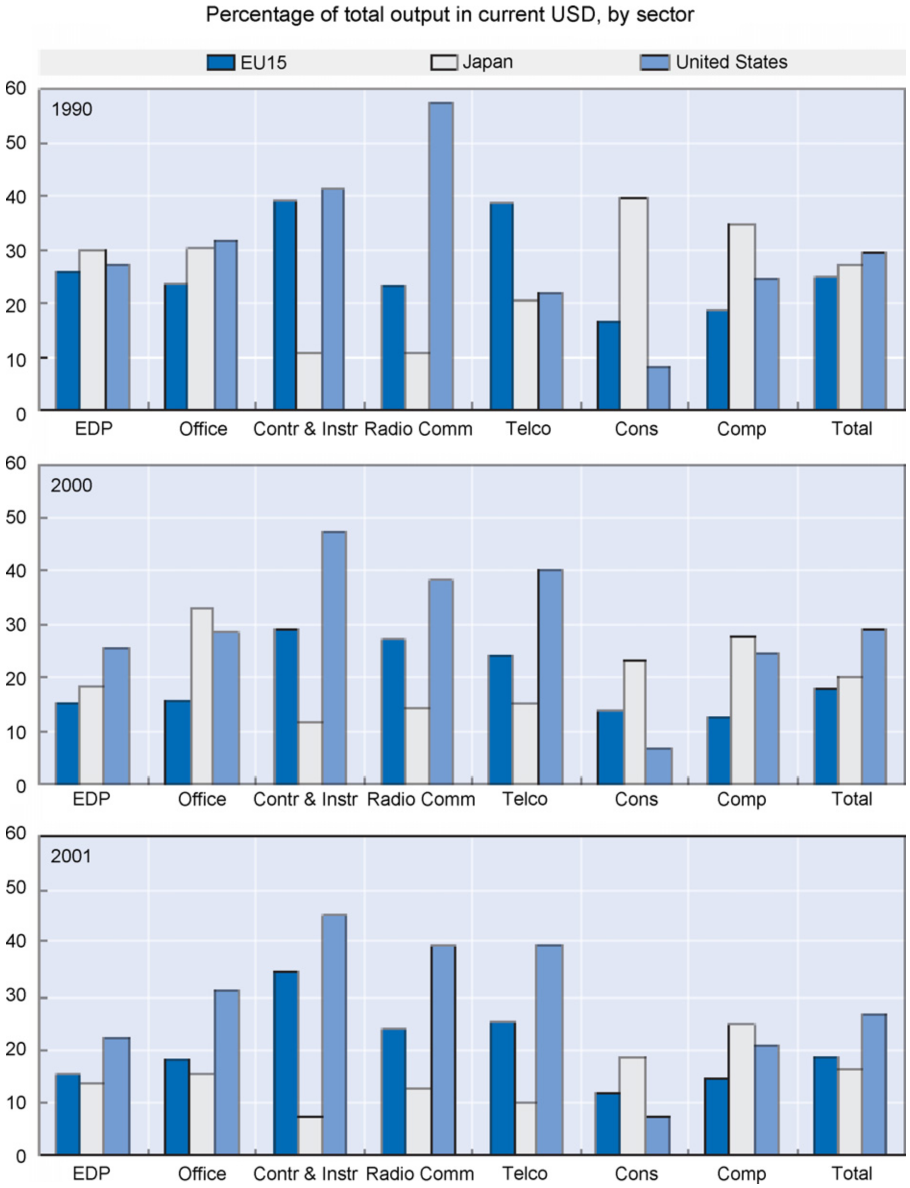

Fig. 3. Share of world ICT production. *Note*. Abbreviations stand for: electronic data processing, office equipment, control and instrumentation, radio communications (including mobiles) and radar, telecommunications, consumer audio and video, components, and total ICT. No data were available for Greece, Luxembourg and Portugal in 1990. Luxembourg data are also not available for the other years. *Source*. Reed Electronics Research, various years. Reproduced in OECD (2004b).

Fig. 3 shows the production shares in several ICT sectors. If the overall rankings of the EU-15 countries, US and Japan have remained more or less stable, variations in individual shares show that the EU has lost the lead even in the telecommunications industry, where in the nineties it had a big advantage. Europe has also declined relative to the United States in office equipment. On the other hand, in radio communications and radar equipment the United States has somewhat lessened its lead relative to Europe (in turn, this has probably been the outcome of the formation of a few European companies, especially in the military sector, with sizes and capabilities that begin to be comparable with those of their American counterparts).

A similar picture comes from the data measuring trade performances in major high-tech sectors. Table 9 depicts export market shares of selected EU countries excluding intra-EU trade. While in aerospace the US has lost some ground and the EU has grown, the opposite has happened in Instruments and Pharmaceuticals.

Table 9
Trade in high-tech industries: export market shares relative to OECD total exports (excluding intra-EU trade)

	1996	1997	1998	1999	2000	2001
			Aerospace			
France	0.12	0.09	0.10	0.12	0.12	0.11
Germany	0.06	0.06	0.06	0.06	0.07	0.10
Italy	0.02	0.02	0.02	0.02	0.02	0.02
UK	0.05	0.11	0.10	0.10	0.10	0.10
US	0.54	0.52	0.52	0.52	0.48	0.45
			Electronic			
France	0.02	0.02	0.02	0.02	0.02	0.02
Germany	0.04	0.04	0.04	0.04	0.04	0.05
Italy	0.01	0.01	0.01	0.01	0.01	0.01
UK	0.03	0.03	0.03	0.03	0.03	0.03
US	0.30	0.31	0.36	0.36	0.36	0.36
			Office machinery and computers			
France	0.01	0.02	0.01	0.01	0.01	0.01
Germany	0.03	0.03	0.04	0.04	0.03	0.03
Italy	0.01	0.01	0.01	0.01	0.01	0.01
UK	0.06	0.05	0.05	0.04	0.04	0.05
US	0.36	0.35	0.38	0.37	0.37	0.38
			Pharmaceutical			
France	0.05	0.05	0.04	0.05	0.05	0.06
Germany	0.13	0.15	0.16	0.15	0.13	0.13
Italy	0.05	0.04	0.04	0.04	0.05	0.04
UK	0.08	0.08	0.07	0.07	0.08	0.07
US	0.21	0.22	0.21	0.21	0.24	0.24
			Instruments			
France	0.03	0.03	0.03	0.03	0.02	0.03
Germany	0.10	0.10	0.10	0.09	0.08	0.09
Italy	0.02	0.02	0.02	0.02	0.02	0.02
UK	0.05	0.05	0.05	0.05	0.05	0.05
US	0.35	0.37	0.38	0.38	0.39	0.39

Note. Our calculations are based on the STAN-OECD database. OECD countries excluding Czech Republic, Hungary, Korea. ISIC revision 3: aerospace industry (353); electronic industry ISIC (32); office machinery and computer industry (30); pharmaceutical industry (2423); medical, precision and optical instruments, watches and clocks (instruments) industry (33).

Combining different sources, the 2004 OECD Information Technology Outlook (OECD, 2004b) explores the performance of the top 250 ICT firms and the top 10 in four sub-sectors (communication equipment and systems, electronics and components, IT equipment and systems, IT services, software and telecommunications). It turns out that 139 of the top 250 firms (56%) are based in the United States and only 33 (13%) in the EU, confirming the overall weakness of the EU among the world industrial leaders, notwithstanding certain sub-sectoral exceptions. So, although six EU firms appear in the top 10 of telecommunication services firms, there are just three in the top 10 of communications equipment and systems firms, 2 in the top 10 of electronics and components firms, and only 1 in the top 10 of software ones. Finally, there are no European firms among the 10 larger firms in IT equipment and systems.

Indeed, these data support the conjecture that, quite independently of the 'bridges' between scientific research and industrial applications, potential corporate recipients in Europe are generally smaller, weaker and slower in seizing novel technological opportunities than their transatlantic counterparts.

This is also well illustrated by those revealing cases where the science is world class, all the 'transfer mechanisms' are in place but hardly any European firms are there to benefit. A striking example of this is computer sciences at Cambridge, *England*: there, an excellent scientific output is mostly exploited by *non-European* firms (from Fujitsu to Microsoft and many others).

Note that the presumed feeble links between science and industry should be one of the most important aspects of the paradox conjecture. Surprisingly, the evidence here is simply non-existent. Curiously the European Commission Third Report on Science and Technology Indicators does not address the issue explicitly, but merely discusses the "science content" of EU technology, which is a rather separate issue (European Commission, 2003, p. 422). Concerning the latter, the number of citations to scientific journal articles in patents that cite science is indeed higher in the US, but this hardly supports the hypothesis that this reflects EU weaknesses in science–industry interactions. Rather, it might primarily reveal the different composition of European technological output, with patterns of specialization which tend to be less 'science based'.

In fact, the few indicators available that may be considered more direct measures of the interaction between business and higher education point to conclusions at odds with the conventional wisdom. As Table 10 shows, the share of private investment in higher education R&D, while low everywhere, is *marginally higher in the EU*

Table 10
Shares of higher education expenditure on R&D (HERD) financed by industry

	1998	1999	2000	2001
Belgium	11.1	10.5	11.8	12.7
France	3.4	3.4	2.7	3.1
Germany	10.5	11.3	11.6	12.2
Spain	7.0	7.7	6.9	8.7
UK	7.3	7.3	7.1	6.2
EU-15	6.4	6.5	6.6	6.8
EU-25	6.4	6.5	6.5	6.7
US	6.1	6.1	6.0	5.5

Source. OECD (2004a).

than in the US and much higher than in Japan. Similar results are obtained if one considers the private sector's annual investment in the public research sector (i.e. the sum of higher education and government R&D) (King, 2004).

5. Wrong diagnoses and misguided policies: some modest alternative proposals by way of a conclusion

The evidence from Europe on the interactions between scientific advances, technological innovations, and industrial evolution (i.e. on central elements of the 'triple helix' linking government policies, scientific research and industry (Etzkowitz and Leydesdorff, 1997)) does indeed highlight dynamics consistent with what we earlier termed the 'SYS synthesis'. Implications of the latter include the continuing paramount importance of basic science shaping the ever-expanding pool of (notional) technological opportunities. Whether those opportunities tend to be actually tapped, however, is also as a function of the capabilities and strategic orientation of business firms (in particular, 'neighbouring ones' in terms of geographical location, nationality, and knowledge 'proximity').

Indeed, the European picture shows worrying signs of weakness with respect to the generation of both scientific knowledge and technological innovation. However, no overall 'European Paradox' with leading science but weak 'downstream' links can be observed. On the contrary, significant weaknesses reside precisely at the two extremes with, first, a European system of scientific research lagging behind the US in several areas and, second, a relatively weak European industry. The latter, we have argued, is characterized on average by a somewhat lower presence in sectors based on new technological paradigms (such as ICT and biotechnologies), by a lower propensity to innovate, and by a relatively weak participation in international oligopolies in many activities.

In turn, such a picture, as we shall argue below, calls for strong science policies and industrial policies. However, this is almost the complete opposite of what has been happening. The belief in a purported paradox, together with an emphasis on the 'usefulness' of research, has led to a package of policies whereby EU support for basic research is largely non-existent. Instead, "Research proposals are expected to identify possible practical as well as scientific benefits; higher priority is being given to user involvement (including partial funding), universities are being invited to extract more revenue from licensing their intellectual properly, and substantial public funds have been spent on 'foresight' exercises designed to create exchange and consensus around future opportunities of applications" (Pavitt, 2001, p. 768).

The 'Framework Programmes' have all been conceived with such a philosophy, and in the most recent one this philosophy is pushed to the extreme with the 'Networks of Excellence'; not only they do not support research but they explicitly prohibit the use of EU money for that purpose!

Similarly, with regards to industrial R&D, the focus on 'pre-competitive' research has meant the emergence of a sort of limbo wherein firms – often in combination with academics – try to tap community money in areas that are too marginal to justify the investment of their own funds. Moreover, the networking frenzy has gone hand-in-hand with a growth in the number and power of research officials (both at the European and the national level), whose main competence is precisely in 'networking', 'steering', writing lengthy reports, and demanding that researchers do the same. Here again, the extreme is perhaps to be found in social sciences. Somewhat like in the old Soviet Union where even papers in mathematics had to begin with a phrase along the lines of "according to the clever intuition of comrade Brezhnev . . .", in many areas one has to begin each research proposal by arguing that what follows is crucial in order to match fashionable keywords such as 'cohesion', 'enlargement', and 'citizenship', even if the real scientific interest lies, say, in the econometrics of panel data or the transmissions mechanisms of monetary shocks. And with all this goes another form of corruption of the ethos of researchers, who have to develop the skills of camouflage and marketing. If our diagnosis is correct, this state of affairs is *detrimental to research, wasteful for society and also bad for business*.

Given this state of affairs, what can be done? Let us conclude with some policy implications of the foregoing analysis. First, *increase support for high quality basic science*, through agile institutions much like the American National Science Foundation (NSF) and relying on world-class peer-review (and also preferably located far away from Brussels, as May (2004) suggests!). Here, the establishment of a European Research Council is a welcome development.

Second, fully acknowledge the differences within the higher education system between research-cum-graduate teaching universities and other forms of tertiary education discussed above. The well-placed emphasis on the role of the first type of institutions often comes under the heading of the 'Humboldt model' as pioneered by Germany more than a century ago. However, nowadays the practice is mostly American, while the confused blend of the functions currently offered in Europe (especially Continental Europe) is good neither for research nor for mass higher education.

Third, push back the boundaries between public or 'open' research and appropriable research. One often forgets that appropriability is socially justified only in so far it provides an incentive to innovation itself. As we have argued above, appropriation of the output of public research does not perform that role. Of course, this applies primarily to *basic* research while the picture is much more blurred for practically oriented disciplines such as engineering. Hence a considerable degree of pragmatism is required. However, we would stand by the general point that too much emphasis on appropriability and IPR is likely to exert a pernicious influence on both the rate and direction of search. Moreover, as we suggested above, it might also represent a significant hindrance to business-led innovation. Europe's lagging behind with regard to the institutional changes leading to a more property-based system of research as compared to the US might, for once, be a blessing in disguise, in that it may be easier for Europe to stop and reverse the tendency (for a thorough discussion of the forgoing appropriability-related points, see Nelson (2004)).

Fourth, develop large-scale, technologically daring missions justifiable in terms of their intrinsic social and political value and able to match in terms of size and ambition the US (often more military-oriented) programs. As Pavitt reminds us, "Scandinavian countries and Switzerland are able to mobilize considerable resources for high quality basic research without the massive defense and health expenditures of the world's only superpower". Hence, he suggests, "the larger European countries and the European Union itself, have more to learn from them than from the USA" (p. 776). Nevertheless, one should not overlook the importance of large-scale far-reaching European programs with ambitious and technologically challenging objectives in such fields as energy conservation, health care, and environmental protection (and perhaps also European rearmament, although this is a much more controversial issue, the discussion of which is beyond the scope of this paper).

Fifth, re-discover the use of industrial policies as a device to foster a stronger, more innovative, European industry. We are fully aware that nowadays 'industrial policy' is a term that cannot be mentioned in a polite company without one being accused of supporting Jurassic 'national champions', distorting competition, fostering production patterns that go against 'revealed' comparative advantages, and so on. We are tempted to answer, "Why not?" ! Certainly the period up to the late 1970s or early 1980s, which was characterized by discretionary interventions by policy makers in the very structure of various industries, witnessed many failures, but there were also several successes. For instance, the European strength in telecommunications, the remarkable presence in semiconductors, and the growing competitiveness in aircraft, are in part the outcome of policy measures of that 'interventionist' era. Today, even within the constraints of the new trade arrangements, much more, we think, could be done to foster European strength (or, for that matter, multiple regional sources of strength) in the most promising technological paradigms, were it not for a self-inflicted 'market worship' (another commodity largely exported by the US, but consumed there quite parsimoniously and pragmatically!).

We are well aware that, by putting forward these modest proposals, we might be accused of conservatism. However, for once we do not mind at all being in the camp of those who try to defend and strengthen a system producing top-level, publicly funded, open science—too often under threat from both the 'property right' colonizers and the 'practical usefulness' advocates. What we advocate is a much pragmatic view of the role that public policies might play in fostering the growth of corporate actors able to efficiently tap an ever-growing pool of innovative opportunities.

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