Research Funding and Research Output:
A Bibliometric Contribution to the US Federal Research Roadmap

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Abstract

In response to the call for a science of science policy, we discuss the contribution of indicators at the macro-level of nations from a scientometric perspective. In addition to global trends such as the rise of China, one can relate percentages of world share of publications to government expenditure in academic research (HERD: Higher-Education Expenditure for R&D). The marginal costs of improving one's share are increasing over time. Countries differ considerably in terms of the efficiency of turning (financial) input into bibliometrically measurable output. A price per paper can be estimated. The percentages of GDP spent on academic research in different nations are significantly correlated to historical contingencies such as the percentage of researchers in the population. The institutional dynamics make strategic objectives such as the Lisbon objective of the EU—that is, spending 3% of GDP for R&D in 2010—unrealistic.

Keywords: R&D expenditure, output indicator, efficiency, nation, S&T policies

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Introduction

In an editorial in *Science* on May 20, 2005, John H. Marburger III called for a "science of science policy." He formulated the challenge as follows: "How much should a nation spend on science? What kind of science? How much from private versus public sectors? Does demand for funding by potential science performers imply a shortage of funding or a surfeit of performers? These and related science policy questions tend to be asked and answered today in a highly visible advocacy context that makes assumptions that are deserving of closer scrutiny. A new 'science of science policy' is emerging, and it may offer more compelling guidance for policy decisions and for more credible advocacy." In response, an Interagency Task Group (ITG) was formed by the US National Science Foundation, the Department of Energy, and other agencies, in order to chart the domain. In November 2008, this ITG published a report containing "A Federal Research Roadmap" which elaborates Marburger's call in considerable detail and sets up a working program for the science of science policy (ITG, 2008).

In this paper, we contribute to the discussion by providing recent data based on scientometric research at the macro-level of nations. This data addresses some of the questions raised about the efficiency of spending on science. To this end, we bring together indicators developed in other contexts (Leydesdorff & Wagner, 2008, 2009; Zhou & Leydesdorff, 2006). We limit ourselves to bibliometric indicators, but proceed by first positioning these in relation to available indicators and other possible approaches. Our data suggests a number of conclusions, and raise questions for further research.

Theoretical contexts

The economic role of science & technology (S&T) entered the political agenda at the end of the 1950s when it became clear that economic growth could no longer be explained in terms of traditional economic factors such as land, labor, and capital. The remaining 'residue' has to be explained in terms of the emerging knowledge base of the economy (Abramowitz, 1956; OECD, 1964). Following the Sputnik shock of 1957, the *Organization for Economic Co-operation and Development (OECD)* was created in 1961 in order to organize and coordinate science and technology policies among the member states, that is, the advanced industrial nations. In 1963, the first *Frascati Manual* was published in which parameters were defined for the statistical monitoring of science and technology on a comparative basis (OECD, 1963).

Output indicators of science emerged in the completely different context of information retrieval and the development of the *Science Citation Index.* During the 1950s and 1960s, the scientific community had itself become increasingly aware of the seemingly uncontrolled expansion of scientific information and literature during the postwar period (Garfield, 1955, 1978). In addition to its use in information retrieval, the *Science Citation Index* produced by the Institute of Scientific Information (ISI) soon came to be recognized as a means to objectify standards (Price, 1963; Elkana *et al.* 1978). The gradual introduction of output indicators (e.g., numbers of publications and citations) could be legitimated both at the level of society—because it enables policy makers and

science administrators to use arguments of efficiency—and internally, because quality control across disciplinary frameworks is difficult to legitimate unless objectified standards can be made available in addition to the peer review process (Martin & Irvine, 1983; Moed *et al.*, 1985).

The econometric and the bibliometric approaches can both be made relevant for studying systems of innovation because innovations take place at interfaces between the knowledge production system and the economy (Rosenberg, 1976; Mowery & Rosenberg, 1979). In addition to industry-based systems of innovation (e.g., Nelson, 1982), the study of national systems of innovation was proposed by Freeman (1987), Lundvall (1988, 1992), and Nelson (1993). In this context, patent statistics are considered as indicators of inventions (Griliches, 1984, 1994; Narin & Olivastro, 1992; Pavitt, 1984; Sahal, 1981). Patent citations can be used for mapping the underlying science base of patents (Jaffe & Trajtenberg, 2002; Leydesdorff, 2004; Porter & Cunningham, 2005; Sampat, 2006; Verspagen, 2006). Because of their legal and economic functions, patent citations can also be considered from perspectives different from the mapping of their knowledge base. For example, patent citations have been used for measuring the economic value of patents (Hall *et al.*, 2002; Sapsalis *et al.*, 2006; Trajtenberg, 1990). This has additionally been done at the level of innovation systems or even companies (Breschi *et al.*, 2003; Engelsman & Van Raan, 1993, 1994; Leten *et al.*, 2007).

Three literatures have emerged which are interrelated, but which have remained somewhat separate because of differences in their analytical perspectives: (*i*) the economic and econometric literature which focuses on the functions of R&D for growth in the economy, (*ii*) the bibliometric literature about indicators of growth in the sciences, and (*iii*) the literature in evolutionary economics which focuses, among other things, on patents as indicators at the interfaces between these two systems. In an authoritative study in the econometric tradition, Coe, Helpman, & Hoffmaister (2008, at p. 12) recently concluded that "there is robust evidence that total factor productivity, domestic R&D capital and foreign R&D capital are cointegrated [share a common trend, L&W], and that both measures of R&D capital are significant determinants of TFP." Four factors were found to make a difference among nations: (*i*) the ease of doing business, (*ii*) the quality of the tertiary education system, (*iii*) intellectual property protection, and (*iv*) the historical origins of the legal system. These conclusions, in our opinion, illustrate the extent to which the development of S&T itself is nowadays still black-boxed from this econometric perspective (Rosenberg, 1982): the qualification of labor, patent statistics, and R&D are considered as exogenous factors which can be expected to stimulate economic growth by interacting in an otherwise complex process.

The bibliometric approach and the perspective of evolutionary economics share a deeper appreciation of the dynamics of science and technology, and their respective literatures. In their groundbreaking book entitled *Patents, Citation, and Innovations: A Window on the Knowledge Economy*, Jaffe & Traitenberg (2002) considered patents and patent citations as providing data for studying the residue which cannot be explained in the econometric models of total factor productivity (TFP). The long-term impact of this residual knowledge factor—that is, R&D and education combined—on the economy is

sometimes assessed to represent more than 30% of economic growth (Denison, 1964, at p. 54; cf. Mansfield, 1972, 1991, 1998; Romer, 1986). Analysts of patents and their citations focus on the decomposition of the databases in terms of industrial sectors (e.g., Grupp *et al.*, 1996; Pavitt, 1984). With the shift to services induced by the knowledge-based economy, information technologies and open source innovations have become more important (Brécard *et al.*, 2006; Jorgenson & Stiroh, 1999; Von Hippel, 2001). S&T tend to operate globally, and therefore provide an additional dynamic of organized knowledge production and control to the economic system (Barras, 1991; Steinmueller, 2002). In a study of the German innovation system, for example, Leydesdorff & Fritsch (2006) showed that knowledge-intensive services and high-tech manufacturing are more "footloose" than medium-tech manufacturing in terms of infusing regions with knowledge.

The decomposition of organized knowledge production and control in terms of differences among the techno-sciences has been central to science and technology studies as a branch of the sociology of science (Whitley, 1984). Publication and citation practices, for example, are discipline-specific (Leydesdorff, 2008). However, under the pressure of the current institutional regime of university rankings, research evaluations, etc., institutional isomorphisms can also be expected which may cross disciplinary boundaries (DiMaggio & Powell, 1983). The availability of the *Arts & Humanities Citation Index*, for example, puts pressure on researchers and research administrations even in the humanities to articulate instruments for comparative assessment (Steele *et al.*, 2006; Linmans, 2008).

The decomposition of the databases in terms of discrete clusters representing disciplines, specialties, interdisciplinary developments, etc., has hitherto remained an unresolved issue on the research agenda of bibliometric indicator studies (Rafols & Leydesdorff, 2009). What can nevertheless be said at the aggregate level in response to the questions raised by Marburger (2005) and the Roadmap (ITG, 2008)? How much should a nation spend on science? How does the emergence of China and other Asian nations impact on the science system and change the competitive relations among nations?

Methods and materials

We use the latest available version of the *Main S&T Indicators* (2008-2) of the OECD (2008), and data from the *Science Citation Index* as available on the Web-of-Science of the Institute of Scientific Information (of Thomson Reuters). The latter are current data of publications and citations. However, we bin this data as yearly data using the tape-years of the ISI. (Publication data may lag with reference to calendar years.) Consequently, 2008 is the last available year. The *Main S&T indicators 2008-2* are often incomplete for 2007, but almost completely available for 2006. All expenditure data are normalized by the OECD in terms of current purchasing power parity, expressed in (millions of) US dollars.

On the output side, our focus is on the *Science Citation Index* because the capital intensity of the social sciences and the humanities is of a different order of magnitude.

More specifically, it is best practice in scientometrics to focus on citable issues, that is, articles, reviews, and letters. In October 2008, the ISI divided the document type "articles" into "articles" and "proceedings papers." This change was taken into account when collecting our data for 2008. Percentages of world shares of publications are based on whole number counts, but the value for the EU-27 was corrected for within-EU publications. The combination of the two databases enables us below to specify some of the dynamics at the level of nations.

Results

Let us first focus on national outputs and then relate this to inputs.

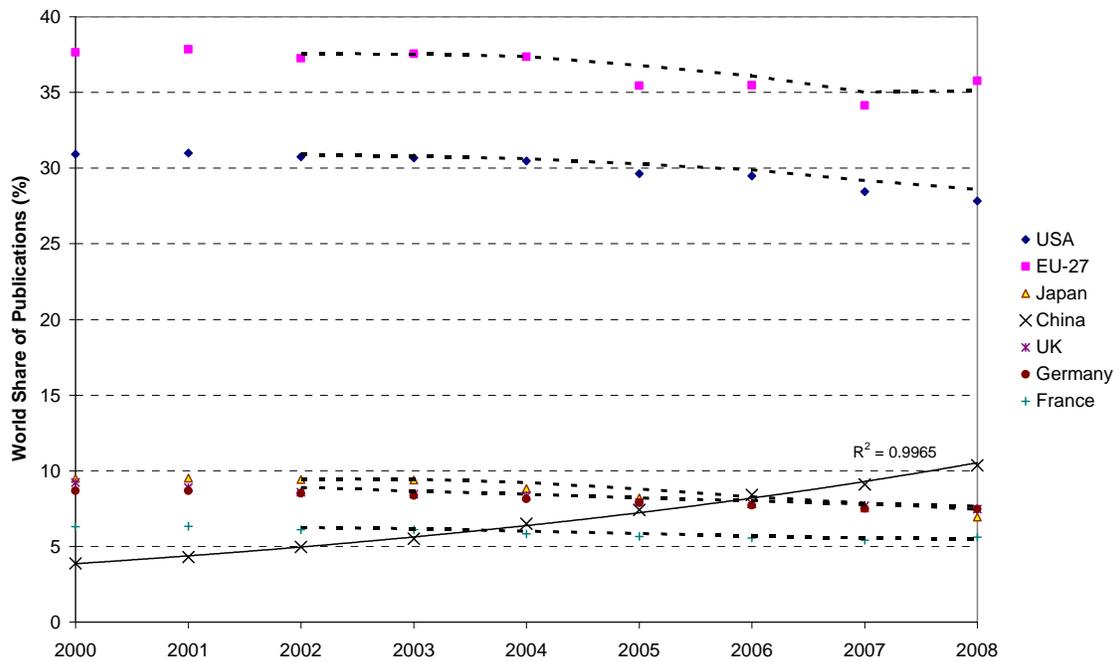*a. Output of nations in terms of publications*

Figure 1: World Share of Publications for some major industrialized countries 2000-2008; based on articles, proceedings papers, reviews, and letters published in journals covered by the *Science Citation Index.*

Figure 1 shows the main output data of the science system in terms of publications, but normalized as a percentage of world share of publications for the period 2000-2008. In our opinion, the number of publications is the most unambiguous indicator of scientific output because no choices of parameters such as citation windows, etc., are involved. We added three-year moving averages as dashed trend lines, and the exponential regression curve for China ($r^2 > 0.99$). As previously, China continues to show exponential growth in both absolute and relative numbers. This leads to a relative decline for all other nations in the database because of the normalization involved in using percentages of world share.

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As reported by Thomson-Reuters Scientific in May 2008, the database was recently extended in terms of "regional" coverage. This is visible in the above figures for the EU-27. The 2008-point reflects a rise from 3.0% to 4.4% for the twelve accession countries of the EU between 2007 and 2008. Some part of the increased share of China in 2008 may also be attributable to this one-time effect in coverage of the database. However, the main trends are clear: (*i*) the figures for China show a spectacular increase, and (*ii*) the USA is affected more negatively by the ongoing changes in the world system, but all industrialized countries have to give way.

In a recent publication, we analyzed the citation patterns in more detail using, for example, the most highly-cited papers of the USA *versus* the EU (Leydesdorff & Wagner, 2009; National Science Board, 2008). In that study, we concluded that the USA tends to lose its dominance because the European countries are catching up, but this process of (mainly North-Atlantic) homogenization is relatively slow (Leydesdorff & Wagner, 2008). If current trends were to continue, China's contribution to world science could be as large as that of the USA by 2014.
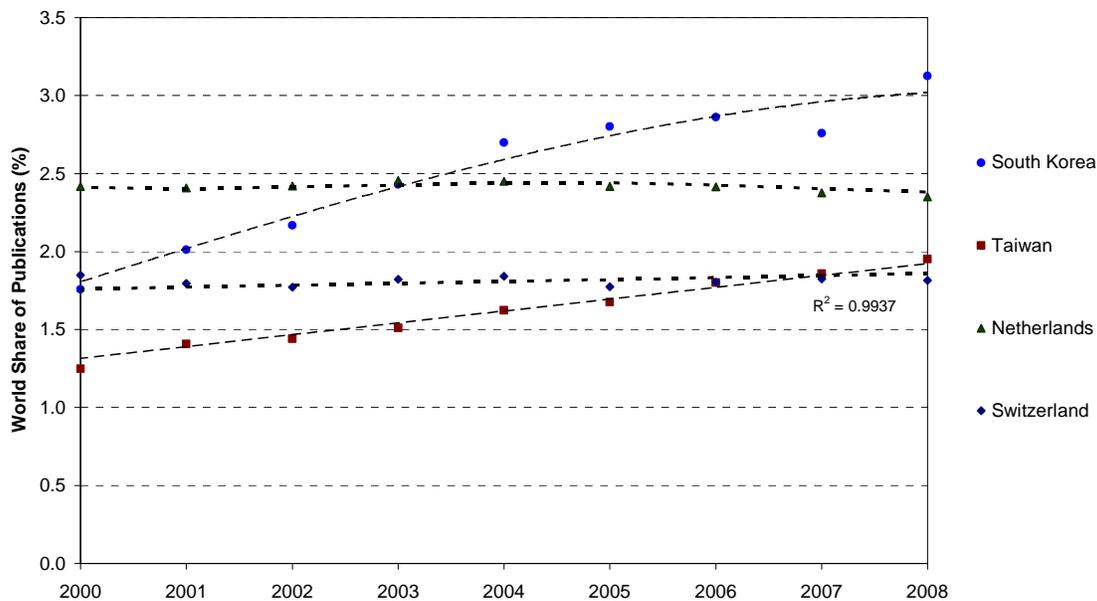

Figure 2: World Share of Publications for some smaller nations 2000-2008; based on articles, proceedings papers, reviews, and letters published in journals covered by the *Science Citation Index.*

Figure 2 shows the same trend lines for the Netherlands and Switzerland as two smaller, but R&D-intensive nations, and Taiwan and South Korea as two of the other so-called Asian-4 (including also Singapore with smaller numbers). The Netherlands is gradually losing in terms of world share of publications, but Switzerland seems to be able to keep its percentage of world share at the current level. Probably, the funding situation makes a

difference between these two countries (cf. King, 2004).[1] South Korea shows a pattern of growth, but approximates its marginal percentage in the most recent years. The Scandinavian countries and the Netherlands also showed this pattern of linear growth with saturation in the 1980s, and Italy and Spain in the 1990s. This suggests that Korea is increasingly integrated into the world system. This is not yet the case for Taiwan, which is still able to convert domestic R&D into internationally oriented R&D output.

We suggest that the exponential curve in the case of China shows the effect of a positive feedback loop in the Chinese system. On the one hand, there is a large reservoir of academics eager to publish internationally and still to be tapped by the international system of publications; on the other, there are institutional incentives in place which stimulate international publishing in terms of financial rewards for individuals and research groups.

b. Output / Input

Since the science system as an international system of scientific publications is mainly based in academia, the relevant segment of the budget is the so-called Higher-Education Expenditure for R&D (HERD) in the OECD statistics. As noted, the OECD data is incomplete, but insofar as they are available all data are standardized in terms of current purchasing power parity (ppp).
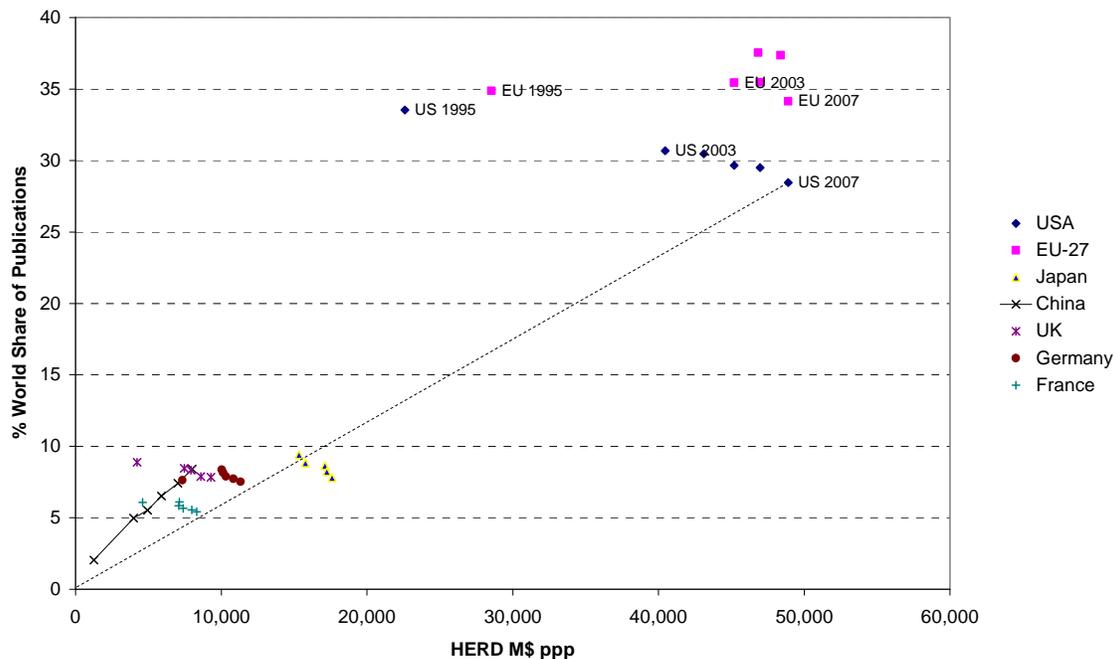

Figure 3: Output (% publications) over input (HERD) for major industrial nations and the EU-27 (1995, 2003-2007).

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[1] The OECD statistics about Higher-Education Expenditure for R&D are unfortunately incomplete in the case of Switzerland (OECD, 2009: 40).

Figure 3 shows the relationship between the percentage of world share of publications and HERD. Figures are provided for 1995 and for the period 2003-2007. As is best visible for the US, countries tend to spend more over time to maintain their marginal percentage of world share of publications at a certain level. Note that these data are already corrected for inflation, and thus one could consider the additional spending as R&D inflation. It seems that the EU-27 is less sensitive to this phenomenon than the USA. We added the linear regression line for the US-2007 in order to enable the reader to see that the USA is spending per percentage point of output more than the European nations and China, but less than Japan. Figure 4 enlarges and details the lower left quadrant of Figure 3.
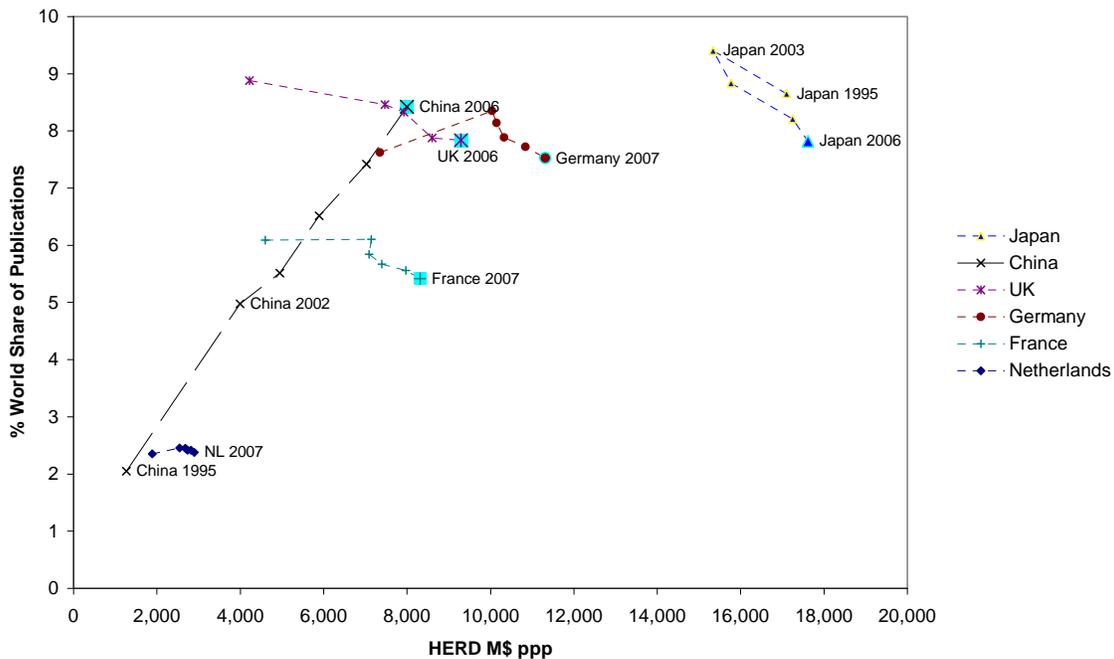

Figure 4: Output (% publications) over input (HERD) for several medium-sized nations.

With the exception of Japan, all nations move with the years from the left to the right, that is, they increase their spending on R&D, and slightly downward, that is, they lose their percentage of world share as explained above. Japan economized on HERD during the 1990s, but joined the club of comparable nations again in this millennium. Germany peaked in terms of output during the 1990s because of unification (Leydesdorff, 2000). France and the UK follow a similar pattern, but the UK is much more efficient in terms of output/input than France. We added the Netherlands as an example of a small European nation.

The curve for China is penciled in as a dashed line. In our opinion, this curve makes transparent what is happening in China: both expenditure and output are growing. China's efficiency (output/input) is now larger than that of the UK, while they are the same size in terms of output. The UK was traditionally highest in converting funding into

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publications, but was surpassed by China not only in terms of numbers of publications, but also in this respect.

c. How much should one spend?

During their meeting in Lisbon in March 2000, the Heads of State of the European Union (the EU-15 at the time) and the European Commission agreed to raise the percentage of GDP to be spent on R&D to 3% in 2010. This objective can be considered as part of the so-called "Lisbon strategy" to make the EU the most competitive player in the knowledge-based economy (European Commission, 2000 and 2005). The underlying assumption that R&D investments will provide a return in terms of economic growth, however, has been debated, for example, in the case of the "Swedish paradox:" Sweden spends more than 3% of its GDP on R&D, and did so already during the 1990s. Furthermore, Sweden leads the OECD scoreboard in terms of various other indicators of knowledge-intensity (patents/ capita, new PhDs, etc.). However, its growth in GDP has remained below that of the OECD average to the extent that Sweden has moved from being one of the richest countries in the world, in term of GDP per capita, to a position below the OECD average (Edquist & McKelvey, 1998; Elg, 2003; Kander and Ejermo, 2008).

Note that from an econometric perspective, one can expect small countries like Sweden to profit from international R&D spillovers (Coe *et al*., 2008). The relatively low and still decreasing percentage ($< 2\%$) that the Netherlands spends is often considered to be compensated by these effects of its open economy. Closer inspection of the OECD-data, however, reveals that relatively similar nations vary considerably in terms of the percentage of GDP they spend on R&D, and that these percentages tend to be rather stable over time. Historical factors such as the percentage of the workforce which is highly educated can be expected to have a long-term impact.
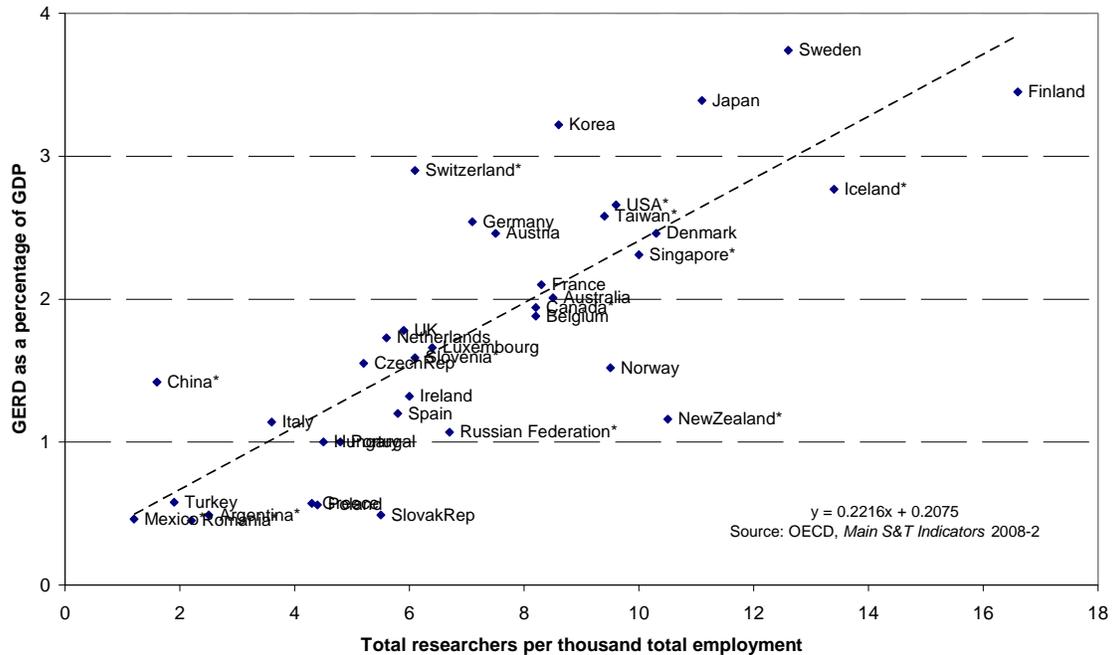
Figure 5: Percentage of GDP spent on R&D versus the permillage of researchers on total employment. Source: OECD, 2009.

In Figure 5, we plotted the %GDP spent on R&D against the total numbers of researchers for a number of countries. The OECD (2009) provides 2006 data which can reliably be compared in the case of the 24 OECD member states. The two indicators correlate significantly: $r = 0.86$ ($p < 0.01$); $n = 24$. In the figure, we used the latest available figures for all countries listed (including a number of non-OECD countries), but asterisked the country names in the additional (non-2006) cases.

Horizontally, Figure 5 shows that countries are able to sustain very different workforces with similar funding efforts. New Zealand, for example, spends not more than Italy in terms of %GDP, but the percentage of its researchers in the workforce is more than three times as high. Along the diagonal, one witnesses the noted correlation. One can argue in the one direction that more government spending allows for more employment in this segment, or in the other direction that a larger share in the workforce corresponds to a stronger lobby for government spending in R&D. The mechanism is not known; the causality may also be circular.

In summary, these statistics suggest that the assumption under the Lisbon objective that government spending in R&D can be considered as a motor of economic growth is not warranted by the data. There is no direct short-term or long-term relation (as shown by the Swedish paradox), and similar countries can vary in terms of spending without producing a noticeable effect on their long-term economic performance. The harmonizing forces in the economy (for example, within the EU) can be analyzed in terms of international R&D spillovers, but this econometric reasoning cannot be turned around. The harmonization in the economy as among the nation states of the EU does not lead to

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similar patterns of R&D spending or to changes in the relative participation of the higher-educated segment of the workforce in the labor market.

Another perspective on the question of R&D funding can be provided by estimating a price per publication. Let us again assume that HERD provides us with the best available input indicator for this measure at the aggregate level, and that output can be measured in terms of citable issues in the *Science Citation Index.* Table 1 shows that the price per publication would be more than US$ 175,000 for the USA, while it is considerably lower for most European countries. Eastern European countries, Russia, and China spend less than 100k per publication. However, Austria and Japan spend more than 200k. Thus, the differences between culturally similar countries (e.g., Germany and Austria) are large, although there are also common trends. The average cost per publication from this list of nations is 131k (± 43k).

2007	$ ppp/publication
Australia*	137,798
Austria	209,165
Belgium	115,328
Canada	191,004
CzechRep	97,939
Denmark	148,556
Finland	141,476
France	156,271
Germany	153,373
Greece	100,054
Hungary	87,047
Ireland	106,923
Italy*	132,441
Japan*	237,973
Korea*	132,019
Luxembourg	89,202
Netherlands	124,708
Norway	193,157
Poland*	70,954
Portugal	137,362
SlovakRep	55,320
Spain*	128,119
Sweden	154,456
Turkey*	154,728
UK*	123,110
USA	175,284
EU-27*	163,216
China*	89,638
Argentina	137,901
Romania	115,938
Russian Federation	62,763
Singapore*	179,017
Slovenia	58,081
Taiwan*	111,104
Israel	108,408

Average	130,852 ± 42,684

Table 1: Cost per publication for various nations. Sources: Web-of-Science and OECD data combined.

Note that the cost per publication is higher for the EU-27 than for most of the EU-nations separately. This is due to the additional funding of R&D by the European Committee which cannot be associated with a separate component in the national outputs.

Conclusions and discussion

Nations differ in terms of their research portfolios and their economic structures. Both research fields and industrial structures are internationally organized. This raises a number of control problems at the national level. International scientific collaboration can be considered as leading to international R&D spillovers, but generates a new set of policy questions in the S&T arena (Wagner, 2008). From the perspective of hindsight, one can consider the OECD as an institution which, in reaction to the internationalization of the Western economies during the 1950s and 1960s, sought to monitor the effects of R&D on economic performance without opening the black box of science and technology itself. The transition from a (nation-based) political economy to a (globalizing) knowledge-based economy, however, makes opening the black box of organized knowledge production and control urgent.

The output statistics from the bibliometric perspective and patent statistics in evolutionary economics reveal other dynamics operating than the equilibrating ones of the market (Nelson & Winter, 1982). Research portfolios develop along historical trajectories and are entrenched in intellectual traditions that differ among nations and world regions. For example, while the USA is firmly committed to health research and has a strong pharmaceutical industry, China and other Asian nations are stronger in traditional fields like physics and chemistry (Park *et al*., 2005).

In our opinion, the discussion at the aggregate level of nations can no longer ignore the underlying complexities. The idea that innovation is coordinated in systems that are integrated at levels other than nationally, raises new questions for science and technology studies, indicator development, and econometric analysis. In a Triple Helix model, for example, governments are one of the partners in university-industry-government relations. Government policies can then be drawn into the analysis as both independent and dependent variables, depending on the research question and the stages in the development under study. Does the political discourse follow the developments in the economy and science and/or steer them (Dosi *et al*., 2006)? Questions about the dynamics of lock-in into and break-out from historical contingencies and traditions (Dolfsma & Leydesdorff, 2009) may prove more important in assessing returns on investments, than levels of spending at specific moments in time (e.g., the Lisbon objective of 3% of GDP in 2010). In our opinion, institutional incentives and constraints at lower levels of organization can be expected to prevail over national or transnational S&T objectives.

References:

Abramowitz, M. (1956). Resource and Output Trends in the United States since 1870. *American Economic Review 46*, 5-23.

Barras, R. (1990). Interactive Innovation in financial and business services: The vanguard of the service revolution. *Research Policy,* 19, 215-237.

Brécard, D., Fougeyrollas, A., Le Mouël, P., Lemiale, L., & Zagamé, P. (2006). Macro-economic consequences of European research policy: Prospects of the Nemesis model in the year 2030. *Research Policy,* 35(7), 910-924.

Breschi, S., Lissoni, F., & Malerba, F. (2003). Knowledge-relatedness in firm technological diversification. *Research Policy,* 32(1), 69-87.

Coe, D. T., Helpman, E., & Hoffmaister, A. W. (2008). *International R&D Spillovers and Institutions*. Cambridge, MA: National Bureau of Economic Research, available at http://www.nber.org/papers/w14069.

Denison, E. F. (1964). Measuring the Contribution of Education (and the Residual) to Economic Growth. In *The Residual Factor and Economic Growth* (pp. 13-55). Paris: OECD.

DiMaggio, P. J., & Powell, W. W. (1983). The Iron Cage Revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review,* 48, 147-160.

Dolfsma, W., & Leydesdorff, L. (2009). Lock-in & Break-out from Technological Trajectories: Modeling and policy implications. *Technological Forecasting and Social Change,* in print.

Dosi, G., Llerena, P., & Labini, M. S. (2006). The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called 'European Paradox'. *Research Policy,* 35(10), 1450-1464.

Edquist, C., & McKelvey, M. (1998). High R&D intensity without high-tech products: a Swedish paradox? In K. Nielsen & B. Johnson (Eds.), *Institutions and Economic Change: New Perspectives on Markets, Firms and Technology* (pp. 131-149). Cheltenham, UK: Edward Elgar.

Elg, L. (2003). *Is there a Swedish "Paradox"?* Stockholm: VINNOVA Innovation Systems, 6 pp.

Elkana, Y., Lederberg, J., Merton, R. K., Thackray, A., & Zuckerman, H. (1978). *Toward a Metric of Science: The advent of science indicators*. New York, etc.: Wiley.

Engelsman, E. C., & Van Raan, A. F. J. (1993). International comparison of technological activities and specializations: a patent-based monitoring system. *Technology Analysis & Strategic Management,* 5(2), 113-136.

Engelsman, E. C., & van Raan, A. F. J. (1994). A patent-based cartography of technology. *Research Policy,* 23(1), 1-26.

European Commission (2000). *Towards a European research area.* Brussels, 18 January 2000; at http://europa.eu.int/comm/research/era/pdf/com2000-6-en.pdf .

European Commission (2005). *Working together for growth and jobs. A new start for the Lisbon Strategy;* at http://europa.eu.int/growthandjobs/pdf/COM2005_024_en.pdf

Freeman, C. (1988). Japan, a New System of Innovation. In G. Dosi, C. Freeman, R. R. Nelson, G. Silverberg & L. Soete (Eds.), *Technical Change and Economic Theory* (pp. 330-348). London: Pinter.

Garfield, E. (1955). Citation Indexes for Science. *Science,* 122(3159), 108-111.

Garfield, E. (1979). *Citation Indexing: Its Theory and Application in Science, Technology, and Humanities*. New York: John Wiley.

Griliches, Z. (Ed.). (1984). *R & D, Patents, and Productivity*. Chicago, IL: University of Chicago Press.

Griliches, Z. (1994). Productivity, R&D and the Data constraint. *American Economic Review,* 84(1), 1-23.

Grupp, H., Münt, G., & Schmoch, U. (1996). Assessing Different Types of Patent Data for Describing High-Technology Export Performance. In *Innovation, Patents and Technological Strategies* (pp. 271-287). Paris: OECD.

Hall, B. H., Jaffe, A. B., & Trajtenberg, M. (2002). The NBER Patent-Citations Cata File: Lessons, Insights, and Methodological Tools. In A. B. Jaffe & M. Trajtenberg (Eds.), *Patents, Citations, & Innovations* (pp. 403-459). Cambrigde, MA/ London: The MIT Press.

ITG (2008). *The Science of Science Policy: A Federal Research Roadmap*. Washington, DC: National Science and Technology Council and the Office of Science and Technology Policy.

Jaffe, A. B., & Trajtenberg, M. (2002). *Patents, Citations, and Innovations: A Window on the Knowledge Economy*. Cambridge, MA/London: MIT Press.

Jorgenson, D. W., & Stiroh, K. J. (1999). Information Technology and Growth. *The American Economic Review,* 89(2), 109-115.

Kander, A., & Ejermo, O. (2008). The Swedish Paradox. In C. Karlsson, B. Johansson & R. Stough (Eds.), *Entrepreneurship and Innovation in Functional Regions*. Cheltenham, UK: Edward Elgar.

King, D. A. (2004). The scientific impact of nations. *Nature,* 430(15 July 2004), 311-316.

Leten, B., Belderbos, R., & Van Looy, B. (2007). *Technological diversification, coherence and performance of firms* (No. MSI 0706). Leuven / Eindhoven: KU Leuven: Department of Managerial Economics, Strategy and Innovation (MSI), 27; available at http://www.econ.kuleuven.be/fetew/pdf_publicaties/MSI_0706.pdf.

Leydesdorff, L. (2000). Is the European Union Becoming a Single Publication System? *Scientometrics,* 47(2), 265-280.

Leydesdorff, L. (2004). The University-Industry Knowledge Relationship: Analyzing Patents and the Science Base of Technologies. *Journal of the American Society for Information Science & Technology,* 55(11), 991-1001.

Leydesdorff, L. (2008). *Caveats* for the Use of Citation Indicators in Research and Journal Evaluation. *Journal of the American Society for Information Science and Technology,* 59(2), 278-287.

Leydesdorff, L., & Fritsch, M. (2006). Measuring the Knowledge Base of Regional Innovation Systems in Germany in terms of a Triple Helix Dynamics. *Research Policy,* 35(10), 1538-1553.

Leydesdorff, L., & Wagner, C. S. (2008). International collaboration in science and the formation of a core group. *Journal of Informetrics,* 2(4), 317-325.

Leydesdorff, L., & Wagner, C. S. (2009). Is the United States losing ground in science? A global perspective on the world science system *Scientometrics,* 78(1), 23-36.

Linmans, J. (2008). *Does 'hard' impact analysis work for the humanities after all?* Paper presented at the Workshop on Research Evaluation, Metrics and Open Access in the Humanities, Trinity College, Dublin, 18-20 September 2008.

Lundvall, B.-Å. (1988). Innovation as an interactive process: from user-producer interaction to the national system of innovation. In G. Dosi, C. Freeman, R. Nelson, G. Silverberg & L. Soete (Eds.), *Technical Change and Economic Theory* (pp. 349-369). London: Pinter.

Lundvall, B.-Å. (Ed.). (1992). *National Systems of Innovation*. London: Pinter.

Mansfield, E. (1972). Contribution of R&D to economic growth in the United States. *Science,* 175(4021), 477-486.

Mansfield, E. (1991). Academic Research and Industrial Innovation. *Research Policy,* 20(1), 1-12.

Mansfield, E. (1998). Academic research and industrial innovation: An update of empirical findings. *Research Policy,* 26(7-8), 773-776.

Marburger III, J. H. (2005). Wanted: Better Benchmarks. *Science,* 308(20 May 2005), 1087-1087.

Martin, B., & Irvine, J. (1983). Assessing Basic Research: Some Partial Indicators of Scientific Progress in Radio Astronomy. *Research Policy,* 12, 61-90.

Moed, H. F., Burger, W. J. M., Frankfort, J. G., & Raan, A. F. J. V. (1985). The Use of Bibliometric Data for the Measurement of University Research Performance,. *Research Policy,* 14, 131-149.

Mowery, D. C., & Rosenberg, N. (1979). The influence of market demand upon innovation: a critical reveiw of some empirical studies. *Research Policy,* 8, 102-153.

Narin, F., & Olivastro, D. (1992). Status Report: Linkage beteen technology and science. *Research Policy,* 21, 237-249.

National Science Board. (2008). *Science and Engineering Indicators*. Washington, DC: National Science Foundation; available at http://www.nsf.gov/statistics/seind08/, 588.

Nelson, R. R. (Ed.). (1982). *Government and Technical Progress: a cross-industry analysis*. New York: Pergamon.

Nelson, R. R. (Ed.). (1993). *National Innovation Systems: A comparative analysis*. New York: Oxford University Press.

Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Cambridge, MA: Belknap Press of Harvard University Press.

OECD. (1963, [3]1976). *The Measurement of Scientific and Technical Activities: "Frascati Manual"*. Paris: OECD.

OECD. (1964). *The Residual Factor and Economic Growth*. Paris: OECD.

OECD. (2009). *Main Science and Technology Indicators.*Vol. 2008/2. Paris: OECD.

Park, H. W., Hong, H. D., & Leydesdorff, L. (2005). A Comparison of the Knowledge-based Innovation Systems in the Economies of South Korea and the Netherlands using Triple Helix Indicators. *Scientometrics,* 65(1), 3-27.

Pavitt, K. (1984). Sectoral patterns of technical change: towards a theory and a taxonomy. *Research Policy,* 13(6), 343-373.

Porter, A. L., & Cunningham, S. W. (2005). *Tech Mining: Exploiting New Technologies for Competitive Advantage*. Hoboken, NJ: Wiley.

Price, D. de Solla (1963). *Little Science, Big Science*. New York: Columbia University Press.

Rafols, I., & Leydesdorff, L. (2009). Content-based and Algorithmic Classifications of Journals: Perspectives on the Dynamics of Scientific Communication and Indexer Effects, *Journal of the American Society for Information Science and Technology,* forthcoming.

Romer, P. M. (1986). Increasing returns and long-run growth. *The Journal of Political Economy,* 94(5), 1002-1037.

Rosenberg, N. (1976). *Perspectives on Technology*. Cambridge: Cambridge University Press.

Rosenberg, N. (1982). *Inside the Black Box: Technology and Economics*. Cambridge, etc.: Cambridge University Press.

Sahal, D. (1981). *Patterns of Technological Innovation.* Reading, Mass.: Addison Wesley).

Sampat, B. N. (2006). Patenting and U.S. academic research in the 20th century: The world before and after Bayh-Dole. *Research Policy,* 35, 772-789.

Sapsalis, E., Van Pottelsberghe de la Potterie, B., & Navon, R. (2006). Academic vs. industry patenting: An in-depth analysis of what determines patent value. *Research Policy* 35(10), 1631-1645.

Solow, R. M. (1957). Technical progress and the aggregate production function. *Review of Economics and Statistics,* 39, 312-320.

Steele, C., Butler, L., & Kingsley, D. (2006). The Publishing Imperative: the pervasive influence of publication metrics. *Learned Publishing,* 19(4), 277-290.

Steinmueller, W. E. (2002). Knowledge-based economies and information and communication technologies. *International Social Science Journal,* 54(171), 141-153.

Steinmueller, W. E. (2002). Knowledge-based economies and information and communication technologies. *International Social Science Journal,* 54(171), 141-153.

Trajtenberg, M. (1990). A Penny for Your Quotes: Patent Citations and the Value of Innovations. *The RAND Journal of Economics,* 21(1), 172-187.

Verspagen, B. (2006). University research, intellectual property rights and European innovation systems. *Journal of Economic Surveys,* 20(4), 607-632.

Von Hippel, E. (2001). Open source shows the way: Innovation by and for users–no manufacturer required. *Sloan Management Review,* 42(4), 82–86.

Wagner, C. S. (2008). *The New Invisible College*. Washington, DC: Brookings Press.

Whitley, R. D. (1984). *The Intellectual and Social Organization of the Sciences*. Oxford: Oxford University Press.

Zhou, P., & Leydesdorff, L. (2006). The emergence of China as a leading nation in science. *Research Policy,* 35(1), 83-104.