return

Can the 'Knowledge-Base' of an Economy Be Measured? *

Loet Leydesdorff
University of Amsterdam, Science & Technology Dynamics
Amsterdam School of Communications Research (ASCoR),
Kloveniersburgwal 48, 1012 CX Amsterdam, The Netherlands
http://www.leydesdorff.net ; loet@leydesdorff.net

Abstract

The competitive advantages in a knowledge-based economy can no longer be attributed to a single node in the network. The network coordinates the subdynamics of (i) wealth production, (ii) organized novelty production, and (iii) private appropriation versus public control. Political economies are increasingly reshaped by knowledge-based developments. These dynamics are complex and can therefore not be expected to contain central coordination. The knowledge infrastructure of systems of innovations, however, can be operationalized in terms of university-industry-government relations. The mutual information in three dimensions can be used as an indicator of the state of development of this 'triple helix' arrangement. National patent statistics and data from the Internet are compared in terms of this indicator. The empirical findings illustrate how the knowledge base is integrated differently at the national and at the global level.

Introduction

Whereas organizations and institutions can be studied in terms of observable units of analysis, knowledge develops operationally. Knowledge flows both within organizations and across institutional boundaries. In order to study organized knowledge production, therefore, one first has to distinguish analytically between the intellectual and the institutional organization of social systems (Luhmann, 1984). The intellectual organization mainly functions over time, whereas the institutional organization tends to provide more structural coordination at each moment in time (Whitley, 1984). The intellectual 'knowledge base' can also be considered as an overlay of the operations carried by institutional manifestations (Luhmann, 1990).

Accordingly, the organization of knowledge can no longer be contained within a single organization. Network arrangements provide the background for knowledge flows (Castells, 1996; David & Foray, 1994). In a knowledge-based economy the institutional arrangements among knowledge organizers (e.g., universities, industries, and governmental agencies) can become a necessary condition not only for producing, but also for retaining wealth from knowledge (e.g., Popper & Wagner, 2002)

In other words, the 'knowledge base' generates a dynamics different from that of a political economy. For example, pharmaceutical corporations can nowadays no longer carry the costs

* I would like to thank Iina Hellsten, Andrea Scharnhorst, Robert Ulanowicz, and Caroline Wagner for their suggestions and comments on previous drafts of this paper.

of biotechnological innovations without relying on knowledge networks (Owen-Smith, Riccaboni, Pammolli, & Powell, 2002). Corporate boundaries increasingly function as mechanisms for the appropriation and shielding of competitive advantages from the knowledge fluxes through the networks (Leydesdorff, 2001a).

Knowledge-based *innovations* operate at the interfaces between supply-side institutions producing novelty (e.g., R&D) and—market or non-market—selection environments. In this process the relevance of previously defined boundaries can be redefined. When the new boundaries become functional for the reproduction of the systems, new retention mechanisms may also become institutionalized. Knowledge-based innovations can thus be considered as the evolutionary operators that change the network structures in which they are reflexively generated (Fujigaki, 1998).

The knowledge-based economy

In the period before the oil crises of the 1970s, that is, in the decades after World War II, social functions were largely organized into institutions on a one-to-one basis (Merton, 1942; Bush, 1945). The oil crises made clear that advanced industrial nations could outcompete low-wage countries only on the basis of the systematic exploitation of their respective knowledge bases (e.g., Nelson & Winter, 1977, 1982; Freeman, 1982). Collaboration across institutional boundaries, however, implies transaction costs (Williamson, 1975). But the new relations may generate longer-term revenues and synergies (e.g., Faulkner & Senker, 1995; McKelvey, 1996).

The trade-off between short and long-term costs and benefits brought governments into play in the interaction between R&D and the economy. The transaction costs can be considered as a macro-investment in establishing new structures of collaboration and competition, for example, at the national level. Thus, a dynamic view of a knowledge-based system could be generated in which institutional agents have continuously to trade-off among optimizations using a variety of criteria. Note that the interfaces potentially generate asymmetries for the various parties involved (Galbraith, 1967).

After the oil crises, the techno-sciences like biotechnology, information technologies, and new materials rapidly became the top priorities for stimulation policies at the national level in the advanced industrial countries (OECD, 1980). These 'platform sciences' (Langford & Langford, 2001) are based on the assumption that rearrangements across disciplinary lines may generate competitive advantages through synergies in the knowledge base that can perhaps be exploited for economic development (Leydesdorff & Gauthier, 1996). Previous attempts at a more direct mission-oriented steering of the sciences had at that time been evaluated as less successful (e.g., Van den Daele, Krohn, & Weingart, 1977; Studer & Chubin, 1980).

In advanced industrial nations, the stimulation of university-industry relations became a second point of attention for S&T policy makers (Rothwell & Zegveld, 1981; OECD, 1988). Why had some countries been more successful than others in exploiting their knowledge-base (Hauff & Scharpf, 1975; Irvine & Martin, 1984)? Why had within countries certain sectors (e.g., chemistry, aircraft) been more successful than others in maintaining knowledge-intensive relations (Nelson, 1982)? Could lessons be learned from best practices across sectors and might such practices be transferable from one national context to another?

In the U.S.A. the national system experimented with granting universities the right to patents on the basis of federal funding (the Bayh-Dole Act of 1980), and systematic efforts were made to raise the level of knowledge-intensity within industry both at the level of the states and by stimulation programs at the level of the federal government (Etzkowitz, 1994; Spencer, 1997). Universities were thus enrolled in the patent system of the U.S.A. (Owen-Smith *et al*., 2002).

Figure 1 exhibits the percentage of patents that can be retrieved using the word 'university' as a search term in the database of the U.S. Patent and Trade Office (at http://www.uspto.gov/). The second curve—of the percentage of universities that can be retrieved using 'university' as a search term among the assignees of patents—shows even more clearly that the effect of the Bayh-Dole Act began to peak in 1997.

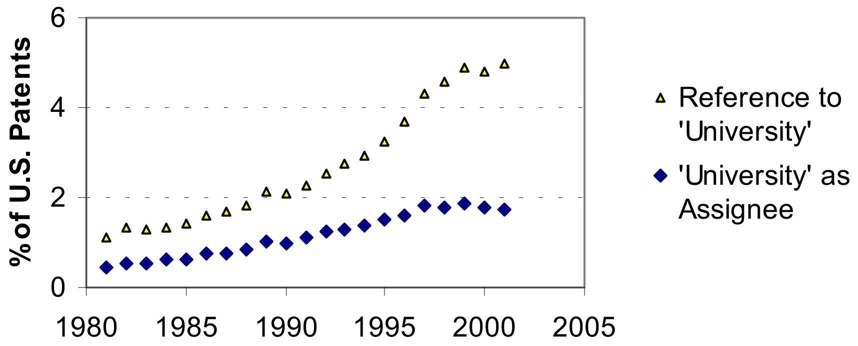

Figure 1
Percentage of U.S. Patents (i) with a reference to the word 'university' and (ii) a 'university' among the assignees

In the period between 1981 and 1997, universities have thus been enrolled as new players in the patenting domain. But what does this indicator teach us with respect to the role of academic research in innovation processes (Rosenberg & Nelson, 1994; Cohen, Nelson, & Walsh, 2002)? Whereas this role can be analyzed historically for innovations on a case-by-case basis, a definition of the relevant system of innovations is needed to determine this role at the aggregate level.

The delineation of systems of innovation

The uncertain definition of a system of innovations in terms of nations, sectors (Pavitt, 1984), technologies, regions, etc., brings players other than the traditional ones into view. From the mid-1980s onwards, for example, the European Union has developed a series of Framework Programs containing new policies for science, technology, and innovation. Both trans-national cooperation and cooperation across sectors have been systematically stimulated. Within the newly emerging context of the Union, regions have tried to promote their positions as a relevant level for the systematic development of the knowledge infrastructure (Braczyk, Cooke, & Heidenreich, 1998; Leydesdorff, Cooke, & Olazaran, 2002)

Has a European system of innovations emerged in relation to the underlying national systems? Have regions (e.g., Catalonia, Flanders, etc.) been successful in establishing their own specific systems of innovation (Riba-Vilanova & Leydesdorff, 2001)? Have sectors (e.g., ICT) been developed using patterns of innovation which differ from those established in a previous cycle of industrial development (Barras, 1990)? How can systems of knowledge-based innovation be delineated and assessed if they cross national boundaries?

These questions have become ever more pressing during the 1990s when the Internet emerged. South- and East-Asian countries seemed initially better equipped for moving ahead in the new e-business given their specific mixes of human resources, flexibilities in industrial structures, and prevailing knowledge infrastructures. How should the previously advanced industrial countries react? Is it sufficient to stimulate ongoing processes of global change locally or should policy frameworks be proposed that enable new collaborating partnerships to be developed? Which criteria for the optimization should then be used (e.g., national, transnational, sectoral)? In other words, the stage was set for a deep reformulation of the very problem of science and technology policy-making in the first half of the 1990s.

Science and technology policies in the 1990s

A redefinition of the problem of science and technology policies became urgent as the Internet signaled its future economic success in the first half of the 1990s. The additional dimension of global communication could be envisaged as changing the phase space of possibilities for international collaboration in science and technology, international trade, and international relations. Structural adjustments of existing institutional arrangements were likely to gain further momentum (Freeman & Perez, 1988).

Gibbons *et al*. (1994) have suggested making a distinction between 'Mode 2' and 'Mode 1' types of the production of scientific knowledge. Whereas 'Mode 1' refers to the traditional shape, largely confined within institutional settings, 'Mode 2' would be communication-driven. Knowledge can then be considered as a codification of communication. A scientific communication can be contained within an institution or even within an individual agent as 'tacit knowledge' and/or it can be 'published' and then brought into circulation.

These dimensions of public and private knowledge resonate with and disturb the established public/private arrangements between industries and governments in the political economy. The knowledge component adds a communication dynamic to the so-called 'differential productivity growth puzzle' between various sectors in the economy (Nelson & Winter, 1975). Existing trade-offs between public control and the private appropriation of competitive advantages can be expected to be increasingly upset when innovations are systematically organized and stimulated (Nelson & Winter, 1977). New regulations (and perhaps new regulatory regimes) are needed when knowledge-based technologies restructure the sectoral organization (Callon, 1998). During the 1990s, increased knowledge-intensity became thus a driver to the reform of political economies.

In a number of papers, Henry Etzkowitz and I have proposed a neo-evolutionary model of a 'triple helix of university-industry-government relations' for these knowledge-based transformations of political economies (Etzkowitz & Leydesdorff, 1997; Leydesdorff & Etzkowitz, 1998). As noted, three functions have to be fulfilled within a system of innovations: wealth generation in the economy, novelty and innovation production that upset the equilibrium seeking mechanisms in market systems, and public control and private appropriation at the interfaces between economic systems and organized novelty production systems. The knowledge infrastructure of university-industry-government relations (e.g., at the level of a nation state) can then be considered as a specific retention mechanism among these three function systems. The local niches and their trajectories are under pressure from global developments (Dosi, 1982).

Advanced industrial states have historically generated 'national systems of innovation' during the past century or so (Freeman, 1988; Lundvall, 1988, 1992; Nelson, 1993). The innovative knowledge flows, however, span boundaries and thus generate new types of competition at the global level (Krugman, 1996). In the Triple Helix model, this selection pressure is represented as an overlay of communications among the institutional agencies which have hitherto carried the knowledge infrastructure: industry, academia, and government. Each of these institutions is organized along international dimensions as well. At the level of the overlay of expectations, one can entertain and recombine possibilities other than those that have been realized hitherto. Thus, the linkages provide the carrying agencies with further access to the knowledge base of an emerging and knowledge-intensive system of coordination.

As the relative weights of the links in the networks change by ongoing processes of collaboration, appropriation, and competition, new balances and unbalances can be expected to generate a feedback in the knowledge infrastructure at other ends. For example, trajectories can be formed historically at interfaces when technologies are 'locked-in' within industries (e.g., the QWERTY keyboard or VHS tapes; cf. David, 1985; Arthur, 1989) or—similarly but between different dynamics—when specific scientific expertise and government policies begin to co-evolve as they sometimes do in the energy and the health sectors (Elzinga, 1985). The state and industry can also become 'locked-in' as in the former Soviet Union.

Co-evolutions between two dynamics continuously generate stabilities between counteracting mechanisms in processes of mutual shaping, whereas a third dynamic of the evolutionary model potentially dissolves previous arrangements at a global level. The interacting subdynamics accordingly shape trajectories *and* regimes endogenously (Nelson, 1994; Leydesdorff & Van den Besselaar, 1998). Policies then have to vary according to which 'lock-ins' can be expected to prevail, and whether and how they can be disturbed.

For example, the market mechanism can reintroduce flexibilities in the case of a bureaucratic lock-in, whereas in the case of a technological lock-in government interventions may be needed to break monopolistic tendencies. Thus, the policies become increasingly a variable dependent on the evolutionary assessment of the knowledge-based system.

Local trajectories and globalized regimes

While the systems under study operate dynamically, knowledge flows between systems can also be stabilized and further developed within the historical institutions that have served their developments hitherto. For example, the well-organized niches of nation states can be considered as providing the stability that is necessary for accessing globalized regimes (Luhmann, 2000, at p. 396).

A global regime emerges from closer interactions between hitherto relatively separate subsystems. The regime emerges as a complex dynamics of the interactions among differently coded communication systems (e.g., the economy, science, and policy-making). However, the networks supporting this exchange generate a structural innovation that changes the unit of evolution. Older arrangements can be expected to survive, but they may have to change their functions as well as their forms (Frenken, 2000; Kauffman, 2000). The emerging configuration of mutual expectations can be expected to change the selection pressure on the institutional arrangements.

One should not reify the 'global level agency' as a metabiology or a supersystem. The various systems of expectations interact and produce an overlay of global expectations *within* the network. The overlay globalizes the system by making representations available beyond the ones which could already be envisaged from the various (subsystemic) perspectives. These recombinations can then be attributed to a next-order or 'global' system, but this evolution remains an internal dynamics that is added to the system as its 'globalization.' The globalization can be entertained reflexively and thus enrich the system. It provides a future-oriented knowledge-base that innovates the historically shaped structures with hindsight. The innovativeness is based on inventing new codifications reflexively by recombining perspectives at interfaces.

Thus, the dynamics of knowledge organized as science and technology induce a reflexive turn in social systems and the study of social systems. The 'reflexive turn' in science & technology studies (Woolgar & Ashmore, 1988) first implied that the idea of a single and universalistic yardstick—as sought in the philosophy of science (e.g., Popper, [1935] 1959)—had to be given up in favour of codes that are continuously being constructed, recombined, and reconstructed. Unlike universal standards, however, asymmetry can be expected to prevail in the exchange relations (Gilbert & Mulkay, 1984). The systems are able to exchange because they have different substances in stock. Internally, the institutions also reproduce the differentiation by operating recursively upon their previous states using their own criteria.

For example, the political system is interested in results from the science system that inform decision making and legitimate policies, but without being burdened with the overwhelming uncertainties that are intrinsic to scientific inference (Beck, 1986). Within the science systems these uncertainties potentially raise new research questions. However, the science system can also develop in relation to problems arising in industrial contexts. New possibilities to patent may arise unexpectedly as externalities within the research process, whereas in other (e.g., industrial) contexts scientific progress can sometimes be considered as an unintended by-product when the focus was initially on the solution of production problems (Rosenberg, 1990).

The interactive and non-linear dynamics in the development of science, technology, and innovation can change professional practices. The new constellations drive the knowledge-based reconstructions of the political economies. The reflexive mechanisms have increasingly been institutionalized in advanced industrial systems since the scientific-technical revolution of the period 1870-1910 (Braverman, 1974; Noble, 1977). In the first stage, the reconstructions remained confined to the physical and chemical properties of materials. More recently, this development has been reflected in the so-called 'techno-sciences' that enable us to analyze and reconstruct also the knowledge-base of biological and institutional systems (Fukuyama, 2002).

The study of knowledge-based systems

Knowledge-based systems do not exist in terms of stable elements, but in terms of operations. Operations, however, can be combined and recombined in a variety of ways. As noted, several authors (e.g., Lundvall, 1992; Nelson, 1993) have proposed considering 'national systems of innovation' as the appropriate units of analysis for innovation studies. The choice of this national perspective allows for a direct link to the possibilities and limitations of policy making by national governments, and it enables the researcher to use national statistics (Lundvall, 1988). From a reflexive angle, however, each communality or dimension can be considered as a construct that can perhaps have been codified, but to a variable extent. Thus, the system of reference for the research question potentially shapes (and blinds) the research design (Skolnikoff, 1993).

For example, the notion of a national identity is nowadays historically changing from a European perspective. The subnational construction of regions has resounded in some regions because of linguistic identities (e.g., Flanders, Catalonia), but in other places (as in France) regional authorities had to be reshaped in order to accommodate European policies and harmonization.

In other words, the units of analysis and the systems of reference can be considered as constructs that tend to shape the analysis (Andersen, 1994). What is relevant from one perspective can be considered as contextual from another. Innovations and knowledge-based reconstructions occur by definition at interfaces and therefore allow for more than a single angle of theoretical appreciation. Consequently, the categories in this reflexive field of science, technology, and innovation studies have to be entertained reflexively, that is, as hypotheses. The specification of uncertainty is a crucial part of the research program.

A second argument against reifying one's categories follows from the reflection on how to declare the time axis in the research design. In contrast to a historical build up, the evolutionary dynamics continuously operates in the present and with hindsight, that is, upon the instantiations of the systems under study (Giddens, 1984). The addition of a virtual dimension to the system at the Internet highlights these evolutionary dynamics. The global dimension tends to invert the time axis in the analysis by reconstructing the past from the perspective of other possibilities perceived in the present or more recently. Note that this development is only a tendency, since the global developments are embedded in historical ones. However, the retrospective view provides us with an analytical angle that is knowledge-based, since it is no longer limited by what was constructed previously.

For example, an analysis of the strengths and weaknesses of a research portfolio does not by itself suggest that one should 'pick the winners' in order to strengthen one's case globally, that is, at the system's level (Irvine & Martin, 1984). The 'winners' may have been yesterday's winners and one may have other reasons to strengthen the hitherto relatively weak groupings or clusters (Porter, 1990). Empirical analysis informs us about the contingencies that can be expected; but since the dynamics are complex, unintended consequences and unforeseeable externalities can also be expected (Callon, 1998). The formative evaluation during the process provides us with signals that can be made the subject of systematic analysis.

Operationalization

How can one move from the analysis of knowledge-based systems to a determination of the relative importance of the theoretical concepts in explaining an observable reality? How can a reflexive analyst make a convincing argument when the notion of a system of reference can always be deconstructed, and the time line may also be inverted in terms of what the historical accounts mean for the present?

Since systems that contain knowledge cannot be considered as given or immediately available for observation; one has to specify them analytically—that is, on theoretical grounds—before they can be indicated and/or measured. To this end the quantitative measurement is thoroughly dependent on qualitative hypotheses. For example, one can raise the question of whether 'Mode 2' currently prevails in the production of scientific knowledge. What would count as a demonstration of this prevalence, and what as a counterargument? Can, for example, instances be specified in which one would also be able to observe processes of transition between the two modes? What should one measure in such instances, and why?

While qualitative analysis reduces the complexity by taking a perspective, quantitative analysis allows us to raise questions about the extent to which a theoretical perspective highlights a relevant dimension. Can the current development of 'biotechnology' in Germany be characterized as 'Mode 2'? How can it be compared with 'biotechnology' in the United States? A policy analyst may always be able to point to contingency, sameness and differences, continuities and change, but the quantitative analysis requires that these categories be specified as *ex ante* hypotheses so that the expectations can be updated by the research efforts.

Empirical research enables us to specify the percentage of the variation that can be explained using one theoretical model or another. Whether 'Mode 2' is 'old wine in new bottles' (Weingart, 1997) or new wine in old bottles depends on the definitions of the bottles and the wines, and the processes of change that are analytically explicated. The definitions of a knowledge-intensive system are themselves knowledge-intensive (Nowotny, Scott, & Gibbons, 2001; Leydesdorff, 2001b). The observations and indicators are also knowledge-intensive, since one can no longer assume that the overwhelmingly available information would answer the research questions precisely (Hicks & Katz, 1996). The crucial question becomes the theoretically informed specification of a selection from the data. Which are the proper systems of reference?

For example, what one understands nowadays under the name of 'biotechnology' is very different from what governments wanted to stimulate in the 1980s (Nederhof, 1988). Analogously, what industries subsume under the category of 'biotechnology' is different from what research councils indicate with this same term. A modern society is pluriform and therefore differentiated in terms of its coordination mechanisms, codifications, and media of communication. The evolutionary perspective then demands an *ex post* delineation of the domains under study, but in the form of proposals and hypotheses.

The data construction is based both on theoretical reflection and on methodological considerations about how one may be able to proceed from the relevant choices to operationalization. For example, one can operationalize ‘biotechnology’ in terms of a set of biotechnology journals in the *Science Citation Index*. If one fixes this journal set *ex ante* in order to make ‘analytical comparisons’ along the time line possible (Narin, 1976; Irvine, Martin, Peacock, & Turner, 1985), one observes the development of ‘biotechnology’ as conceptualized at the beginning of the data collection. If one defines the journal set dynamically, one studies the changing meaning of ‘biotechnology’ in relation to other journal clusters. If one determines the journal set *ex post* one refers to the most recently available understanding. The latter definition can be made relevant for policy, while the former definitions inform historical studies.

Furthermore, using a journal set provides us with a focus on the scientific publication system. The use of patent data provides us with a focus on technological inventions. These two systems are differently codified and therefore can be expected to exhibit different dynamics. The methodological problems reflect decisions that have to be taken on theoretical grounds. The theoretical grounds can only be made relevant for the scientometric enterprise if they can be formulated as hypotheses that have to be operationalized before one is able to draw conclusions.

Patent indicators

In order to demonstrate my point, let me provide empirical data based on the U.S. national patent database, on the one hand, and based on the Internet as a globally developing system, on the other. Using precisely the same methods for retrieval, I am then able to further specify the difference between a national system and a globally developing system.

‘University’, ‘industry’, and ‘government’, and the various combinations with Boolean ‘AND’ operators can be used as keywords in both databases. As above (see Figure 1), I searched the patent database for the number of occurrences of these terms in the file on a year-to-year basis. For reasons of comparison with the Internet searches, the time series is now limited to the period 1993-2001. Table 2 first provides the results of these searches.

Year	University	Industry	Government	UI	UG	IG	UIG	Total number of patents
1993	3063	9716	2619	401	588	334	63	110540
1994	3359	10568	2855	479	684	390	89	114564
1995	3710	10800	2828	529	771	410	93	114864
1996	4552	12147	3149	703	963	488	114	122953
1997	5406	12699	3604	814	1199	583	168	125884
1998	7623	17068	4708	1254	1658	807	266	166801
1999	8326	18553	4856	1352	1735	844	235	170265
2000	8488	19368	4831	1399	1776	865	267	176350
2001	9190	20812	5136	1591	1868	996	296	184172

Table 2
The number of hits for the search terms ‘university,’ ‘industry,’ and ‘government’ and their combinations in the database of the U.S. Patent and Trade Office.

The values for 'university and industry' (UI), 'university and government' (UG), and 'industry and government' (IG) can be considered as indicators of the bilateral links, whereas the value of UIG represents the trilateral communality between these three dimensions. In general, the data span a three-dimensional system as exhibited in Figure 2.

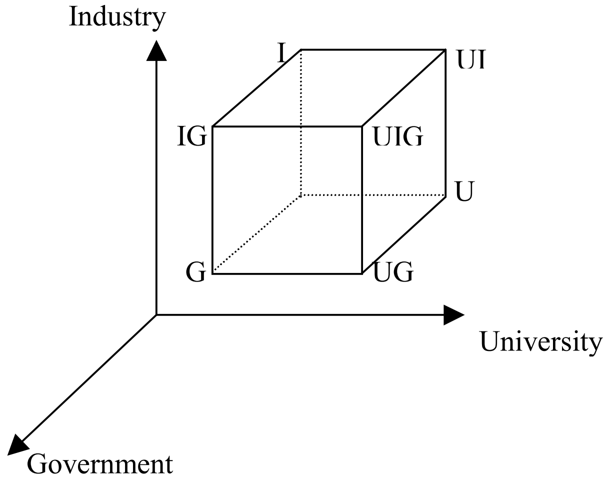

Figure 2
University-Industry-Government relations in three dimensions

As different from co-variation between two dimensions or co-occurrence measurement, mutual information or transmission can be defined analytically in three dimensions (Abramson, 1963).[2] Two states of a triple helix system can then be distinguished: in Figure 3 the three sets exhibit an overlap, whereas in Figure 4 this overlap has vanished. The mutual information in three dimensions (T_{UIG}) can become negative in the latter case, while this indicator has a positive value in the former.

---

[2] The transmission in three dimensions (x, y, z) can be defined as follows (Abramson, 1963, at p. 129):

$$T(xyz) = \Sigma_{xyz} P(xyz) \log \{[P(xy).P(xz).P(yz)] / [P(x).P(y).P(z).P(xyz)]\}$$

Or in another notation:

$$T(xyz) = H(x) + H(y) + H(z) – H(xy) – H(yz) – Hxz) + H(xyz)$$

In the first formulation, P(x) stands for the probability of an event x and P(xy) for the probability that x and y occur together, etc. These probabilities can be measured by counting frequencies of (co-occurrences) of events, as will be shown in the empirical examples below.

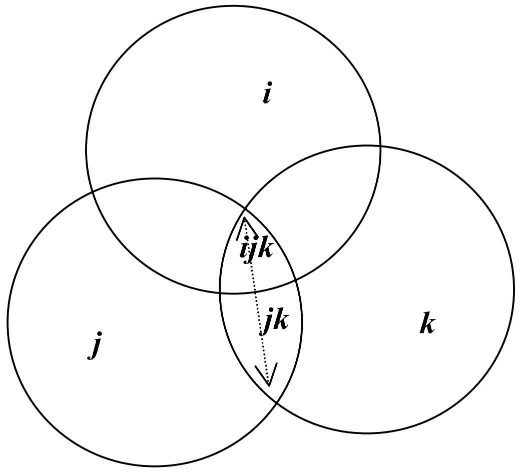

Figure 3
Three subsystems with a center of coordination

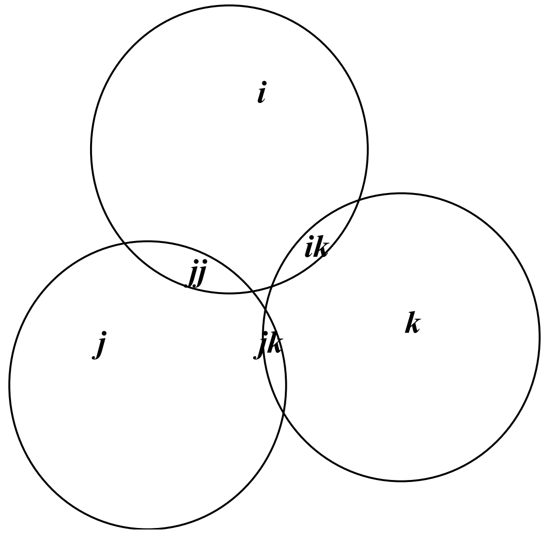

Figure 4
Three subsystems without a center of integration

When the three subsystems (represented here as sets of documents containing the search terms 'university', 'industry', and 'government') are closely coupled by sharing a communality in the variation (e.g., in the case of an étatist regime or in corporatist arrangements), the value of the transmission is positive. When the three dynamics are completely uncoupled, the mutual information vanishes ($T_{UIG} = 0$). However, when the three domains are liberally coupled through uncoordinated bi-lateral relations, this indicator can also become negative. Thus, the indicator provides us with a measure for the state of a Triple Helix system whenever the relevant dimensions can be specified so that the relevant relations can be counted.

Conceptually, the generation of a negative entropy such as mutual information corresponds with the idea of complexity that is contained or 'self-organized' in a network of relations that lacks central coordination. The system then propels itself in an evolutionary mode. The 'global' reduction of the uncertainty by the negative transmission is a result of the network structure of bi-lateral relations (Figure 5).

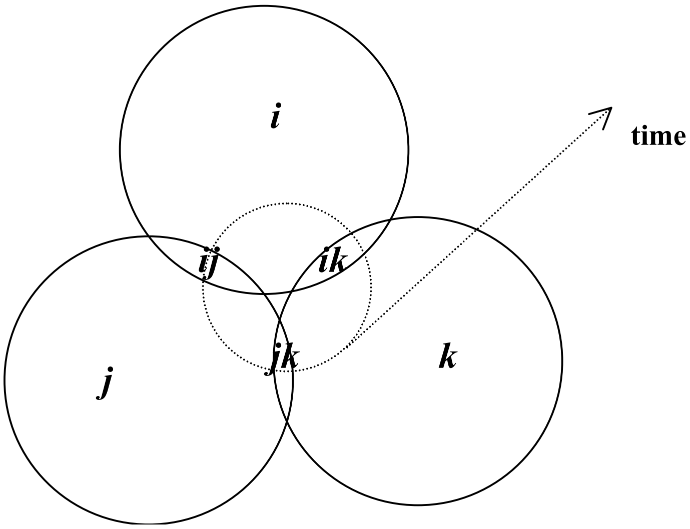

Figure 5
Three subsystems with hypercyclic integration in a globalized dimension

The three- (or more-)dimensional structures operate globally by constraining and enabling local substructures. However, the overall structure cannot be perceived completely from any of the positions in the network since there is no center of coordination. However, an evolving structure in a virtual dimension can be hypothesized and then also be attributed a value using the algorithm as an indicator. The globalizable expectations, however, remain embedded in the local situations, albeit in a distributed and therefore uncertain mode. The embedded uncertainties cannot be observed, but by using algorithmic indicators one can appreciate the latent structures of coordination.

Figure 6 provides the value of T_{UIG} for the time-series of patent data during 1993-2001. The figures show that bilateral relations prevail to the extent that the value of T_{UIG} is negative, but that the U.S. national patent system became further integrated during the 1990s.

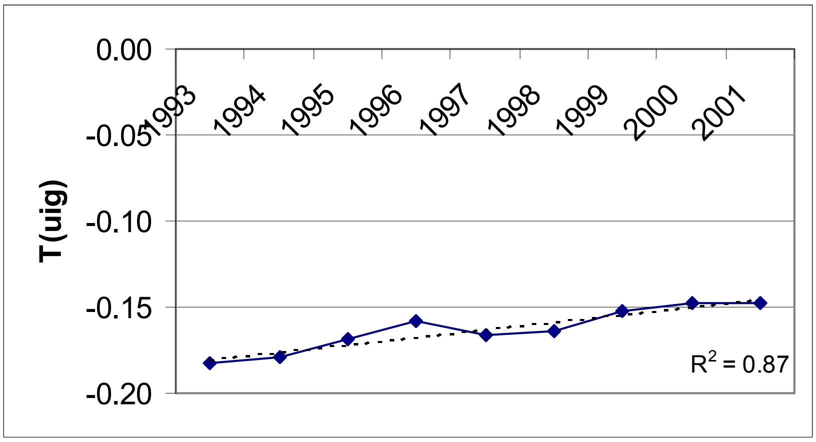

Figure 6
The mutual information among ‘university,’ ‘industry,’ and ‘government’ relations in the database of the U.S. Patent and Trade Office

The curve suggests that this system is integrating. With hindsight, the Bayh-Dole Act can thus be considered as having provided the patent system with one more degree of freedom, that is, by allowing universities increasingly to become players in this institutional field. The patent system, however, remains a system of legal control by a national government and therefore under the pressure of integration. Additional new players can be expected to be enrolled within this system in due time.[3]

Webometric data

The increasing integration in the patent database is not a trivial result as can be demonstrated by the next figure. Figure 7 is based on performing precisely the same exercise at the Internet using the *AltaVista Advanced Search Engine*.[4] In this case, the mutual information in three dimensions decreases during the expansion of the Internet in the second half of the 1990s.

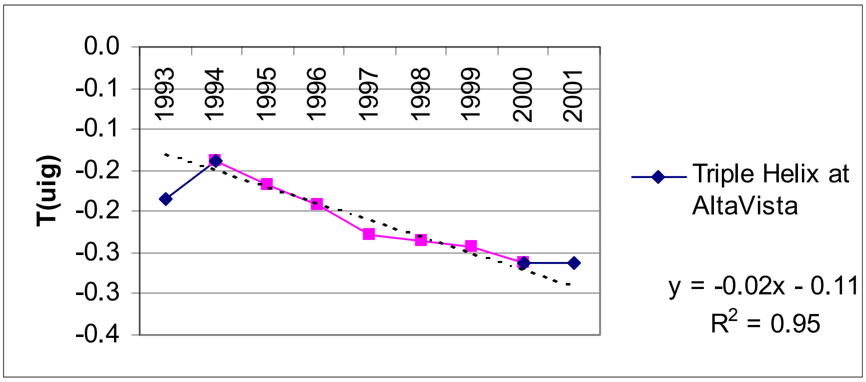

Figure 7
The mutual information among 'university,' 'industry,' and 'government' relations as retrieved at the Internet using the *Altavista Advanced Search Engine.*

The 'self-organization' of these Triple Helix relations at the Internet seems to have flattened in the most recent years. Perhaps the flattening of the curve illustrates that the process of endogenous expansion of the Internet has been interrupted temporarily as the e-business has gone into a recession during these last two years.

Table 3 provides the data underlying this representation in a format similar to that of Table 2. However, the changes are not apparent by visual inspection of the data. Unlike variables, the study of fluxes (dx/dt) requires an algorithmic approach and the results can therefore be counter-intuitive.

[3] During the period 1976-1992, T_{UIG} had remained equal to – 0.190 ± 0.008.
[4] I used the *AltaVista Advanced Search Engine* because this engine is unique in allowing searches with both Boolean operators and time delineations. For the methodological problems involved in using this tool, see (Leydesdorff, 2001a).

Year	University	Industry	Government	UI	UG	IG	UIG	Total number of websites
1993	3611	927	961	286	175	169	55	24234
1994	25816	5742	6710	2136	2122	1572	661	242541
1995	105091	30136	29613	10995	10066	8018	3822	804950
1996	322413	116022	89306	35107	27213	23987	10267	3083682
1997	685294	319203	241205	81198	63385	63425	23852	7600808
1998	1335472	739447	508962	163704	127801	147622	49954	18505865
1999	2489213	1697130	1001254	330962	235690	306541	93729	39825697
2000	4767111	3700306	2041151	641888	462717	573324	179264	238256064
2001	25965252	21952451	12167787	3060229	2487492	3258061	790680	1104501047

Table 3
The number of hits for the search terms 'university,' 'industry,' and 'government' and their combinations using the *AltaVista Advanced Search Engine* (March 25, 2002)

Note that the Internet data are time-stamped in the present (in this case at March 25, 2002). As the Internet evolves, previous representations are continuously overwritten. The search engines also change, using additionally their own reflexive dynamics (Leydesdorff, 2001a).

The measurement of complex and codified communications

What can the above pictures teach us? As noted, the word 'university' can be expected to mean something different in a patent application than on the Internet. Furthermore, the meaning of a word may change over time. For example, it may have become more important for an applicant to make his or her collaboration with a university visible in a patent application without necessarily implying that these collaborations did not exist previously.

Our pervasive problem with measurement in the case of complex dynamics is that both the values of the variables and also the meanings of the variables may change with the choice of the system of reference and over time. If one tries to measure change in both the meanings of the variables and the values of the variables using a single design, the understanding tends to become confused because one loses a clear definition of a baseline (Studer & Chubin, 1980, at pp. 269 ff.).

Knowledge-based developments cannot be equated with the development of institutional units (Collins, 1985) or with fixed journal sets (Narin, 1976). The evolutionary focus on flows of communications makes it necessary first to hypothesize *what* each system of communications is communicating when it operates. For example, a system of citations can be expected to communicate something different from a system of co-occurrences of words or a (re-)distribution of institutional addresses. Citations relate papers along trajectories over time, whereas institutional addresses of coauthorships, for example, can also be used for mapping at specific moments in time.

The specification of a system of reference in terms of an *operation*—as different from a unit of analysis—extends the analysis with a reflection on the historical time horizon. Only after solving these conceptual puzzles, can one meaningfully raise the question of operationalization and the consequent measurement. In order to operationalize operations—

as different from observable units of analysis—one first needs to specify a hypothesis concerning 'what' the systems under study communicate specifically. The systems can only be delineated in terms of what it is assumed to communicate. Upon the specification of a hypothesis of 'what' the system communicates, one can proceed to the specification of 'how' one expects this information to be communicated, for example, in terms of which medium. The answer to the how-question of what is (re)distributed and exchanged refers to a potentially measurable indicator. For example, is the intellectual content expected to be exchanged in terms of scientific articles or in terms of trade in patents?

In the historical dimension, I have elaborated above on the issue of inverting the time axis because statisticians have been inclined to build on databases using a historical perspective. Historically interested sociologists share this interest in temporal order in the materials because the quantitative data can then be used as illustrations for the narratives when 'following the actors' (Latour, 1987). The study of knowledge-intensive developments, however, requires us to take a reflexive turn towards the data gathering process, both in the quantitative and in the qualitative domains. The focus is no longer on the actors, but on the order in the actions and communications from a hindsight perspective. Has a new order emerged? One has to specify which assumptions went into the data collection, and whether these assumptions are valid when questions currently on the agenda of S&T policies are raised.

Conclusion

I have argued that a fundamental reformulation of the problems of Science, Technology, and Innovation Policies became urgent during the 1990s. Three models have been proposed for the study of innovation systems: (i) the distinction of a 'Mode 2' type of knowledge production, (ii) the model of 'national systems of innovation,' and (iii) the Triple Helix model of university-industry-government relations.

The authors of the 'Mode 2' thesis (Gibbons *et al*., 1994) have argued that the new configuration has led to a dedifferentiation of the relations between science, technology, and society. Internal codification mechanisms (like 'truth-finding') were discarded by these authors as an 'objectivity trap' (Nowotny *et al*., 2001, at pp. 115 ff.). From this perspective, all scientific and technical communication can be equated and compared with other communication from the perspective of science, technology, and innovation *policies*.

In my opinion, the 'Mode 2' model focused on the political or managerial representations of systems that are also different and continuously differentiating. The systems under study are specifically integrated at the organizational interfaces, for example, in the case of successful innovation. However, they can be expected otherwise to restore their own orders by differentiating again in terms of the specificity of their respective communication codes. This asymmetry of the differentiation is needed if one wants to contribute to a next integration.

Differentiation and integration do not exclude one another, but rather depend on one another as different dimensions of the communication. A specific integration can be expected to mean something different in the various dimensions that were integrated. The communication enables us to construct an integration, but the underlying systems compete both in terms of their definitions of social realities and in terms of the performative representations that they construct at the localizable interfaces. Systems of innovations solve the puzzle of how to interface different functions in the communication. The solutions and failures are manifest at the level of historical organization. The latter can then also be reshaped.

Evolutionary economists have argued in favor of studying 'national systems of innovation' as hitherto the most relevant level of integration. Indeed, they have provided strong arguments for this choice (Lundvall, 1992; Nelson, 1993; Skolnikoff, 1993). However, these systems are continuously being restructured under the drive of global differentiation of expectations. Economies are interwoven both at the level of markets and in terms of multinational corporations, sciences are organized internationally, and governance is no longer limited within national boundaries. The most interesting innovations can be expected to involve boundary-spanning mechanisms.

In sum, I concur with the 'Mode 2'-model in assuming a focus on communication as the driver of systems of knowledge production and control. However, the problem of structural differences among the communications and the organization of interfaces remains crucial to the understanding of innovation in a global and knowledge-based economy. The wealth of knowledge and options for further developments have to be retained by reorganizing institutional arrangements with reference to global horizons.

The Triple Helix model of university-industry-government relations tries to capture both dynamics by introducing the notion of an overlay that feeds back on the institutional arrangements. Each of the helices develops internally, but they also interact in terms of exchanges of both goods and services and in terms of knowledge-based expectations. The various dynamics have first to be distinguished and operationalized, and then sometimes they can also be measured. I have argued that the dynamics among the dimensions can then be measured using algorithmic indicators.

The strength of this research program is that it is no longer assumed to be possible to generalize on the basis of intuitions. Empirical results are expected to inform us, but the results can also be counterintuitive. One may be able to appreciate unexpected results by innovating one's theoretical assumptions about the relevant systems of reference. If the various subdynamics can be better understood, one may also be able to develop simulation models on the basis of the reconstructions.

There is an intimate connection between the algorithmic evaluation of indicators and simulation studies. When analyzing knowledge-based systems, indicators study knowledge production and communication in terms of the traces that communications leave behind, while simulations try to capture the operations and their possible interactions. The common assumption is that knowledge production, communication, and control are considered as operations that change the materials on which they operate. The historically observable units of analysis are reflexively supplemented with units of operation that can only be specified on the basis of theoretical knowledge.

return

References

Abramson, N. 1963. *Information Theory and Coding*. New York, etc.: McGraw-Hill.

Andersen, E. S. 1994. *Evolutionary Economics: Post- Schumpeterian Contributions* London Pinter.

Arthur, W. B. 1989. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *Economic Journal 99*: 116-131.

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

Beck, U. 1986. *Die Risiko-Gesellschaft*. Frankfurt a.M.: Suhrkamp.

Braczyk, H.-J., P. Cooke, P., and M. Heidenreich, eds. 1998. *Regional Innovation Systems*. London/ Bristol PA: University College London Press.

Braverman, H. 1974. *Labor and Monopoly Capital. The Degradation of Work in the Twentieth Century*. New York/London: Monthly Review Press.

Bush, V. 1945. *The Endless Frontier: A Report to the President*. Reprinted, New York: Arno Press, 1980.

Callon, M. 1998. An essay on framing and overflowing: economic externalities revisited by sociology. In *The Laws of the Market*, 244-269. Malden, MA, and Oxford: Blackwell.

Castells, M. 1996. *The Rise of the Network Society*. Malden, MA, and Oxford: Blackwell.

Cohen, W. M., R. R. Nelson, and J. P. Walsh. 2002. Links and Impacts: The Influence of Public Research on Industrial R&D. *Management Science 48*(1): 1-23.

Collins, H. M. 1985. The Possibilities of Science Policy. *Social Studies of Science* 15: 554-558.

David, P. A. 1985. Clio and the Economics of QWERTY. *American Economic Review, 75:* 332-337.

Dosi, G. 1982. Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change. *Research Policy, 11*, 147-162.

Elzinga, A. 1985. Research, bureaucracy and the drift of epistemic criteria. In *The University Research System,* edited by B. Wittrock and A. Elzinga, 191-217. Stockholm: Almqvist & Wiksell.

Etzkowitz, H. 1994. Technology Centers and Industrial Policy: the Emergence of the Interventionist State in the USA. *Science and Public Policy 21*(2): 79-87.

Etzkowitz, H., and L. Leydesdorff, eds. 1997. *Universities in the Global Knowledge Economy: A Triple Helix of University-Industry-Government Relations*. London: Pinter.

Faulkner, W., and J. Senker. 1995. *Knowledge frontiers, public sector research and industrial innovation in biotechnology, engineering ceramics, and parallel computing*. Oxford: Oxford University Press.

Freeman, C. 1982. *The Economics of Industrial Innovation*. Harmondsworth: Penguin.

Freeman, C., and C. Perez. 1988. Structural crises of adjustment, business cycles and investment behaviour. In *Technical Change and Economic Theory,* edited by G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete , 38-66. London: Pinter.

Frenken, K. 2000. A Complexity Approach to Innovation Networks. The Case of the Aircraft Industry (1909-1997), *Research Policy 29(2)*, 257-272.

Fukuyama, F. 2002. *Our Posthuman Future: Political Consequences of the Biotechnology Revolution*. New York: Farrar Straus & Giroux.

Galbraith, J. K. 1967. *The New Industrial State*. Penguin: Harmondsworth.

Gibbons, M., C. Limoges, H. Nowotny, S. Schwartzman, P. Scott, and M. Trow. 1994. *The new production of knowledge: the dynamics of science and research in contemporary societies*. London: Sage.

Gilbert, G. N., and M. J. Mulkay. 1984. *Opening Pandora's Box. A Sociological Analysis of Scientists' Discourse*. Cambridge: Cambridge University Press.

Hauff, V., and F. W. Scharpf. 1975. *Modernisierung der Volkswirtschaft. Technologiepolitik als Strukturpolitik.* Frankfurt a.M: EVA.

Hicks, D., and J. S. Katz. 1996. Science policy for a highly collaborative science system. *Science and Public Policy, 23*: 39-44.

Irvine, J., B. Martin, T. Peacock, and R. Turner. 1985. Charting the decline of British science. *Nature, 316*: 587-590.

Irvine, J., and B. R. Martin. 1984. *Foresight in Science: Picking the Winners*. London: Frances Pinter.

Kauffman, S. A. 2000. *Investigations*. Oxford, etc.: Oxford University Press.

Krugman, P. 1996. *The Self-Organizing Economy*. Malden, MA, and Oxford: Blackwell.

Langford, C., and M. Langford. 2001. Funding Strategic University Research in Canada. *Paper presented at the Annual Meeting of the Society for the Social Studies of Science (4S)*, Boston, MA, November 2001.

Latour, B. 1987. *Science in Action*. Milton Keynes: Open University Press.

Lewison, G., and P. Cunningham. 1991. Bibliometric Studies for the Evaluation of Trans-National Research. *Scientometrics 21*: 223-244.

Leydesdorff, L. 1995. *The Challenge of Scientometrics: the development, measurement, and self-organization of scientific communications*. Leiden: DSWO Press, Leiden University; at <http://www.upublish.com/books/leydesdorff-sci.htm>

Leydesdorff, L. 2001a. Indicators of Innovation in a Knowledge-based Economy. *Cybermetrics*, 5(1), Paper 2, at <http://www.cindoc.csic.es/cybermetrics/articles/v5i1p2.html>.

Leydesdorff, L. 2001b. Re-Thinking the Relations Between Texts and Contexts in Science. *Science & Public Policy 26*(6): 484-486.

Leydesdorff, L. 2001c. *A Sociological Theory of Communication: The Self- Organization of the Knowledge-Based Society.* Parkland, FL: Universal Publishers; at <http://www.upublish.com/books/leydesdorff.htm>.

Leydesdorff, L., and P. van den Besselaar. 1998. Technological Development and Factor Substitution in a Non-linear Model. *Journal of Social and Evolutionary Systems 21*: 173-192.

Leydesdorff, L., P. Cooke, and M. Olazaran. 2002. Regional Innovation Systems in Europe (Special Issue). *Journal of Technology Transfer 27*(1): 5-145.

Leydesdorff, L., and H. Etzkowitz. 1998. The Triple Helix as a model for innovation studies. *Science and Public Policy 25*(3): 195-203.

Leydesdorff, L., and H. Etzkowitz. 2001. The Transformation of University-Industry-Government Relations. *Electronic Journal of Sociology 5*(4), at <http://www.sociology.org/content/vol005.004/th.html>.

Leydesdorff, L., and É. Gauthier. 1996. The Evaluation of National Performance in Selected Priority Areas using Scientometric Methods. *Research Policy 25*: 431-450.

Leydesdorff, L., and G. Heimeriks. 2001. The Self-Organization of the European Information Society: The case of 'biotechnology'. *Journal of the American Society for Information Science & Technology 52*(14): 1262-1274.

Luhmann, N. 1984. *Soziale Systeme. Grundriß einer allgemeinen Theorie.* Frankfurt a. M: Suhrkamp [Social Systems (Stanford University Press, Stanford) 1995].

Luhmann, N. 1990. *Die Wissenschaft der Gesellschaft*. Frankfurt a.M.: Suhrkamp.

Luhmann, N. 2000. *Organization und Entscheidung*. Opladen: Westdeutscher Verlag.
Lundvall, B.-Å. 1988. Innovation as an interactive process: from user-producer interaction to the national system of innovation. In *Technical Change and Economic Theory,* edited by G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, 349-369. London: Pinter.
Lundvall, B.-Å., ed. 1992. *National Systems of Innovation*. London: Pinter.
McKelvey, M. D. 1996. *Evolutionary Innovations: The Business of Biotechnology*. Oxford: Oxford University Press.
Merton, R. K. 1942. Science and Technology in a Democratic Order. *Journal of Legal and Political Sociology 1*: 115-126.
Narin, F. 1976. *Evaluative Bibliometrics: The Use of Publication and Citation Analysis in the Evaluation of Scientific Activity*. Washington, DC: National Science Foundation.
Nederhof, A. J. 1988. Changes in publication patterns of biotechnologists: An evaluation of the impact of government stimulation programs in six industrial nations,. *Scientometrics 14*: 475-485.
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. 1994. Economic Growth via the Coevolution of Technology and Institutions. In *Evolutionary Economic and Chaos Theory: New directions in technology studies,* edited by L. Leydesdorff and P. van den Besselaar, 21-32. London/ New York: Pinter.
Nelson, R. R., and S. G. Winter. 1975. Growth Theory from an Evolutionary Perspective: The Differential Productivity Growth Puzzle. *American Economic Review 65*: 338-344.
Nelson, R. R., and S. G. Winter. 1977. In Search of Useful Theory of Innovation. *Research Policy 6*: 35-76.
Nelson, R. R., and S. G. Winter. 1982. *An Evolutionary Theory of Economic Change* Cambridge, MA: Belknap Press of Harvard University Press.
Noble, D. 1977. *America by Design*. New York: Knopf.
Nowotny, H., P. Scott, and M. Gibbons. 2001. *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty*. Cambridge, etc: Polity.
OECD. 1980. *Technical Change and Economic Policy*. Paris: OECD.
OECD. 1988. *Biotechnology and the Changing Role of Government*. Paris: OECD.
Owen-Smith, J., M. Riccaboni, F. Pammolli, and W. W. Powell. 2002. A Comparison of U.S. and European University-Industry Relations in the Life Sciences. *Management Science 48*(1): 24-43.
Pavitt, K. 1984. Sectoral patterns of technical change: towards a theory and a taxonomy. *Research Policy 13*: 343-373.
Popper, K. R. [1935] 1959. *The Logic of Scientific Discovery*. London: Hutchinson.
Porter, M. E. 1990. *The Competitive Advantage of Nations*. London: Macmillan.
Riba-Vilanova, M., and L. Leydesdorff. 2001. Why Catalonia cannot be considered as a Regional Innovation System. *Scientometrics 50*(2): 215-240.
Rosenberg, N. 1982. How exogenous is science? In *Inside the Black Box: Technology and Economics*, 141-159. Cambridge: Cambridge University Press.
Rosenberg, N. 1990. Why do firms do basic research (with their own money)? *Research Policy 19*: 165-174.
Rosenberg, N., and R. R. Nelson. 1994. American universities and technical advance in industry. *Research Policy 23*: 323-348.

Rothwell, R., and W. Zegveld. 1981. *Industrial Innovation and Public Policy*. London: Pinter.
Skolnikoff, E. B. 1993. *The Elusive Transformation*. Princeton, NJ: Princeton University Press.
Spencer, J.-C. 1997. Publicly supported non-defence R&D: the USA's Advanced Technology Program. *Science and Public Policy, 24*(1), 42-52.
Studer, K. E., and D. E. Chubin. 1980. *The Cancer Mission. Social Contexts of Biomedical Research*. Beverly Hills, etc.: Sage.
Van den Daele, W., W. Krohn, and P. Weingart, eds. 1977. *Geplante Forschung: Vergleichende Studien über den Einfluss politischer Programme auf die Wissenschaftsentwicklung*. Frankfurt a.M.: Suhrkamp.
Weingart, P. 1997. From "Finalization" to "Mode 2": old wine in new bottles? *Social Science Information 36*: 591-613.
Whitley, R. D. 1984. *The Intellectual and Social Organization of the Sciences*. Oxford: Oxford University Press.
Williamson, O. E. 1975. *Markets and Hierarchies: Analysis and Antitrust Implications. A study in the Economics of Internal Organization*. New York: Free Press.
Woolgar, S., and M. Ashmore, eds. 1988. *Knowledge and Reflexivity: New Frontiers in the Sociology of Knowledge*. London: Sage.
Wouters, P., J. Annerstedt, and L. Leydesdorff. 1999. *The European Guide to Science, Technology, and Innovation Studies*. Brussels: European Commission, DG XII <http://www.chem.uva.nl/sts/guide/>.

return