The Mutual Information as an Indicator of Complexity and Self-Organization in Relational Systems

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Abstract
University-industry-government relations can be considered as providing a networked infrastructure for knowledge-based innovation systems. The knowledge infrastructure sustains a dynamic of fluxes at the network level. Whereas the relations between the institutions can be measured as variables, the interacting fluxes generate a probabilistic entropy. The mutual information among the three institutional dimensions provides us with an indicator of this entropy. When the indicator is negative, self-organization may emerge and temporarily stabilize in the overlay of communications among the carrying agencies. The various dynamics of Triple Helix relations at the global and national levels, in different databases, and in different regions of the world, are distinguished using scientometric and webometric data.

1. Introduction

Double helices can under circumstances stabilize in a coevolution, but triple helices may contain all kinds of chaotic behaviour. In the context of innovation studies, Henry Etzkowitz and I proposed a Triple Helix model for studying the dynamics of university-industry-government relations (Etzkowitz & Leydesdorff, 1995). Our argument for developing this neo-evolutionary model was that a knowledge-based regime of innovations can be expected to remain in transition.

A Triple Helix may contain double helices as temporary stabilizations, but a system of three dynamics is meta-stabilized. Under specific conditions this next-order system can also be globalized and then exhibit self-organization. Thus, the Triple Helix model of innovation may be sufficiently complex to encompass the different species of chaotic behaviour observable in the networks of innovation under study (Leydesdorff & Etzkowitz, 1998).

The advantages of using the Triple Helix model can be specified with reference to different research traditions. First, one is able to study specific configurations of university-industry-government relations as *instantiations* of the Triple Helix dynamics of a knowledge-based innovation system (Giddens, 1984). In this context of theoretical specification, the Triple Helix metaphor can function as a heuristics: the institutional configurations in knowledge-based systems are considered as the outcome of three interacting subdynamics of competitive systems: (a) the economic dynamic of wealth generation through exchange, (b) the knowledge-based dynamic of reconstruction and innovation over time, and (c) the political and managerial need and urge for normative control at the interfaces. The carriers of these three functions do no longer have to exhibit a one-to-one correspondence to industry, university, and government, respectively. The institutions can be expected to experiment with new formats in their mutual arrangements.

The neo-evolutionary model of the two layers of functions and institutions operating upon each other opens a space of possible interactions. For example, participants who are entrained in co-evolutions of mutual shaping between two helices can be expected to 'lock-in' and then shape trajectories (David, 1985; Arthur, 1988). The internal perspectives of these participant-observers can be distinguished from the perspective of an external (that is, third) observer. The switch to the external perspective enables the analyst to search for options emerging from interactions that cannot be perceived from within the coevolution. The configuration under study can then be reconstructed.

The two layers of functions and institutions can be considered as degrees of freedom. For example, one can question whether a network at the institutional level is functionally efficient and

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whether it provides dynamic scale effects. The functional and the institutional perspectives can be used for the optimization and the reorganization in different cycles.

2. The representation of a Triple Helix *dynamics*

A Triple Helix configuration can be depicted statically using social network analysis or in more general terms, as partially overlapping Venn-diagrams. First, consider the three institutional spheres as sets that overlap in the intersections, as follows:

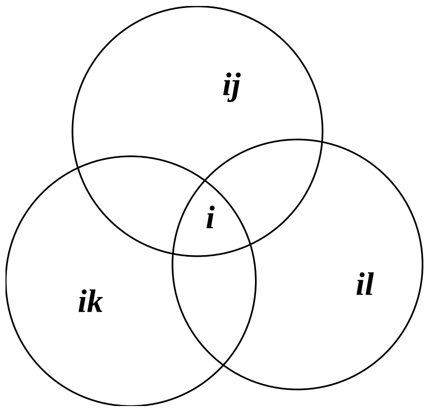

Figure 1
A Triple Helix configuration with positive overlap among the subsystems

In this configuration, the three helices share a common ground or origin in the overlap area indicated in the figure as *i*. Under conditions, however, this overlap can become zero or even negative. This configuration can be depicted as follows:

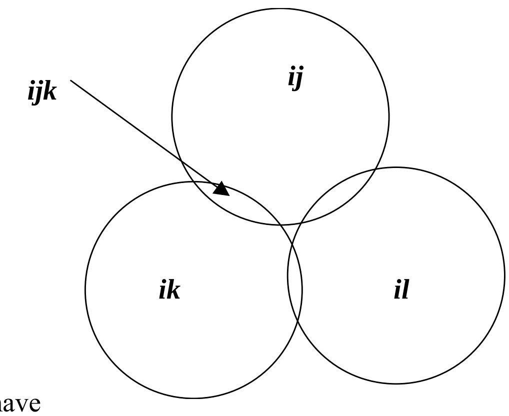

Figure 2
A Triple Helix configuration with negative overlap among the subsystems

In this representation, the three helices have differentiated to such an extent that the communality *i* has been dissolved. This system operates over time in terms of different communications at the respective interfaces (e.g., *ijk*). If all the interfaces operate, one can consider the result as the emergence of a 'hypercycle' (Figure 3). The hypercyclic configuration integrates the three systems in a distributed mode. It fails to integrate completely, or one can also say that the integration remains subsymbolic.

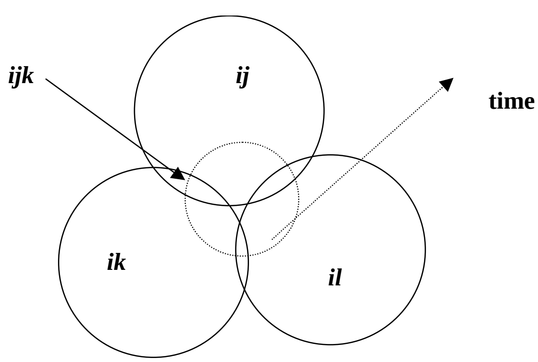

Figure 3. *Ex post integration in an 'emerging' hypercycle by recombining different interactions*

This configuration can be expected to exhibit 'self-organizing' properties because the various transmissions are no longer integrated at a single place. While a common domain of instantaneous integration is lacking at a certain moment in time, each integration leads over time to a re-differentiation. Integration in this case takes place over the time dimension.

It can be shown that under the condition of a lack of overlap among the three sets, the mutual information in three dimensions is negative (Abramson, 1963). From the perspective of each binary interface, the third dimension remains then 'latent' as a structural given in the background. This third system entertains interfaces with each of the first two, but not directly (or less so) with their interaction. The structural function of the third system remains beyond the control of each two relating systems, but this latent structure in the network reduces the uncertainty that prevails when the first two systems interact.

In the Triple Helix model of university-industry-government relations this hypercyclic integration can be identified as an overlay of negotiations and exchange relations among the institutional carriers of the Triple Helix dynamics. Insofar as the hypercycle operates it functions as a virtual feedback on the network of relations among the institutional agents at each moment in time.

3. Methodology

The mutual information in the three dimensions of the Triple Helix enables us to measure networks at each moment in time in terms of probability distributions and to evaluate the measurement results in terms of the dynamics. Unlike co-variation, correlation or co-occurrence measurements, the mutual information is defined in the case of interactions among three dimensions. However, the mutual information in three dimensions can no longer be considered as a similarity measure. It informs us about the size and the sign of the probabilistic entropy generated by the interactions within the complex dynamics.

Conceptually, the generation of a negative entropy corresponds with the idea of complexity that is contained or 'self-organized' in a network of relations that lacks central coordination (like in Figure 3 above). The network system may then be able to propel itself in an evolutionary mode by alternating and recombining the various subdynamics like in a resonance. The reduction of the uncertainty is a result of the bi-lateral relations operating upon each other. The network contains more uncertainty-reducing structure than is visible for the interacting agents at their respective interfaces. This negative entropy is generated because the flux is constrained by the existing structure of institutional relations.

How does this relate to the measurement? Triple Helix observations can be measured in terms of relevant variables (e.g., budgets, collaborations, citations). The historical description of a specific configuration can be considered as measurement with nominal variables (that is, words used for the description). However, one can often specify the intensity of the relationship at a more aggregated level using measurement scales other than the nominal one.

For example, when comparing science parks, one may be able to count instances in which government agencies were involved in these academic-industry relations, and to which extent. In other cases, one may be able to measure also output. The measurements can be based on various measurement scales, but the results of analyzing the networks can always be considered as relative frequency distributions in the various dimensions.

Independently of the answer to the question how the network relations are operationalized and measured, the observations of Triple Helix configurations can thereafter be organized in a three-dimensional array using the format visualized in Figure 4. Different variables (e.g., word usage) can also be measured in more than one of the three institutional dimensions. This leads to a co-variation or mutual information between the dimensions. However complicated the data gathering may be, this does not affect these methods for analyzing Triple Helix data in terms of the three dimensions indicated.

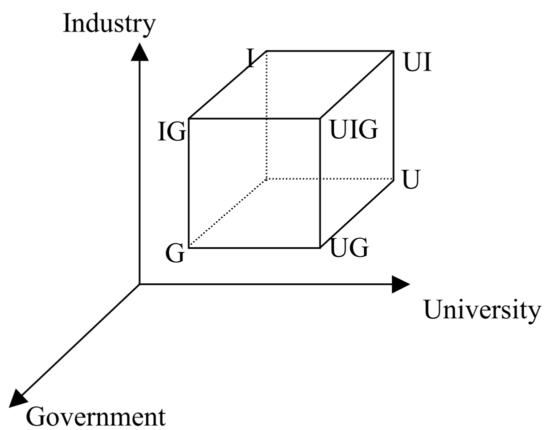

Figure 4
The three-dimensions of measurement in a Triple Helix configuration and their combinations

Methodological questions about the data collections and the measurement can thus be distinguished from methodological questions with respect to the data analysis. This study focuses on the development of an indicator that can be used after and relatively independently of how the data were collected.

In general, the uncertainty in three dimensions can be formulated using Shannon's (1948) mathematical theory of communication, as follows:[1]

$$H_{ijk} = - \Sigma_i \Sigma_j \Sigma_k p_{ijk} \log(p_{ijk})$$

The mutual information between two dimensions is equal to the transmission (T) of the uncertainty (Theil, 1972):

$$T_{ij} = H_i + H_j - H_{ij}$$

Abramson (1963, at p. 129) showed that the mutual information in three dimensions can be derived as:

$$T_{ijk} = H_i + H_j + H_k – H_{ij} – H_{ik} – H_{jk} + H_{ijk}$$

or in our case of data about university-industry-government (UIG) relations, as:

$$T_{UIG} = H_U + H_I + H_G – H_{UI} – H_{IG} – H_{UG} + H_{UIG}$$

Note that the uncertainty of the variables measured in each of the interacting systems (H_U, H_I, and H_G) is reduced at the system's level by the relations at the interfaces between them, but the three-dimensional uncertainty adds positively to the uncertainty that prevails. Because of this alteration of the signs, the three-dimensional transmission can also become negative.

4. Results

In order to show the usefulness of this indicator, I apply it to relatively straightforward data like search results with the terms 'university,' 'industry,' 'government,' and their combinations with Boolean AND operators in various databases. As noted, the measurement problems in the data collections are backgrounded in favour of the data analysis. The research question behind the searches is the extent to which the relations among these retrieval terms enable us to reveal a Triple Helix dynamics operating. At which level can a self-propelling dynamic of network relations be observed, and to what extent? I first turn to the Internet for retrieving relevant time-series data and then use the *Science Citation Index* to measure these relations at national and international levels.

4.1 The Triple Helix at the Internet

University-industry-government relations can be measured at the Internet, for example, in terms of the occurrences and co-occurrences of the words 'university,' 'industry,' and 'government' (Leydesdorff & Curran, 2000). Using various search engines, Bar-Ilan (2001) showed, among other things, how sensitive the Internet is to measurements at different moments in time (Rousseau, 1999). However, the *AltaVista Advanced Search Engine* has remained the sole search engine that enables the analyst to combine the various Boolean options with specific time frames (e.g., years) so that time series of data in various dimensions can be generated (Leydesdorff, 2001a).[2]

The search terms 'university,' 'industry,' 'government,' and their combinations with Boolean AND-operators were used for the years 1993-2001. All measurements were performed on 24 March 2002, using the AltaVista Advanced Search Engine. The stability of the Search Engine was controlled during the search time at a minimum of once per hour. The results of these searches are shown in Figure 5.

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[1] If the two-base is used for the logarithm, the uncertainty (H) is measured in bits of information.

[2] Google offers an API-service that allows for programming searches in this domain, including the Julian calendar date (Sylvan J. Katz, *personal communication*).

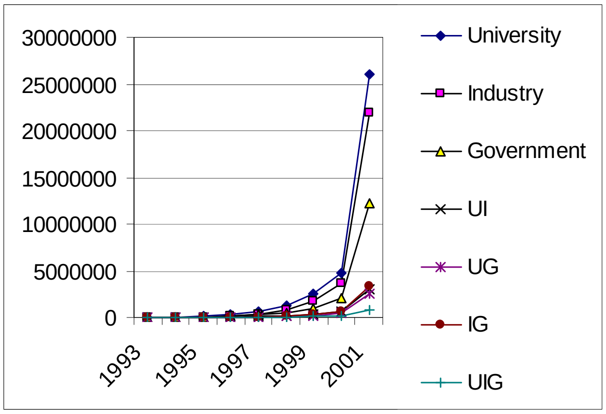

Figure 5. Results of searches using the *AltaVista Advanced Search Engine*

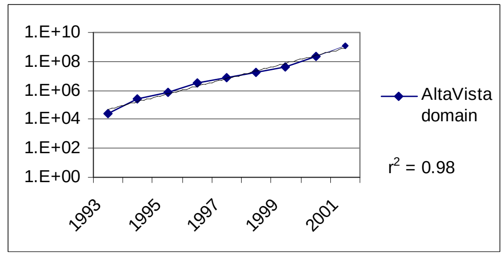

Figure 6. Exponential growth curve of the *AltaVista* domain during the period 1993-2001

Figure 5 first shows that the Internet has continued to expand rapidly. In Figure 6 this growth of the AltaVista domain is shown in logarithmic format. Remember that AltaVista provides only one specific representation of the data at the Internet (Butler, 2000; cf. Leydesdorff, 2001a).

When the data is organized in a three-dimensional array as explained above, the transmission in three dimensions T(uig) can be calculated for each year.[3] This leads to Figure 7.

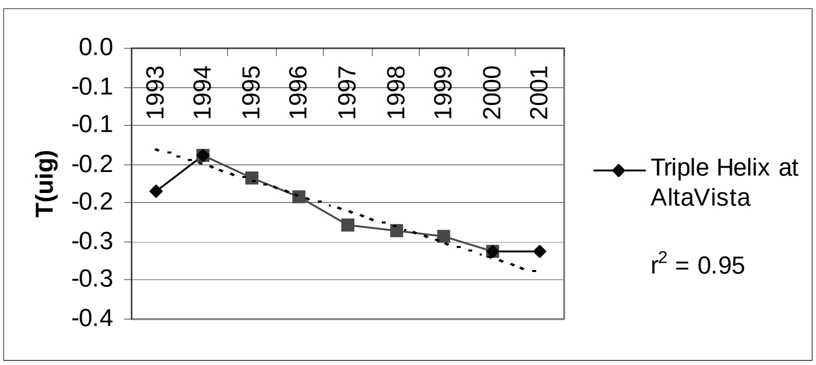

Figure 7. Mutual information in three dimensions ('university,' 'industry,' 'government') as measured using the *AltaVista* Advanced Search Engine (March 24, 2002).

Figure 7 shows that the values for T(uig) are always negative, but the curve decreases linearly during the period 1994-2000. This period witnessed the booming and the potential self-organization of the so-called new economy. The decrease of the value of the transmission in three dimensions is steady during this period ($r^2 = 0.95$). Perhaps the flattening of the curve in recent years illustrates that the process of endogenous expansion of the Internet has been interrupted temporarily as the e-business has gone into a recession. Note that this change in the dynamics is not noticeable upon visual inspection of the growth data in Figures 5 and 6.

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[3] For the computation of the mutual information among the three dimensions, one has to assume that the search for 'university' provides us with the (margin) total for this search term. The results of the searches 'university AND industry', etc., have then to be subtracted from the total number of hits in order to find the relevant number for single occurrences of the word 'university'. The subtraction assumes Boolean consistency in the search engine, but in this case of search engines at the Internet, this condition is only statistically true. For the purposes of this study the relatively small error terms in data gathering were neglected. As noted, the focus here is on developing the indicator for the data analysis and not on improving the techniques for retrieval.

4.2 Testing for Systemness in the Overlay of Triple Helix Relations

What does the effect of increasingly negative values for T(uig) teach us when compared to the descriptive statistics? Does it indicate the self-organization of a virtual dimension in the overlay of relations generated by the co-occurrences? Can this, indeed, be considered as an indication of increasing self-organization of the system of relations? Are the underlying data in each of the helices also being reorganized by the emerging system at the overlay level?

Emerging systemness in data sets can be tested against the alternative of historical growth of the elements of a system along the time axis (Leydesdorff, 1995). While the overlay in the Triple Helix model may exhibit systemness, the carrying institutions continue to develop historically; but the overlay system would then provide another selection environment for them at the global level, that is, in a (historically changing) present. Negative entropy first indicates that the overlay system provides the carrying systems with information relevant to reduce the uncertainty in the present. But has this feedback also become stabilized as another dynamic?

In the case of emerging systemness, one can expect a data set increasingly to contain the Markov property. The Markov property states that the current state of a system is the best prediction of its next stage. If systemness is not achieved, however, the normalized sum of the longitudinal predictions for the various elements provides us with the best prediction for a next state. These two hypotheses (of systemic development versus independent development of the elements, respectively) can be tested against each other for predicting next year's data. When the predicted values are subsequently observed, the quality of the two predictions can be evaluated (e.g., Leydesdorff & Oomes, 1999; Riba-Vilanova & Leydesdorff, 2001).

This test was applied using the time series data 1993-2000 for the prediction of 2001 data. Comparison with the observed data for 2001 led to the following results:

Prediction of the value in 2001	7 categories (U, I, G, UI, UG, IG, UIG)	four categories (UI, UG, IG, UIG)	three categories (UI, UG, IG)
on the basis of the univariate time series (1993-2000)	2.06	5.93	5.06
on the basis of the previous year (2000) (Markov property)	2.83	5.54	4.15
hypothesis of systemness	- 0.77 (rejected)	0.39	0.91

Table 1. *Testing the hypothesis of systemness in the Triple Helix overlay of University-Industry-Government Relations. (All values are in millibits of information.)*

The results show that the prediction of the 2001 data on the basis of the same data for the previous year (Markov property assumed) is inferior to the prediction on the basis of the time series of the various categories in the case of considering the whole system of seven search categories (left column of Table 1). Thus, the hypothesis that the representation would develop as a system is rejected.

When the analysis is limited to the three bi-lateral relations (right column of Table 1), the hypothesis of systemness in the data is corroborated. The quality of this latter prediction is worsened by including the trilateral relations (middle column). Similar results were obtained when using the prediction of data for the year 2000 on the basis of the time-series 1993-1999, but the results were then even more pronounced.[4]

[4] (see next page)

In summary, these results suggest that the system of representations of university-industry-government relations at the Internet is developing as a set of bilateral relations. The bilateral relations generate a negative entropy as another selection mechanism and in this sense enable the global system to self-organize the complexity in the data using a virtual overlay of network relations. This development, however, has slowed down recently.

4.3 The Triple Helix in the *Science Citation Index* (2000)

In the next application of the mutual information in three dimensions on Triple Helix data, I used the 1,432,401 corporate addresses on the CD-Rom version of the *Science Citation Index 2000*. These addresses point to 725,354 records contained in this database on a total of 778,446 items. Only 3.7 % of these records contain no address information.[5] Our research focuses on the international coauthorship relations in this data, but we will report on that project elsewhere (Wagner & Leydesdorff, in preparation). Here, I focus on University-Industry-Government relations in this data set.

An attempt was made to organize all these addresses automatically in terms of their attribution to university-industry-government relations. The routine first attributed a university label to addresses that contained the abbreviations 'UNIV' or 'COLL.' Once an attribution was made, the record was set aside before further attributions were made. The remaining addresses were subsequently labeled as 'industrial' if they contained one of the following identifiers 'CORP', 'INC', 'LTD', 'SA' or 'AG'. Thereafter, the file was scanned for the identifiers of public research institutions using 'NATL', 'NACL', 'NAZL', 'GOVT', 'MINIST', 'ACAD', 'INST', 'NIH', 'HOSP', 'HOP ', 'EUROPEAN', 'US', 'CNRS', 'CERN', 'INRA', and 'BUNDES' as identifiers. This relatively simple procedure enabled us to identify 1,239,848, that is 86.6% of the total number of address records, in terms of their origin as 'university,' 'industry,' or 'government.' The distribution is exhibited in Table 2:

	Number of records	*Percentage*
'University'	878,427	61.3
'Industry'	46,952	3.3
'Government'	314,469	22.0
– (not identified)	192,553	13.4
Total	1,432,401	100

Table 2. *Number of records in the Science Citation Index 2000 that could be attributed with a Triple Helix label using a routine*

The addresses refer thus identified to 676,511 (93.3%) of the 725,354 records in the database that contain address information. Furthermore, the address information also contains the country names. For the purpose of this study, records containing an address in England, Scotland, Wales or Northern

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prediction of the value in 2000	7 categories (U, I, G, UI, UG, IG, UIG)	four categories (UI, UG, IG, UIG)	three categories (UI, UG, IG)
on the basis of the univariate time series (1993-1999)	1.25	3.14	3.36
on the basis of the previous year (1999) (Markov property)	2.34	0.27	0.30
hypothesis of systemness	- 0.89 (rejected)	2.87	3.06

Table 1a. Testing the hypothesis of systemness in the Triple Helix overlay of University-Industry-Government Relations for the year 2000. (All values are provided in millibits of information.)

[5] The total number of authors in this database is 3,060,436. Thus, on average each record relates to four authors, but at two addresses.

Ireland were additionally labeled 'UK,' and analogously a dataset for the EU was composed containing all records with addresses in the 15 member states. The label 'Scandinavia' was added to all records containing an address in Norway, Sweden, Denmark, and Finland. A subset of the 120,086 internationally co-authored papers could analogously be defined.

For all these subsets a three-dimensional transmission of Triple Helix relations can be calculated. The results of this calculation are shown in Table 3.

	number	% ti	**T(uig) in mbits**	UI	UG	IG	UIG	Univers	Industry	Govern
All	676511	93.3	**-77.0**	16270	108919	4359	5201	543123	41242	232096
USA	232571	92.5	**-74.4**	7200	37834	1782	2666	200149	18154	66416
EU	257376	93.0	**-50.1**	4455	52112	1485	2028	206747	11192	101545
UK	68404	93.1	**-63.1**	1719	13098	394	690	54823	3970	26202
Germany	61017	94.7	**-43.4**	1028	14003	407	664	51283	2799	23701
France	41112	90.3	**-52.1**	439	11593	452	530	26133	1928	26595
Scandinavia	30939	95.8	**-31.6**	490	8477	162	371	26542	1263	13005
Italy	28958	89.9	**-29.4**	362	7133	87	262	25633	905	10526
Netherlands	18357	95.3	**-25.4**	372	4482	106	259	16379	863	6593
Japan	67715	97.9	**-92.1**	4147	12492	954	1311	56534	9732	21664
PR China	22116	99.5	**-14.9**	237	4610	68	114	18196	480	8583
Taiwan	8390	97.4	**-17.1**	148	2163	19	52	7454	250	3120
Singapore	2931	99.0	**-23.9**	104	476	7	17	2598	145	809
S. Korea	12038	98.3	**-40.1**	351	2341	87	91	10345	676	3978
Russia	22767	98.6	**-24.2**	76	6315	162	138	11507	478	17611
India	10916	89.2	**-78.1**	97	1813	61	55	6099	407	6492
Brazil	9120	91.0	**-22.4**	137	1727	32	52	7968	267	2885
internat. Coauthored	120086	98.9	**-21.9**	4550	47054	1349	2545	107569	9422	61138

Table 3. University-industry-government relations for various countries and regions using ISI's *Science Citation Index 2000.*

Table 3 suggests a very different pattern for the Triple Helix developments in various world regions. The Triple Helix overlay operates within the U.S.A. and notably Japan at a much higher level of self-organization than in Europe. Within the European Union, one can observe a scale with the U.K. at the leading end, but the smaller units (e.g., The Netherlands) at much lower levels. Russia and Brazil are even less integrated from this perspective, but India exhibits the western pattern despite the low numbers ($T < -0.70$).

In terms of the three-dimensional transmission, Japan is by far more networked in a Triple Helix mode than the other countries included in this analysis. This can already be seen on visual inspection of the numbers. For example, the number of papers with both university and industry addresses in Japan is 4147 against 4455 for the whole EU. This corresponds to 7.3% and 2.2% of all university papers in these two subsets, respectively.

In France the ratio of university papers coauthored with industry is only 1.7%. In this case, the relation between industry and government is even stronger than the one between the university sector and industry. The relations between university research and public sector research are strong everywhere, but in France, Russia, and India public sector research is larger than university research in terms of scientific output. The East-Asian countries demonstrate how the industrial participation in the network knowledge production system can be the crucial variable for the self-organization of the Triple Helix system.

Note that more than 39% of the internationally coauthored papers contain an address of both a university and a government agency. Yet, the relative low numbers of *bilateral* coauthorship relations of universities and government agencies with industrial partners indicates a low level of institutional differentiation in this subset as well.

Furthermore there seems to be a size effect of the T(uig) indicator among nations, but this correlation is not statistically significant. The main distinction is visible as a pattern of collaboration that is culturally specific. The academic system on the continent in Europe seems much more traditional in its patterns of collaboration than in the U.S.A. and Japan. University-Government relations are more established in the European nations than University-Industry relations. Russia and France are the most extreme cases in this respect. The papers based on international collaborations exhibit the least development in this Triple Helix mode of relations among all the subsets.

It should be emphasized that we use the data from the *Science Citation Index* as representations. Note that classification into sectors was only statistical. Industry is weakly represented in this data. Collaborations with industry may often not lead to scientific publications. The purpose of this study was to demonstrate the use of three-dimensional transmissions as a methodology for data analysis and not for data collection. Data collection will usually require much more care. However, independently of the refinement of the measurement, network data about university-industry-government relations can always be written as relative frequency distributions. The indicators of the three-dimensional transmissions can then be applied to a comparison of the state of the Triple Helix configurations under study.

5. Conclusions

Triple Helix configurations can be measured as network data. The representations need by no means be restricted—like in this study—to the terms 'university,' 'industry,' and 'government' as search terms in a database. However, I have used the results from these relatively straightforward searches in order to explain how the algorithmic indicator of mutual information in three dimensions enables us to distinguish among observable Triple Helix arrangements. Other representations can also be evaluated in this way.

For example, one could measure the discourse in an academic set of papers in terms of word (co)occurrences and then compare the results of this analysis with a similar one for the relevant industry and government sets of papers. Matrices (or higher-order arrays) of words used in different instances can be compared in terms of their relative overlap. The 'mutual information' in two dimensions can be considered as a measure of the covariation. On each side of each interface, one expects remaining variations, for example, terms which are used (or have meaning) within industry, but not in academia.

If the data representation is containing the three institutional dimensions of the knowledge infrastructure, the representation can be evaluated in terms of the development of the knowledge base using the three-dimensional transmission. In this study, I used scientometric and webometric representations in order to show how Triple Helix relations work differently at the national and at the global level. However, the algorithm works equally well on sociometric data. The method allows us to investigate to which extent the university-industry-government networks under study exhibit the knowledge *infrastructure* that sustains a *dynamics* of knowledge-based developments.

The development of the dynamic knowledge base can be studied using the three-dimensional transmission *because* entropy can be considered as a measure of the flux. The three-dimensional transmission is generated as a potentially negative entropy within the system composed by the interacting subdynamics. Whether the overlay of the relations has also become systemic and how it then operates, for example, in terms of bilateral and/or trilateral relations could be analyzed further using information-theoretical measures (Leydesdorff, 2001b).

At the global level, the system of representations at the Internet has gone through a rapid phase of expansion and has exhibited a negative transmission in these three dimensions that is further deepening. The self-organization of the probabilistic entropy in this representation, however, was based on the system of bi-lateral relations. Using the *Science Citation Index* for mapping coauthorship relations, different patterns of integration became visible in various cultural regions of the globe. Industry seems far less integrated into the academic system in Europe than in the U.S.A. and in Japan. In the People's Republic of China and Taiwan, industrial participation in the publication production system is still very low, but the relatedness with academia is in good shape when one looks at the percentages. If this emerging pattern can be developed in terms of its volume, one can expect a further decrease in the mutual transmission in the three dimensions. This can be considered as a policy implication of this model.

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