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The Measurement of Synergy in Innovation Systems: Redundancy Generation in a Triple Helix of University-Industry-Government Relations

(4 May 2017)

Loet Leydesdorff,*[a] Henry Etzkowitz,[b] Inga Ivanova,[c] and Martin Meyer [d]

Abstract
The Triple Helix of university-industry-government relations can first be considered as an institutional network. However, the correlations in the patterns of relations provide another topology: that of a vector space. Meanings are provided from positions in this latter topology. Meanings can be shared, and sharing can generate redundancy; increasing redundancy provides new options and reduces uncertainty. This evolutionary dynamics feeds back on the institutional networks which develop historically. Meaning is provided from the perspective of hindsight and with reference to other options; codes of communication open horizons of meaning. The codes operate as selection mechanisms and reinforce the perspectives of hindsight so that rationalized expectations can be entertained in a knowledge base. The knowledge base evolves in terms of providing new options by making distinctions possible. The vertical differentiation in inter-human communications operates upon the horizontal differentiation in TH relations and *vice versa*. The trade-off between the evolutionary generation of redundancy and the historical variation providing uncertainty can be measured as negative and positive information, respectively. Reducing uncertainty improves the innovative climate, and the generation of new options (redundancy) is crucial for innovation systems. In a number of studies of national systems of innovation (e.g., Sweden, Germany, Spain, China), this TH synergy indicator has been used to analyze regions and sectors in which uncertainty was significantly reduced. The quality of innovation systems can thus be quantified at different geographical scales and in terms of sectors such as high- and medium-tech manufacturing or knowledge-intensive services.

Keywords: Triple Helix; Non-linear Dynamics; University-Industry-Government Relations; Redundancy; Innovation Systems; Knowledge Base

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1. Introduction

The Triple Helix of University-Industry-Government Relations emerged as a research program from a confluence of Henry Etzkowitz's longer-term interest in the entrepreneurial university (Etzkowitz, 1983, 1998, and 2002; cf. Clark, 1998) with Loet Leydesdorff's interest in the evolutionary dynamics of science, technology, and innovation. Etzkowitz contributed a chapter entitled "Academic-Industry Relations: A Sociological Paradigm for Economic Development" to the book *Evolutionary Economics and Chaos Theory: New directions in technology studies* (Leydesdorff & van den Besselaar, 1994). Leydesdorff argued in the Epilogue of this book that more than two interacting dynamics are needed for studying technology and innovation from an evolutionary perspective.[1] Trajectories can be stabilized historically as a result of "mutual shaping" between two dynamics, but a third dynamic can be expected to disturb (destabilize) this tendency toward equilibrium and contribute to shaping a next-order (globalized instead of stabilized) system such as a technological regime (Dosi, 1982). Different from an observable trajectory, a regime structures the expectations.

The sociologist Simmel noted already in 1902 that the transition from a dyad to a triad is fundamental to systems formation (Bianconi, Darst, Iacovacci, & Fortunato, 2014; Simmel, 1950). A triad can be commutative: are the friends of my friends also my friends? The order of the communications in a triad can generate asymmetries: two loops in one direction and one in the other may lead to a path different from that resulting from one loop in the first direction and two in the opposite. This system thus becomes path-dependent: one cannot go back without

[1] Precursors of using the Triple-Helix metaphor can be found in Lowe (1982) and Sabato (1975). Lewontin (2000) uses the metaphor in a biological context.

friction to a previous state, as in an equilibrium system. An innovation system develops historically along trajectories. The triadic overlay has a dynamic different from the sum of the bi-lateral relations. It provides an emerging selection environment at the regime level.

Etzkowitz & Leydesdorff (2000) considered this emerging operation as a "communication overlay." Ivanova & Leydesdorff (2014) characterized the resulting communication system as a "fractal manifold:" the bilateral arrangements can be broken open (at all scales) by the third along each side of the triangle. A fractal manifold is scale-free because it develops endogenously in terms of reconstructions (which are needed because of the fractioning). The triads are nested at different levels and along different axes. In other words, a complex system can be expected to develop which is both horizontally and vertically differentiated (Simon, 1973).

The TH has hitherto focused on horizontal differentiation (and integration) among universities, industries, and governments. In this chapter, we report on the further elaboration of the institutional model of university-industry-government relations into an evolutionary model of innovations as a vertical differentiation. We argue that the knowledge base evolves in terms of providing new options by making distinctions possible (Spencer Brown, 1969). Increases (and decreases) in the number of options can be measured in terms of a trade-off between redundancy and uncertainty generation. We discuss the development of an instrument for the measurement of this balance in TH relations.

2. Institutional and evolutionary TH models

If sufficiently complex, institutional networks can carry the evolution of a knowledge base. However, the knowledge base develops with another dynamics on top of the institutional layer in terms of functions such as "supply," "demand," and "control" (Figure 1). These functions have to be specified at each level and sector contextually.

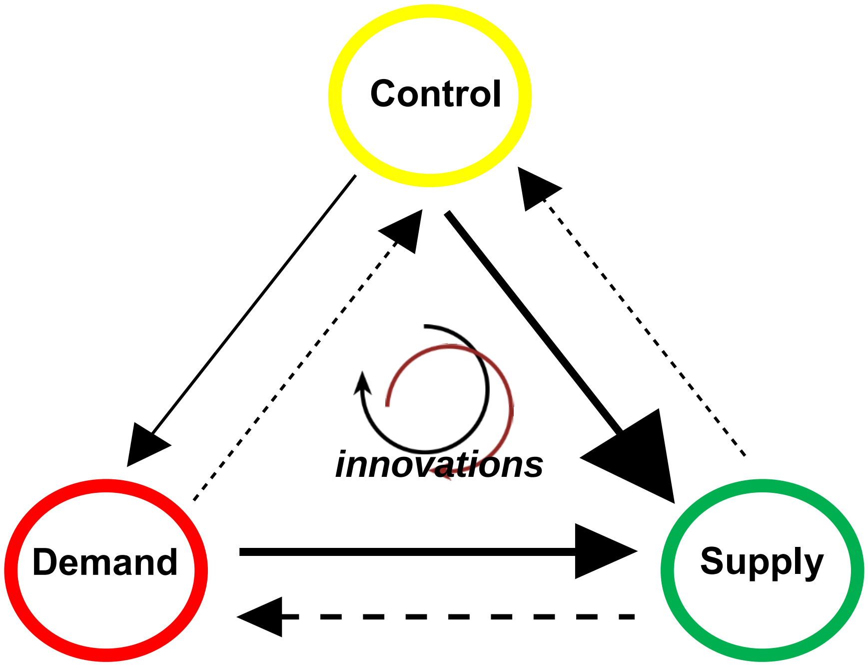


Figure 1: The generalized Triple-Helix model of innovations.
Source: derived from Petersen *et al*. (2016, Figure 1, p. 667)

In a study of medical innovations, for example, Nelson *et al.* (2011) distinguished among demand articulation for innovation in terms of diseases, supply in terms of new treatments, and control in terms of practical experiences and evaluations. Petersen *et al*. (2016) measured these three dynamics in terms of medical subject headings (MeSH terms that are attributed by PubMed/MEDLINE). Branch "C: diseases" of this index was considered as an articulation of demand, “D: drugs and chemicals” as supply, and “E: techniques and equipment” as conditioning the translations between supply and demand. Using the Triple-Helix indicator—to be discussed below—windows of opportunity for new medical technologies were indicated.

The various dynamics are related in the events; in the latter case, for example, as co-classifications of publications by PubMed/MEDLINE. Unlike the TH model of university-industry-government *relations*, the evolutionary model includes both relations and non-relations or, in other words, *correlations* among distributions of relations. The correlations span a vector space in which the relations and the carriers at the nodes occupy *positions*. In the case of three distributions, correlations between each two distributions can be spurious because of the third one. The latent dimension can contribute with either a plus or a minus sign. For example, university-industry relations in a nation or region may be excellent because of government policies or despite these policies.

In other words, each third helix can feedback or feedforward on the relations between the other two. From the perspective of this generalized TH model, university-industry-government relations can be considered as the special case of focusing on institutional relations. From the evolutionary perspective, the analysis of relations is not a purpose but a means to study the potential synergy in new arrangements. The institutions and their relations develop historically and are therefore directly observable (“phenotypically”). However, functions can be specified as theoretically informed expectations (“genotypically;” Langton, 1989). The TH model assumes that institutional arrangements evolve because of new options for (*i*) knowledge production, (*ii*) wealth generation, and (*iii*) regulation.

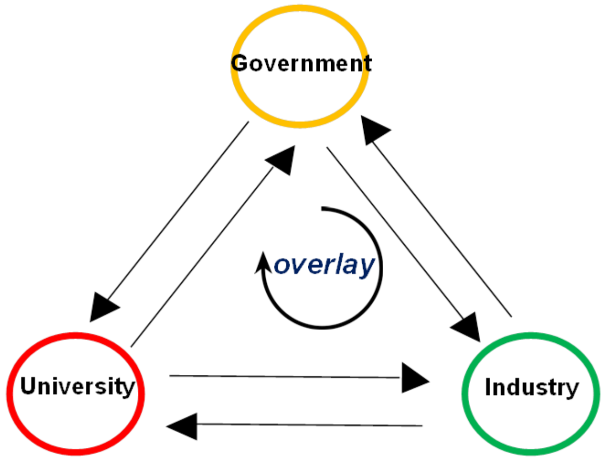
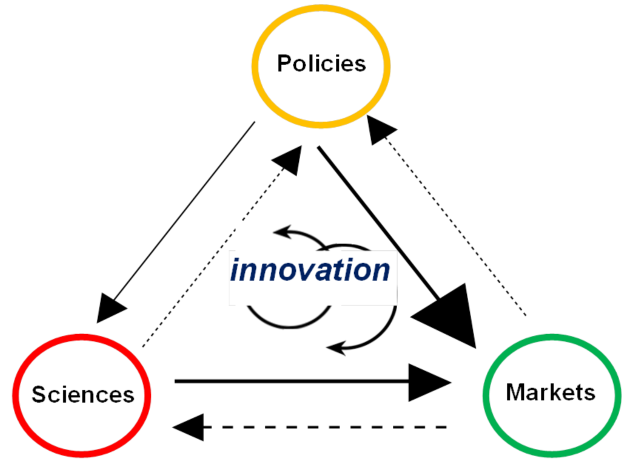
 • University-Industry-Government Relations • (Inter-)institutional • entrepreneurship (agents) • network analysis; graphs; • historical cases ("phenotypes"); • inductive: ➢ "best practices"; comparative case studies (Saad & Zawdie, 2011); ➢ Bottom-up (e.g., Li, Arora, Youtie, & Shapira, 2016); ➢ policy analysis (Etzkowitz, 2008; Zhou & Peng, 2008) (Etzkowitz & Leydesdorff, 1995-2000)	 • Correlations among social coordination mechanisms • evolutionary modeling of innovations (constructs) • in the vector space: ➢ TH synergy indicator; ➢ redundancy (overlap) as a source of innovations; (Ivanova & Leydesdorff, 2014; Leydesdorff & Ivanova, 2014)

Table 1: Summary of the differences between the institutional and evolutionary TH models.

Table 1 summarizes the differences between the institutional and evolutionary model. The two models are intrinsically related as models for explaining emergence (Padgett & Powell, 2012). The institutional TH model focuses on relations (Storper, 1997; cf. DiMaggio & Powell, 1991). The relations are considered as first-order attributes to the nodes (e.g., institutions). Interactions among the relations in a triadic (or more-dimensional) configuration lead to a second-order dynamics among the first-order attributes (Figure 2).

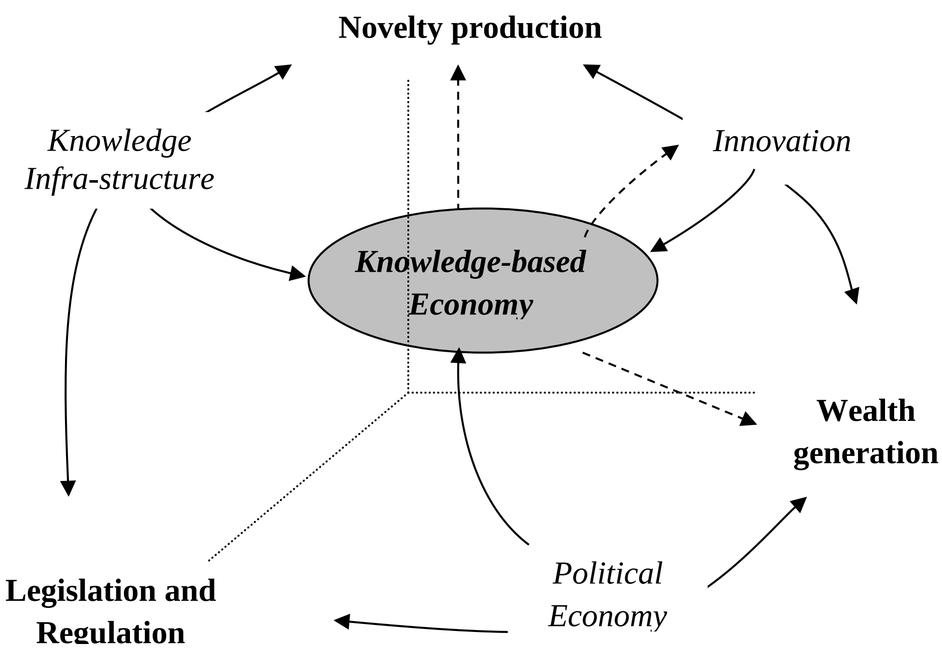


Figure 2: The first-order interactions generate a knowledge-based economy as a next-order system. (Source: Leydesdorff, 2010, at p. 379.)

Whereas the functions of wealth generation and governance have been central to the analysis of political economy, the study of the knowledge-based economy includes the additional dynamics of innovations (Schumpeter, [1939] 1964; see Figure 2). The tri-lateral interactions among the bi-lateral ones generate a feedback on the constituent helices and their bi-lateral relations *by providing another selection environment*.

The institutional restructuring is one of the relevant subdynamics of the complex dynamics of societal innovation and entrepreneurship. Invention and institutionalization takes place at the boundaries between institutional spheres. The relations and arrangements among institutions furthermore are sensitive to policy interventions. The institutional dynamics leads to path dependencies along historical trajectories. Between the historical variation and the selection mechanisms operating one can expect a non-linear dynamics of creative destruction and agglomeration (Schumpeter, [1911] 1949; cf. Soete & ter Weel, 1999) and reconstructions on the basis of competitive advantages (Cooke & Leydesdorff, 2006). The criterion of generating synergy in configurations of relations can provide a frame of reference for institutional reform since the lower the resulting uncertainty, the "smarter" specializations in terms of options that can be realized can be.

In summary, the TH cannot be considered as a single method or model; it is a theme that binds together the transition of political economy into a knowledge-based economy as a macro development with the study of transitions at micro- and meso-levels based on and leading to knowledge-based innovations. The study of knowledge-based economic developments can be pursued at both institutional and functional levels. The institutional dynamics provide the social embedding to the evolving systems (Freeman & Perez, 1988). The model can be considered institutional insofar as the explanation is in terms of networked relations among institutional agents (Powell, 1990; Storper, 1997). The model is neo-evolutionary since more than a single selection is assumed and the selection environments can change and interact (Nelson, 1995; Nelson & Winter, 1982). The networks of relations generate and retain the evolutionary dynamics (Padgett & Powell, 2012).

Knowledge-based innovation systems can be studied at macro, meso, or micro levels. Using the TH indicator, one is able to decompose the macro in terms of micro- and meso-levels. Thus, the issue of whether systems of innovation are national, regional, sectorial, etc. (e.g., Braczyk, Cooke, & Heidenreich, 1998; cf. Carlsson, 2006) can be addressed empirically. A systemic development can be distinguished from non-systemic (e.g., incidental) co-variation. One can ask, for example, how much synergy is indicated at regional or national levels. Furthermore, one can quantify how much cross-border synergy the national level adds to the sum of the regional systems of innovation.

The TH indicator provides a specific methodology which does not have to be used in a TH study. Much depends on the research question and the kinds of data available. Crucial for the TH theme, in our opinion, is the extension of the economic and political analysis with attention to cognitive structuration (Giddens, 1979). Let us first specify the transition towards a knowledge-based economy in the macro-historical context, and then proceed to discuss quantitative studies using contemporary data.

2. The Emergence of a Knowledge-based Economy

After studying in the British Library for almost a decade, in 1857 Marx published his "rough draft" of *Capital* under the title *Grundrisse: Foundations of the Critique of Political Economy* (Marx, [1857] 1973). In this study, Marx envisaged the possibility of a knowledge-based economy as an alternative to the political economy that he criticized for ideologically accepting the extraction of wealth from labour, and thus condoning exploitation. As he put it:

> Nature builds no machines, no locomotives, railways, electric telegraphs, self-acting mules etc. These are products of human industry; natural material transformed into organs of the

> human will over nature, or of human participation in nature. They are *organs of the human brain, created by the human hand;* the power of knowledge, objectified. The development of fixed capital indicates to what degree general social knowledge has become a *direct force of production,* and to what degree, hence, the conditions of the process of social life itself have come under the control of the general intellect and been transformed in accordance with it. To what degree the powers of social production have been produced, not only in the form of knowledge, but also as immediate organs of social practice, of the real life process. (at p. 706).

Note that Marx specified an indicator of this transition: "the development of fixed capital." He discussed its operationalization at length (in the *Grundrisse*) and set himself the task to study the possibility that science and technology had become greater sources of societal wealth than labour. A model with two independent variables was not available in his time.

After another ten years of study, Marx (1867) concluded in *Capital* that the main contradiction at the time remained the one between capital and labour. In the footnotes as a subtext (e.g., p. 393, note 89), however, Marx repeats that "the technology shows us the active relation of the human kind to nature, the immediate production process of our lives …" If technology could enable us to free man from work sufficiently, the nature of capitalism would change, since "*the basis of this mode of production falls away*" (p. 709; italics in the original). In other words, a regime change is envisaged that is different from the communist revolution.

In his time, Marx witnessed the prelude to the emergence of a knowledge-based economy. William Henry Perkin's research on dyestuffs in England during the late 1850s, for example, developed into an industry in Germany (Beer, 1959; cf. Braverman, 1974, pp. 161f.; Etzkowitz, 2008, p. 25). However, Noble (1977, at p. 7) argued that "the major breakthroughs, technically speaking, came in the 1870s." He dated what he calls "the wedding of the sciences to the useful arts" as the period between 1880 and 1920. Braverman (1984) introduced the concept of a "scientific-technical revolution" for indicating this same period when he formulated the regime change as follows:

> The scientific-technical revolution … cannot be understood in terms of specific innovations—as is the case of the Industrial Revolution, which may be adequately characterized by a handful of key inventions—but must be understood rather in its totality as a mode of production into which science and exhaustive engineering investigations have been integrated as part of ordinary functioning. The key innovation is not to be found in chemistry, electronics, automatic machinery, aeronautics, atomic physics, or any of the products of these science-technologies, but rather in the transformation of science itself into capital. (pp. 166f.)

The incorporation of science and technology into the production process makes the system evolve with a different dynamics (Schumpeter, [1939], 1964). Whereas both markets and political institutions can be considered as equilibrium-seeking (Aoki, 2001), the non-equilibrium dynamics of the social production of knowledge makes evolution theory relevant to the analysis of innovation systems (Allen, 1994; Dasgupta & David, 1994; Malerba, Nelson, Orsenigo, & Winter, 1999; cf. Hodgson & Knudsen, 2011). After WW II, the new field of "evolutionary economics" gradually emerged as central to innovation studies (Andersen, 1994; Martin, 2012). However, it took until the 1980s before the debate about the knowledge-based economy and its institutional conditions became salient. Before that time, the confrontation between liberal and communist models of political economy dominated the cold war. However, with the demise of the Soviet Union (1991) and the opening of China after 1989, this debate about political economy lost its prominence.

Using Friedrich List's (1841) model of national systems of political economy, Freeman (1987) first proposed the model of "national systems of innovation" after studying Japan from a West-European perspective (Lundvall, 1988; cf. Nelson, 1982; Hall & Soskice, 2001). Freeman & Perez (1988) developed a macro-model of business cycles which updates Marx's dialectics of production relations and production forces. Using historical examples, these authors argue that long-term cycles ("techno-economic paradigms") are generated by "key factors" (such as oil in the previous cycle, or information in the current one) that can rapidly become abundant and thus cheaper. The structural crises between the new paradigm and existing institutions and industries call for adjustments. National innovation systems compete in terms of adjustments by means of institutional reforms. The key factors which trigger next cycles, however, remained exogenous in this model, since the dynamics generating the "key factors" are not specified.

Nelson & Winter (1977; 1982) called for evolutionary models of technological innovation that would endogenize the technological dimension. How is the knowledge base generated within the system? Rosenberg (1976), for example, proposed to study selection in terms of focusing devices and inducement mechanisms. Under the condition of war, for example, national governments can be expected to invest in military technologies. Problems with the measurement of the knowledge base, however, seemed prohibitive in opening the black box further than in terms of historical descriptions (Rosenberg, 1982; Pinch & Bijker, 1984) or "history-friendly" models (Geels, 2002;

Malerba, Nelson, Orsenigo, & Winter, 1999). How can one proceed from case descriptions and historical "phenotypes" to the specification of an evolutionary dynamics (Andersen, 1992; 1994)?

Within this program of studies, the issue of measurement became increasingly important. In his Presidential address to the American Economic Association, Griliches (1994, p. 14) mentions the problem of measurement as a main constraint in research: "After decades of discussion we are not even close to a professional agreement on how to define and measure the output of banking, insurance, or the stock market (see Griliches, 1992). Similar difficulties arise in conceptualizing the output of health services, lawyers, and other consultants, or the capital stock of R&D. While the tasks are difficult, progress has been made on such topics." How can one measure innovations and innovation systems?

For decades, Freeman and Pavitt curated a database of innovations at the Science Policy Research Unit (SPRU) of the University of Sussex (Pavitt, 1984). In collaboration with Eurostat, in 1992 the OECD developed the so-called "*Oslo Manual*" entitled *Guidelines for Collecting and Interpreting Innovation Data* (OECD, 1992). The harmonization of national statistics is a first condition for making it possible to compare among "national systems of innovation" in terms of their strengths and weaknesses and perhaps to formulate best practices. However, neither innovation survey data nor patent data can be integrated easily—i.e., without theoretical assumptions—into the measurement of "national systems of innovation." Patents, for example, are indicators of invention, and inventions are only proxies of innovation (Griliches, 1994; Jaffe & Trajtenberg, 2002; Sahal, 1981).

The assumption of the national level for measurement was criticized by authors favoring regional perspectives (e.g., Braczyk & Cooke, 1998) and resounded with the European Union's perspective on transnational and inter-regional innovation systems. The knowledge-based economy provided a metaphor which leaves the systems level open (Carlsson, 2006). The economy is not defined institutionally, but functionally. At an expert meeting of the OECD in 1994 about developing indicators for the knowledge-based economy (Foray & Lundvall, 1996), however, Carter (1996) warned that the measurement of knowledge had remained an unsolved problem (cf. Godin, 2006). Andersen (1994) raised the question of "what is evolving?" in a knowledge-based economy as studied in "evolutionary economics." Problems of operationalization and measurement thus came to the forefront.

During the second half of the 1990s, the OECD hosted a program about "the knowledge-based economy" (David & Foray, 1995; Foray & Lundvall, 1996). In an evaluation, David & Foray (2002) cautioned that the terminology—knowledge-based economy—"marks a break in the continuity with earlier periods, more a 'sea-change' than a sharp discontinuity" (*ibid*., p. 9). The authors noted that transformations can be analyzed at a number of different levels, and argued that "knowledge" and "information" should be distinguished more carefully by analyzing the development of a knowledge-based economy in terms of codification processes (Cowan and Foray, 1997; Cowan, David and Foray, 2000).

Codification is a communication-theoretical problem: information can be provided with meaning, and specific meanings can further be codified as knowledge. The dynamics of the codification of information into knowledge are very different from the dynamics of government at different levels or the dynamics of markets in industrial sectors. The construction of knowledge-based systems is bottom-up; the retention of economic wealth from knowledge, however, focuses on the downward arrow. How can the constructed advantages (Cook & Leydesdorff, 2006) be used for innovation? The theoretical challenge is to combine the perspective of codification into discursive knowledge with evolutionary and systemic perspectives (Luhmann, 1975).

3. The Operationalization of the Triple Helix

The Triple Helix model takes the challenges thus articulated, as starting points for further analysis and theorizing, but with the goal of operationalization and measurement. David & Foray's (2002) "break in the continuity with earlier periods" is appreciated as the new role and the transformative dynamics of the social organization of knowledge. This adds a third structural dynamic to the economy and to the political system regulating the economy. The dynamic of codification operates in terms of trajectories and regimes (Dosi, 1982). A regime has one more degree of freedom than a trajectory. Whereas trajectories are shaped in a landscape (Geels, 2002; Sahal, 1985), the knowledge-based regime is hyper-geometrical. It can be considered as the "genotype" of the observable "phenotypes" along trajectories.

The genotype of the techno-economic evolution is not given like the DNA in biological systems. This "genotype" remains a construct that is open to partial reconstruction as knowledge is further developed (Langton, 1989). In other words, Andersen's (1992) question of "what is evolving?"

can now be answered: knowledge is a *cognitive* construct that evolves by generating new options. This evolving construct is socially retained and embedded along historical trajectories. These latter, however, are *social* constructs. Both dynamics are enacted and interact in events and actions generating and breaking relations.

Unlike the positive sciences which study domains that can be defined empirically, studies of socio-cognitive systems develop cognitive means to study knowledge-based developments as their empirical domain. This raises questions of reflexivity (Ashmore, 1989; Latour, 1988; Wouters, 1999). The cognitive dimension cannot be observed as given naturalistically; it needs to be specified as a cognitive construct. The specification is performative in that it changes the expectations. Expectations can be tested against observations. Because of this constructivist constraint in the study of knowledge-based systems, the analysis remains at the edge of philosophy and develops what has been called an "empirical" (Krohn, Layton, & Weingart, 1978; van den Daele & Weingart, 1975) or "concrete" philosophy of science (Husserl, 1929, p. 159; Leydesdorff, 2015). This philosophy of science is concrete, since its status is one of hypothetical knowledge in need of the observation and testing of the contexts in which it is generated and which it transforms.

Do the observable instantiations inform us about the evolving system(s) by enabling us to improve our expectations? The measurement of science is nowadays further developed in the scientometric tradition. However, scientometricians are confronted with the same reflexivity problem—albeit from a different perspective—when the question is asked: of "what do the indicators indicate?" When measuring, for example, the spectacular increases in international co-authorship relations in recent decades (Glänzel & Schubert, 2005; Persson, Glänzel, & Danell, 2004; Wagner & Leydesdorff, 2005), does one indicate the growth of knowledge or only institutional expansion (van den Daele *et al*., 1979)? How do social relations reflect or perhaps interfere with cognitive constraints and opportunities? Can one infer from the one to the other dimension?

In an attempt to bridge the gap between qualitative theorizing and quantitative methods, Callon, Law, & Rip (1986) proposed juxtaposing the social, technical, and cognitive dimensions by considering networks of science and technology as heterogeneous. From this perspective, different units of analysis such as texts, authors, and cognitions are juxtaposed in networks with *a priori* equal status (as "actants"). Based on the semiotic tradition, these "actants" are considered representations in a network whose dynamics can be mapped using co-words or other symbolic references (e.g., citations; Small, 1978; Wouters, 1998).

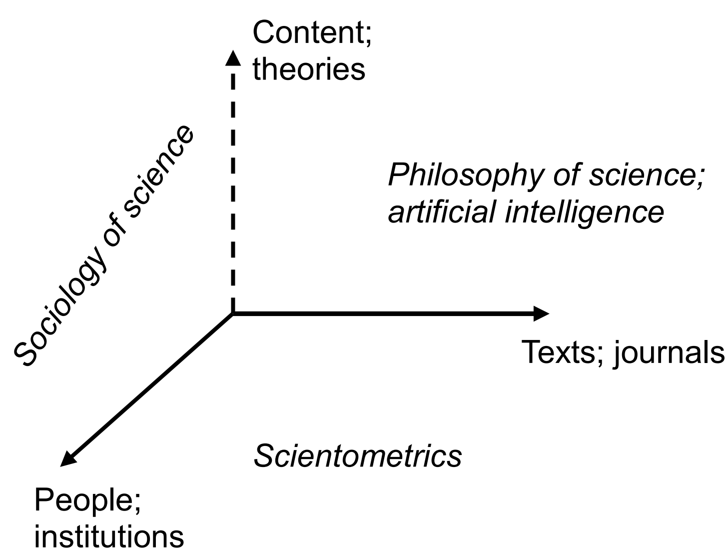


Figure 3: Three main dimensions of science. Source: Leydesdorff (1995, p. 3).

Alternatively, one can distinguish among dimensions and relate networks of different character (e.g., Braam, Moed, & van Raan, 1991a and b). For example, one can use more-dimensional (i.e., *n*-mode) networks. Using Figure 3, one of us proposed to distinguish in science studies more fundamentally among texts, people, and cognitions as three different units of analysis which cannot be reduced to one another. One can attribute texts to authors or vice versa, but the variation among the authors is different from the varieties among the texts. One can expect different—albeit interacting—dynamics along the three axes of cognitive content, social agency, and textual structures. Texts, for example, can be aggregated into journals or archives, whereas agents can be organized into institutions or groups. The dynamics of knowledge include, for example, the validation of new knowledge claims (Fujigaki & Leydesdorff, 2000).

The three analytically distinguishable dynamics (in this case, social, cognitive, and textual) can also be considered as selection mechanisms operating upon one another. In a co-evolutionary model, the variation-generating dimension ("helix") can act as the selection mechanism at a next moment. Each two selection mechanisms operating upon each other can lead to "mutual shaping" along trajectories A third selection environment, however, makes the system hyper-selective (Bruckner, Ebeling, Montaño, & Scharnhorst, 1996); one adds a "virtual order" or, in other words, "an absent set of differences, temporarily 'present' only in their instantiations, in the constituting moments of social systems" (Giddens, 1979, p. 64). One can expect skewed distributions in the outcome (e.g., scientometric distributions) because of selections operating upon one another (Seglen, 1992).

In other words, we submit that the TH operates in different topologies at the same time: the topology of the network of relations, and a vector space spanned by correlations providing structure in the background. In the latter, the zeros (non-relations) are as important as the ones (Deacon, 2012, pp. 3-9). Structures operate deterministically at each moment of time, but over time the selection mechanisms operate upon one another, and thus structures are also at variance. Both relations and non-relations can be considered as events that are selectively provided with meaning in the vector space. Meanings provided from different perspectives can be shared to differing extents. The sharing generates overlap and redundancy, while the communications in terms of relations continuously generate variation containing (Shannon-type) information. Redundancy and information add up to the maximum entropy at each moment of time. However, the mechanisms of generating redundancy and information are different: information is generated historically, while redundancy is specified discursively in the knowledge base. The generation of redundancy—and not the generation of information—makes the system knowledge-based.

4. The generation of redundancy

Redundancy R was defined by Shannon (1948) as follows:

$$R = \frac{H_{max} - H_S}{H_{max}} = 1 - \frac{H_S}{H_{max}} \quad (1)$$

The maximum information content of a system (H_{max}) is equal to the logarithm of the number of possible states N: i.e., $H_{max} = log(N)$. Eq. 1 specifies that H_{max} is composed of two components:

the system states hitherto realized [$H_s = -\sum_i p_i * \log(p_i)$] and the states which are possible given the definition of the system, but which were not (yet) realized [$H_{max} - H_s$].

For an innovation system, the number of options still available—that is, the redundancy—may be more important than the past record of already realized options; particularly when a system runs out of options. When redundancy is generated, the relative uncertainty H_s/H_{max} decreases (*ceteris paribus*) because H_{max} increases. The exploration of new options (e.g., diversification) becomes less risky under the condition of less uncertainty (Freeman & Soete, 1997). The generation of redundancy, in other words, can be expected to improve the climate for entrepreneurship and innovation.

Shannon (1948) deliberately abstained from the further specification of redundancy as loops in the information transfer. From his perspective, redundancy and coding are needed for error-correction in the transmission (as "excess information"; Shannon, 1945). Error-correction, however, assumes a norm and thus a social system. We argue that meanings are provided from the perspective of hindsight and therefore against the axis of time. Insofar as meaning processing requires relationship and communication, Shannon-type information is generated, but at another level—that is, in the relational network space. The relational network can be rewritten as a matrix which can be analyzed in terms of eigenvectors. The focus on this vector space provides a different perspective on the same information.

Since Shannon (1948) defined information as probabilistic entropy,[2] the development of information follows the second law of thermodynamics and can therefore only be positive (Krippendorff, 2009a and b). The generation of redundancy, however, can be positive or negative depending on the feedback and feedforward loops in the meaning processing as different from information processing. Feedback and feedforward loops can be expected to propel information and meaning in clockwise or counter-clockwise cycles (see Figure 1 above); that is, with potentially opposite signs (Ulanowicz, 2009; Ivanova & Leydesdorff, 2014). The relative information content of a message (H_s/H_{max}) can be enlarged or reduced by adding or constraining redundancy.

In other words, options other than those already realized are added or removed by mechanisms different from the second law. However, the number of options in a social system can increase much faster than their realizations. In a model, for example, the realizations are considered as special cases among possible states. As the models are refined, more distinctions and therefore options are made available. A knowledge-based economy seeks to exploit the increases of redundancy as a source of wealth.

5. The Triple Helix Indicator of Mutual Redundancy

How can redundancy be generated in relations among communication systems? Figure 4 visualizes a relationship between two sets as an overlap.

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[2] Shannon used H in Gibb's formulation of the entropy ($S = k_B * H$); k_B is the Boltzmann constant which provides the thermodynamic entropy S with the dimensionality Joule/Kelvin. However, H is dimensionless.

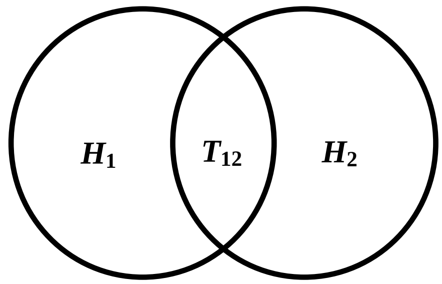

Figure 4: Mutual information between two sets of messages.

The formula for mutual information (or transmission *T*) follows according to the rules of set theory:

$$H_{12} = H_1 + H_2 - T_{12} \tag{2}$$

One subtracts the overlap (T_{12}) from the summation because otherwise one would count mutual information twice. However, if one sums the two sets as whole sets—accepting and including redundancy as surplus information—one obtains:

$$Y_{12} = H_1 + H_2 + T_{12} \tag{3}$$

Redundancy adds to the information content as "excess information" (Shannon, 1945). Comparing Eqs. 2 and 3, mutual redundancy $R_{12} = -T_{12}$. Whereas T_{12} is Shannon-type information and therefore positive, R_{12} consequentially is expressed in terms of negative bits of information.

Eq. 2 can be rewritten in a more general format as follows:

$$T_{12} = \sum_{i=1}^{n=2} H(x_i) - H(x_1, x_2) \geq 0 \quad (4)$$

And for more than two dimensions as follows:

$$\sum_{i=1}^{n=3} H(x_i) - H(x_1, x_2, x_3) = \sum_{ij}^{3} T_{ij} - T_{123} \quad (5)$$

...

$$\sum_{i=1}^{n} H(x_i) - H(x_1, \ldots, x_n) =$$

$$\sum_{ij}^{\binom{n}{2}} T_{ij} - \sum_{ijk}^{\binom{n}{3}} T_{ijk} + \sum_{ijkl}^{\binom{n}{4}} T_{ijkl} - \cdots + (-1)^n \sum_{ijkl\ldots(n)}^{\binom{n}{n}} T_{ijkl\ldots(n)} \quad (6)$$

The left-side terms of Eqs. 5 and 6 are positive because of the sub-additivity of entropy (Eq. 4). The alternation of the sign for mutual information in *n* dimensions [Eq. 6: $(-1)^n \sum_{ijkl\ldots(n)}^{\binom{n}{n}} T_{ijkl\ldots(n)}$] is an analytical consequence of this sub-additivity. Taken apart, T_{ijk} and next-order terms can no longer be considered as Shannon-type information because of the sign changes (Krippendorff, 2009a and b). With the opposite sign, however, T_{ijk} can be considered as a measure of mutual redundancy. For *n* dimensions, the mutual redundancy R_n is:

$$R_n = -[(-1)^n T_{1234\ldots n}] = -[\sum_{i=1}^{n} H(x_i) - H(x_1, \ldots, x_n)]$$

$$+[\sum_{ij}^{\binom{n}{2}} T_{ij} - \sum_{ijk}^{\binom{n}{3}} T_{ijk} + \sum_{ijkl}^{\binom{n}{4}} T_{ijkl} - \cdots + (-1)^{1+n} \sum_{ijkl\ldots(n-1)}^{\binom{n}{n-1}} T_{ijkl\ldots(n-1)}] \quad (7)$$

R_n can be positive or negative: the first term on the right side of Eq. 7 is necessarily negative (because of the minus sign); but the second term is positive entropy in a set of relations. The outcome is balanced and therefore empirical. The more negative the sum, the more options are generated.

In other words, mutual redundancy is generated in a trade-off between selective structures and a variable configuration of relations. This configuration can be reorganized; for example, in terms of developing new institutional arrangements. The minimalization of the second (positive) term provides us with a criterion for the evaluation of changes in the relations. (We have not yet elaborated this perspective.) The positive term is historically contingent, whereas the negative terms reflect the structure(s) in the system. As noted, these structures are not given naturally, but are (re)constructed. The techno-cultural evolution based on distinguishing (Spencer Brown, 1969) thus transforms the historical developments.

As new options are made available, the domain of what Kauffman (2000) called "adjacent others"—diversification options at the border between historically realized and possible, as yet unrealized states—is changed. The shaping of new relations and loops changes the phase space first along historical trajectories. However, possibly unintended loops may feedback or feedforward on existing loops and can trigger a next cycle of redundancy generation, such as a change in the technological regime (Rice & Cooper, 2010). A change at the regime level implies a redefinition of the selection mechanisms in the vector space since another dimension is added. One can expect that what "demand," "supply," and "control" mean will have changed after such a transition. For example, the demand for innovation in horse shoes changed after the introduction of the automobile. Although the automobile first emerged necessarily along a trajectory, the car system followed as a regime with many feedback loops. Feedback loops stabilize the system, whereas feedforward ones destabilize; but they enhance globalization beyond the boundaries currently given.

In summary, the information-theoretical perspective provides us with a model of techno-economic evolution in addition to the measurement instrument of the TH indicator. The regime level adds another selection environment reorganizing the trajectories (Dosi, 1982; Frenken & Leydesdorff, 2000). This selection environment—a communication field or overlay—emerges first as a second-order interaction term among bi-lateral relations, but then becomes analytically different from the selection environments from whose interactions and overlaps it emerged.

5. The measurement

The TH indicator was first developed in the context of the institutional TH model as a quantification of the balance between bi- and trilateral relations among universities, industries, and governments (Leydesdorff, 2003; Park & Leydesdorff, 2010).[3] The indicator can be derived using the Shannon formulas (e.g., Abramson, 1963; McGill, 1954) as:

$$T_{123} = H_1 + H_2 + H_3 - H_{12} - H_{13} - H_{23} + H_{123} \tag{8}$$

[3] Mutual information in three dimensions was suggested for this purpose by Robert Ulanowicz at a meeting in Toronto in 2002.

As noted above, T_{123} is not a Shannon measure since it can be negative. (The Shannon measure with a positive sign is $\sum_{ij}^{3} T_{ij} - T_{123} \geq 0$; see Eq. 5 above). In the three-dimensional case, mutual redundancy $R_{123} = T_{123}$. (In the two-dimensional case, however, $R_{12} = - T_{12}$.) R measures mutual redundancy in a configuration of relations under study.

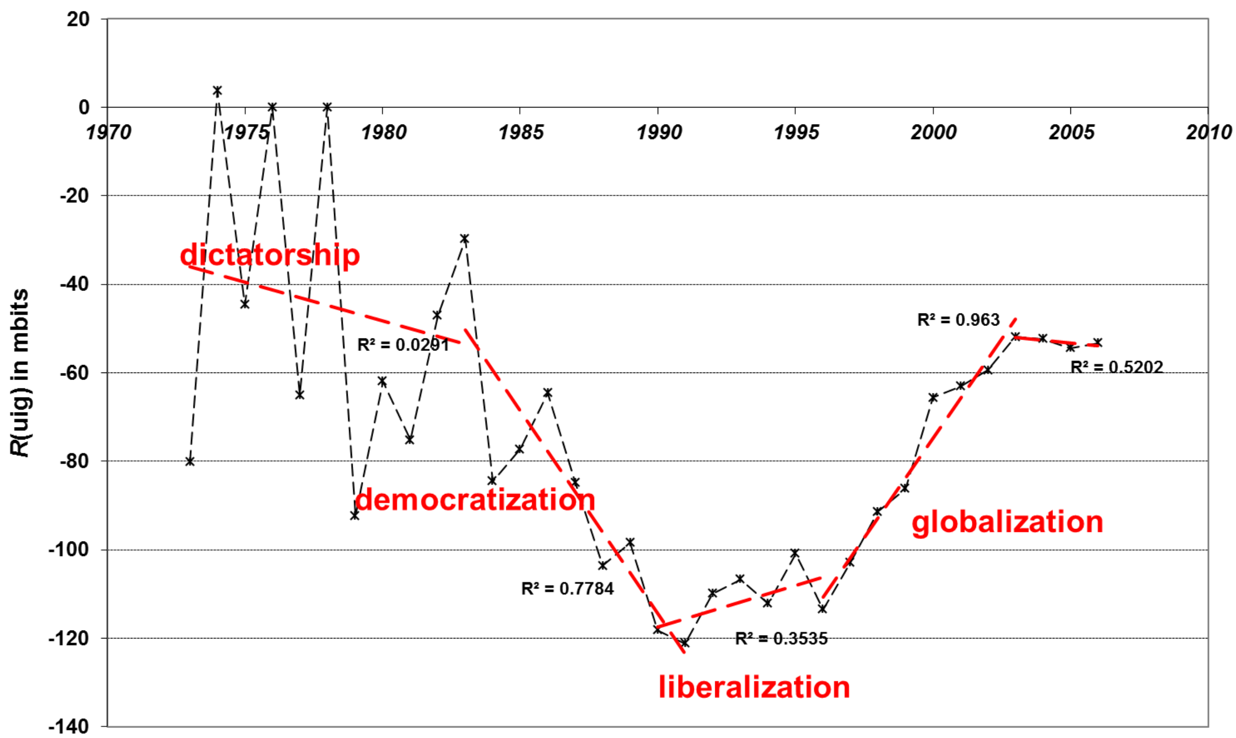

Figure 5: The development of mutual redundancy in South Korean university-industry-government relations during the dictatorship, the periods of democratization, liberalization, and globalization, respectively. Source: elaborated from Park & Leydesdorff (2010, at p. 645).

Figure 5, for example, is based on using all publications in the Science Citation Index (SCI) with at least one South Korean address in the byline. These publications were evaluated in terms of university-industry-government co-authorship relations. The figure shows the development of the TH indicator R_{123}. Whereas initially the system was hierarchical and state-controlled, the dictatorship regime relaxed gradually during the 1970s. This tendency was strengthened during the period of democratization during the 1980s. After the status of a more advanced economy is reached, the pendulum in the balance between uncertainty and redundancy generation swings back when Korea enters increasingly the world market, leading to full OECD membership in 1996. The internationalization of the research system uncouples from the national system of publications, and mutual redundancy thus decreases in absolute value (or, in other words, becomes less negative). Communication becomes more efficient or, in other words, less redundant.

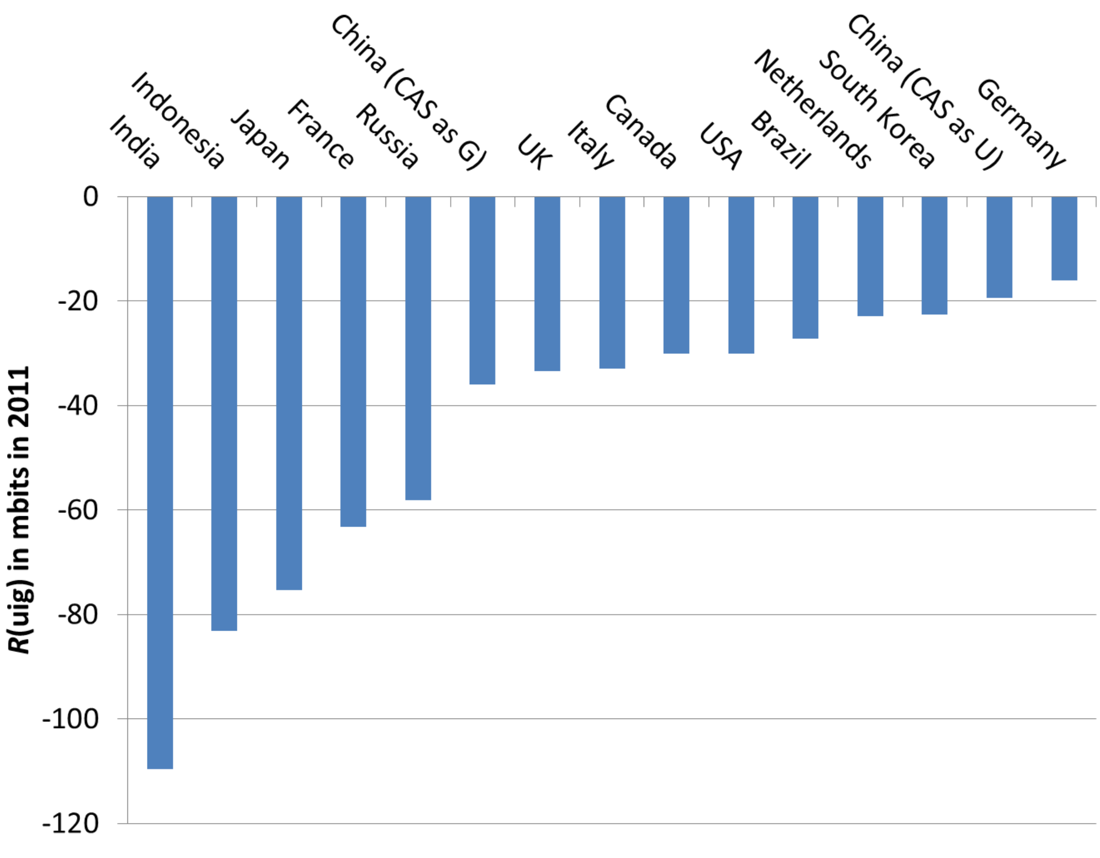

Figure 6: University-industry-government co-authorship relations in 2011, evaluated in terms of mutual redundancy. Source: Ye, Yu, & Leydesdorff (2013).

Based on SCI data, Figure 6 shows the strong integration at the national level in the case of some Asian countries (India, Indonesia, and Japan), whereas OECD member states (e.g., Germany and South Korea) are oriented more globally. The Chinese data provide us with an opportunity to consider publications of the Chinese Academy of Science (CAS) as either university or government. The CAS is gradually making this transition (Zhang, Chen, Zhu, Yam, & Guan, 2016). When CAS publications are considered as university publications, the Chinese system can be compared with South Korea and Germany in terms of its local (national) versus global orientation. As government publications, however, CAS firmly anchors the Chinese publication system at the national level. The different patterns of TH configurations in developed versus developing nations have been further investigated by Choi, Yang, & Park (2015a and b).

6. Measuring the Knowledge Base of Innovation Systems

In studies focusing on university-industry-government relations, one can count seven instances (U, I, G, UI, UG, IG, and UIG) and then evaluate the combinations in following three-dimensional cube of information (Figure 7):

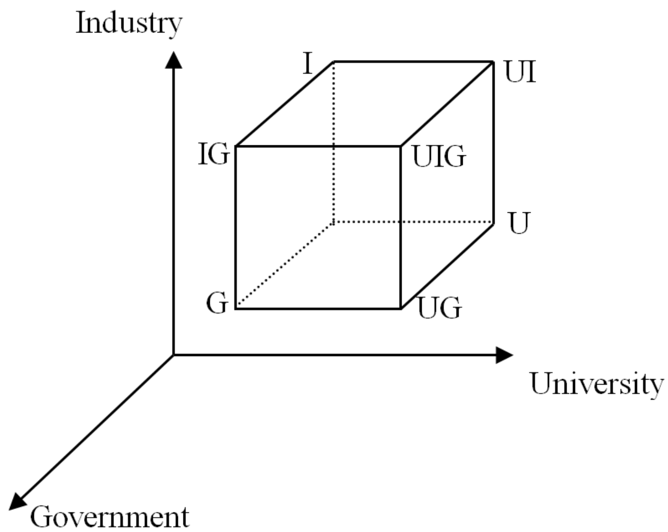

Figure 7: University-industry-government relations and a three-dimensional vector space.

Note that the eighth option {U=0; I= 0; G=0} is not counted in this (relational) model. Along each of the axes, however, one can refine the measurement. Instead of "university," for example, one can distinguish among disciplines in terms of departments and faculties, given that university-industry relations are very different in biomedicine, engineering, or the social sciences. Similarly, industry can be differentiated among sectors (e.g., medium and high-tech) and the dimension of government can be made more precise as national, regional, city, etc.

Using Storper's (1997) metaphor of a "holy trinity of technology, territory, and organization," one can organize firms (or universities) in terms of technological classes, geographical addresses, and organizational size, and study the interactions among these three dimensions. Which regions or sectors contribute most to the generation of redundancy? In the case of Sweden, for example, the complete set of (micro) firm data for Sweden at Statistics Sweden was N = 1,187,421 in November 2011. This Swedish data contains address information in terms of 290 units at the lowest (NUTS5) level of municipalities,[4] a technology classification into 21 classes,[5] and nine classes of numbers of employees which allow us to distinguish between small, medium-sized, and large companies (Leydesdorff & Strand, 2013, p. 1894, Table 2).[6]

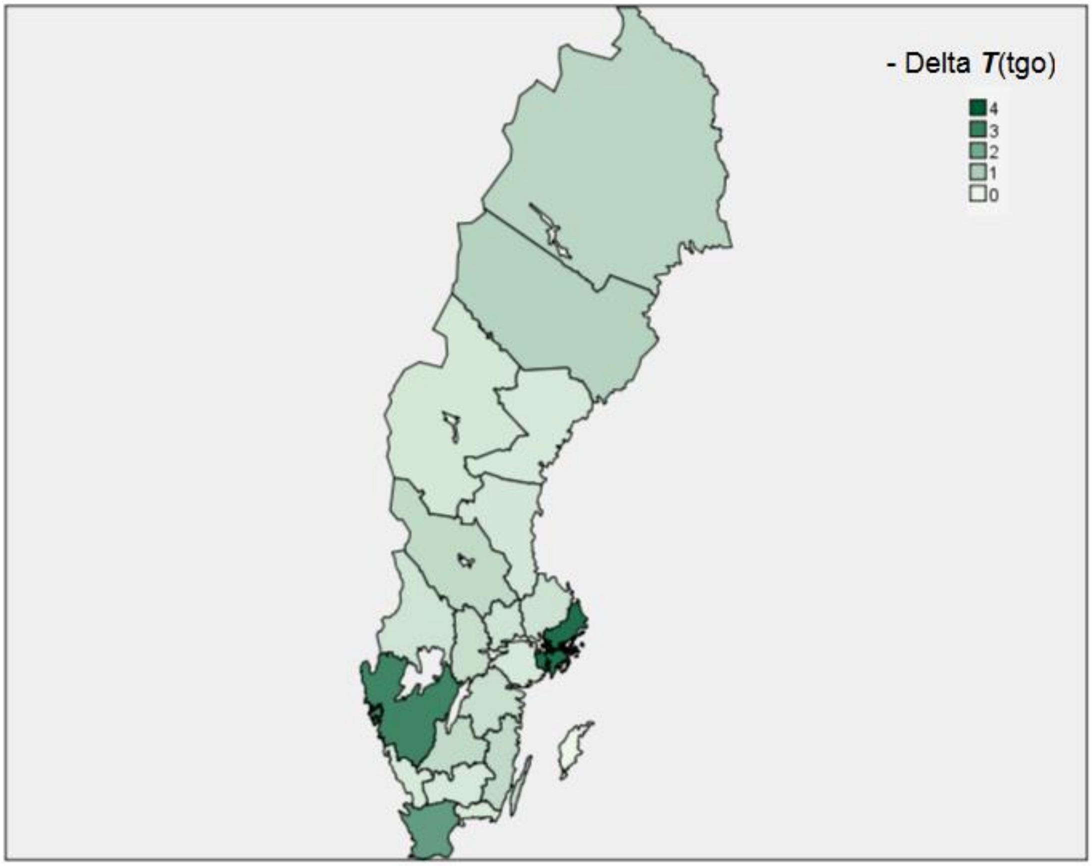

Figure 8: Contributions to redundancy at the level of 21 Swedish counties (NUTS-3).

[4] *NUTS* is an abbreviation for *Nomenclature of territorial units for statistics*, a system developed and maintained by EuroStat.
[5] A concordance table between the Swedish sector classification and the NACE codes (Nomenclature générale des Activités économiques dans les Communautés Européennes) can be found at http://www.scb.se/Grupp/Hitta_statistik/Forsta_Statistik/Klassifikationer/_Dokument/070129kortversionSnisorterad2007.pdf . Unfortunately, the technological classification is less specific than the NACE codes of the OECD.
[6] One can organize the data as a three-dimensional array using, for example, consecutive sheets in an Excel workbook, or one can write three attributes for each firm and use the TH calculator available at http://www.leydesdorff.net/software/th4. This software computes the TH indicator R_{ijk} and all the two-dimensional and one-dimensional components.

Figure 8 shows the results for the 21 counties in Sweden at the level NUTS-3. As could be expected, mutual redundancy is highest (in absolute value) for Stockholm (–3.49 mbits), Västre Gotalands län (–2.91 mbits), and Skåne (–2.31 mbits). These three counties host the major universities and dominate the picture within the nation; together they account for (8.71 / 17.95 =) 48.5% of the summed redundancies of the regions at this geographical scale (NUTS-3).

One of the advantages of entropy statistics is that the values can be fully decomposed. Analogously to the decomposition of probabilistic entropy (Theil, 1972: 20f.), mutual redundancy in three (or more) dimensions can be decomposed into groups as follows:

$$R = R_0 + \sum_G \frac{n_G}{N} R_G \qquad (2)$$

When one decomposes in the geographical dimension, R_0 represents redundancy generated between regions; R_G is the synergy generated at a geographical scale G; n_G is the number of firms at this geographical scale; and N the total number of firms in the aggregate (N = 1,187,421 in the Swedish case).

The between-group redundancy (R_0) can be considered as a measure of the synergy among regions. A negative value of R_0 indicates an additional synergy (i.e., redundancy generation) at the next level of national agglomeration among the lower-level geographical units. In the Netherlands and Norway, for example, such a surplus was found at the national level; in Germany, this surplus was found at the level of the federal states (*Länder*). Whereas one cannot compare the quantitative values of R_0 across countries—because these values are sample-specific—one is allowed to compare the indicator in terms of the positive or negative signs of R_0 and as percentages of the total synergy (R_{123}).

Table 2. Between-group synergy at different geographical scales in the Swedish innovation system. Source: Leydesdorff & Strand, 2013.

Geographical scale	*ΣR in mbits*	*R_0*	*R_0 as % contribution*
NUTS0 (national level)	-22.56		
NUTS1 (3 Landsdelar)	-22.08	-0.48	2.2
NUTS2 (8 Riksområden)	-19.84	-2.72	13.7
NUTS3 (21 Counties)	-17.95	-4.61	25.7

Table 2 shows that in the case of Sweden, the surplus of the national system is –4.61 mbit (on top of the aggregation of the results at individual counties). This is 25.7% of the –22.56 mbit measured for Sweden as a national system. In other words, one quarter of the reduction of uncertainty in the national system is realized at a level higher than within the regions. At the next level of aggregation (NUTS2), an additional synergy of (22.56–19.84) = 2.72 mbits, or 13.7%, is realized. Among the three *Landsdelar* (NUTS1), however, only 0.5 mbit, or 2.2% of the national sum total, is reduced by this further aggregation. In other words, the Swedish national system is organized hierarchically, as indeed is suggested by most of the literature about Sweden.

Analogous to the geographical decomposition, one can also decompose redundancy in terms of industrial sectors or firm sizes. In a series of studies, we decomposed a number of national systems of innovation: Germany (Leydesdorff & Fritsch, 2006), the Netherlands (Leydesdorff, Dolfsma, & van der Panne, 2006), Sweden (Leydesdorff & Strand, 2014), Norway (Strand & Leydesdorff, 2014), Italy (Cucco & Leydesdorff, manuscript), Hungary (Lengyel & Leydesdorff, 2011), the Russian Federation (Leydesdorff, Perevodchikov, & Uvarov, 2015), and China (Leydesdorff & Zhou, 2014). In the case of the Netherlands, Norway, Sweden, and China, the national level adds to the sum of the regions. In the Netherlands, the (inter-regional) highways to Amsterdam Airport (Schiphol) are probably the most important axes of the knowledge-based economy. In Sweden, the synergy is concentrated in three regions (Stockholm, Gothenburg, and Malmö/Lund); in China, four municipalities which are administered at the national level participate in the knowledge-based economy more than comparable regions.

In Norway, foreign-driven investments along the west coast in the marine and maritime industries drive the transition from a political to a knowledge-based economy. The synergy in terms of the development of new options is larger in these coastal regions than in the regions with the traditional universities in Oslo and Trondheim. Hungary's western part is transformed by integration into the European Union, whereas the eastern part has remained a state-led innovation system. The capital Budapest occupies a separate position as a metropolitan system of innovations. The national level no longer adds synergy to the sum of the synergies in these three regional systems.

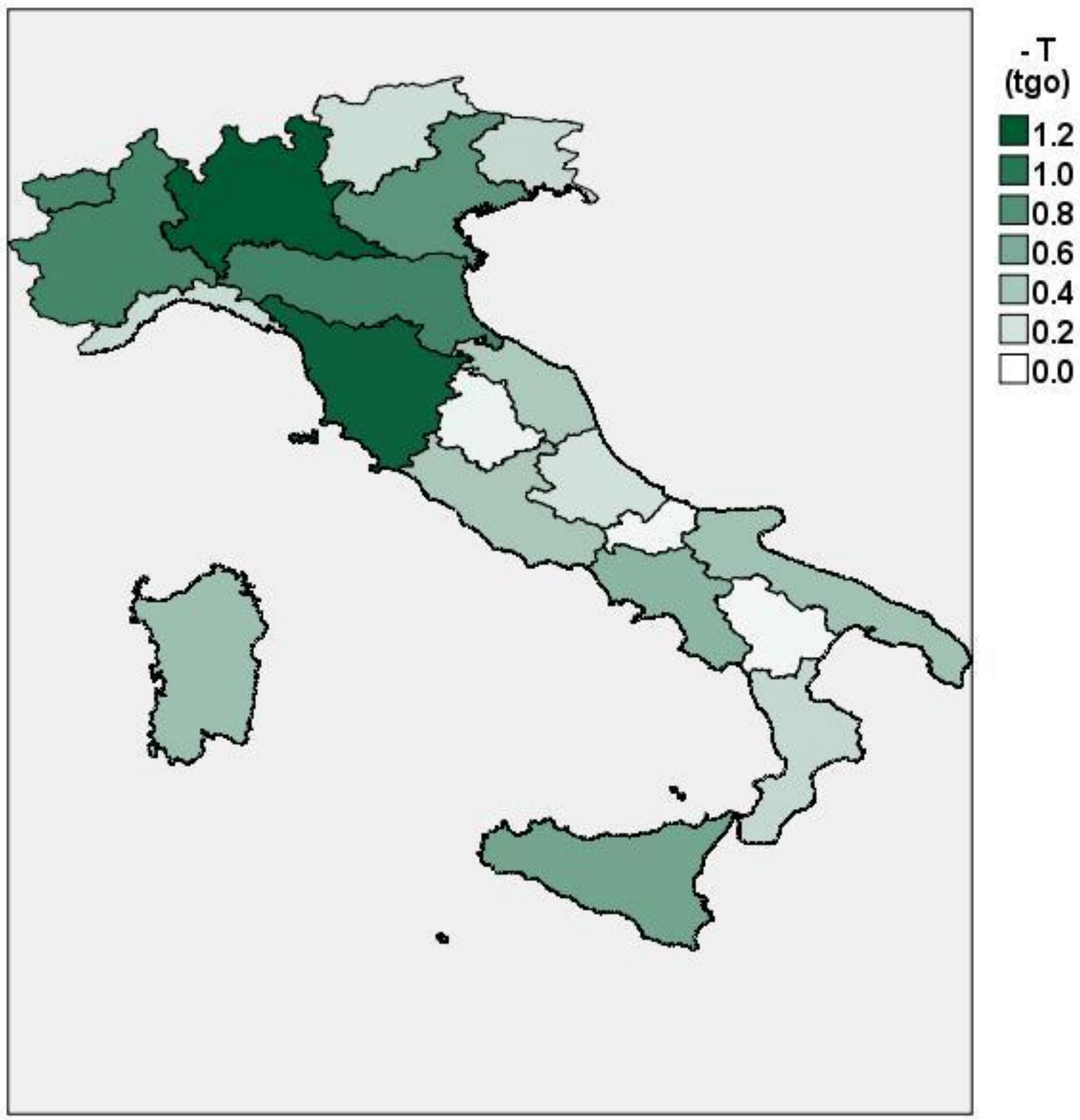

Figure 9: Decomposition of Italy in terms of regions; *n* of firms = 4,480,473. Data: Statistics Italy (IStat), 2007. Source: Cucco & Leydesdorff, 2013.

In a study of Italy, we first used the administrative units (NUTS2 regions) provided by Eurostat and the OECD. The data is the complete set of 4.5 million Italian firms registered at Statistics Italy in 2007. Figure 9 shows that the main division in this country is between the northern and southern parts of the country. (Sicily has a special position.) In other words, the pattern is opposite to the one for Sweden summarized in Table 2 above: the regions are administrative artifacts, while the country is organized in terms of two main innovation systems, each with a different dynamics. The aggregation among the lower-level regions indicates the role of the national system, but this role is different in the northern and southern parts of Italy. The perspective on Italy in terms of regions (e.g., OECD, 2009) is not supported by these results.

One of the conclusions to be drawn throughout the studies of the more advanced economies, is that knowledge-intensive services (KIS) do not contribute to the local synergy in regions because they are not coupled geographically. For example, if one offers a knowledge-intensive service in Munich and receives a phone call from Hamburg, the next step is simply to take a plane to Hamburg, or perhaps to catch a high-speed train. In other words, it does not matter whether one is located in Munich or Hamburg as knowledge-intensive services uncouple from the local economy. The main competitive advantage is proximity to an airport or train station. In a study of the Russian Federation, however, the national level could be shown to disorganize synergy development at lower levels. Knowledge-intensive services sufficiently cannot circulate in Russia because of their integration into the (localized) state apparatuses.

Relative “foot-looseness” (Vernon, 1979) of KIS can also be expected in the case of high-tech knowledge-based manufacturing; but the expectation is different for medium-tech manufacturing, because in this case the dynamics are often more embedded in other parts of the economy (Cohen & Levinthal, 1990). A number of policy implications follow from these conclusions and considerations. Footloose companies cannot be expected to contribute to the strengthening of the integration within a given region. High-tech knowledge-intensive services, however, may require a laboratory. One would expect medium-tech manufacturing to be more embedded and thus to generate more employment than high-tech.

In summary, the different country studies show that the patterns can be very different among nations as well as among regions within nations (e.g., Yoon & Park, 2016). The dynamics are also different when comparing the sciences with markets: in publication systems uncoupling and international (that is, non-localized) orientation can be considered as improvements to the system, while in the case of regional developments the focus is on retaining "wealth from knowledge" and thus on developing local synergies. The discussion of the potential uncoupling from geographical locations by knowledge-intensive services illustrates how the different dynamics can also be interwoven. High-tech and knowledge-intensivity tend to induce globalization, including volatility, since stabilization is not a priority. The trade-off between the knowledge-based economy self-organizing at the global level and the lower-level organization in networked instantiations can be measured in considerable detail using the TH indicator.

While the dynamics are complex, the results can be counter-intuitive because the *a priori* categories are being tested as hypotheses. Where are empirically the windows of opportunity for coupling self-organizing and differentiation with integration into organized forms and along trajectories? In a recent study of Spain, for example, Andalucia as a region (at the NUTS2 level) did poorly in generating mutual redundancy, but Sevilla as a town within this region (NUTS3) showed a different pattern (Porto Gomez & Leydesdorff, in preparation). In summary, one of the major functions of these studies is to revise and inform the categories used for making such assessments. Revision may make them more knowledge-based and thus enhance the visibility of new options.

7. Institutional Retention

Note that the TH indicator is a systemic indicator. Activities in a specific region (e.g., Linköping in Sweden; Etzkowitz & Klofsten, 2005) may have been very successful in terms of developing university-industry-government relations, but entrepreneurship is a form of action. One can even expect governments and European policies to develop action plans to stimulate "less favoured regions." However, the TH-indicator informs us about the environments of these entrepreneurial activities. The chances of being successful as an innovative entrepreneur are statistically higher in Stockholm than in Linköping because of the relative reduction of uncertainty in the former region. This conclusion is not meant to discourage entrepreneurship in lagging regions. On the contrary, one may also conclude as a policy implication that some regions do not need support because the dynamics of the knowledge-based economy is already self-organizing in these regions.

Action, entrepreneurship, and local organization combine and integrate technical opportunities, market perspectives, and geographical resources (e.g., endowments). Selection mechanisms, however, differentiate on the basis of different criteria. Insofar as the criteria interact, redundancy may be generated. In other words, the complex dynamics is both differentiating and integrating. The neo-evolutionary model focuses on the structural differentiation: how is the system driven to change? The (neo-)institutional perspective on university-industry-government relations focuses on integration in action; for example, in terms of academic entrepreneurship. From this perspective, the focus is on finding new ways to enhance innovation, such as the invention of venture capital. The cognitive dimension is endogenized into this model in the context of policy innovations. For example, priority programs at strategic research sites such as the emergence of new interdisciplinary fields (e.g., computer science) have been synthesized since the mid-20th century (Etzkowitz & Peters, 1991). New fields are actively co-constructed as opposed to a previous model of branching into specialization (Ben-David & Collins, 1966).

Despite the intrinsic relations between the institutional and evolutionary models, the resulting research programs are different in important respects. A range of metrics have been developed from the institutional perspective on Triple Helix relations. These approaches do not present a single model for capturing “the Triple Helix,” but focus on different aspects of Triple Helix relations. Contributions link diverse themes ranging from conceptual work on entrepreneurial science (e.g., Etzkowitz, 1998; 2003) and academic capitalism (Slaughter, 1997), or entrepreneurial universities (Clark, 1998) that can act as regional innovation organizers (Etzkowitz *et al.*, 2000), to research on indicators such as university patenting and licensing (OECD, 2003; Saragossi & Van Pottelsberghe, 2003) and academic inventors (e.g., Meyer *et al.*, 2003; Etzkowitz, 2016). The theoretical frameworks of the empirical studies span a large domain including organization studies, business and management, network science, etc. It is beyond the scope of this chapter to review all these approaches which touch upon the TH theme.

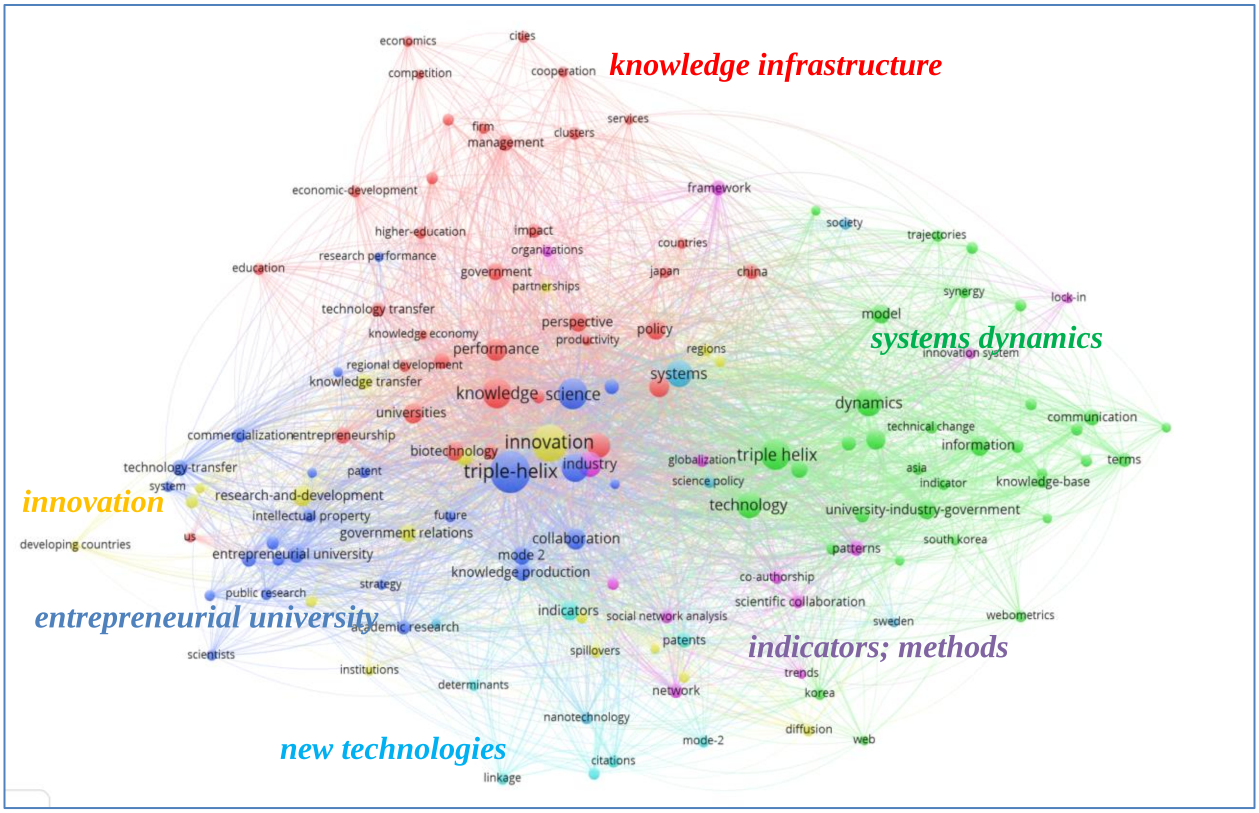

Figure 10: Semantic map based on 139 keywords attributed five or more times to 492 documents retrieved from the Social Science Citation Index and the Arts & Humanities Citation Index on November 16, 2016; search string: 'ts="Triple Helix" OR ts="university-industry-government relations"'. VOSviewer used for the layout and clustering.

Figure 10 shows a co-word map based on 139 keywords attributed five or more times to 492 documents retrieved from the Social Science Citation Index and the Arts & Humanities Citation Index on November 16, 2016 using the search string: 'ts="Triple Helix" OR ts="university-industry-government relations"'. Seven clusters are distinguished, among them three major ones in red, green, and blue. "Triple-helix" as an adjective (with hyphen) is positioned in the blue-coloured cluster on the left side labeled "entrepreneurial university." "Triple helix" as a substantive (without hyphen) is positioned in the green cluster on the right side labeled "systems dynamics." The main cluster in red at the top relates the TH theme to studies of higher education and university policies. Scientometric indicators and social networks are indicated at the bottom with keywords that refer to new technologies such as "nanotechnology."

A considerable number of contributions is concerned with capturing academic entrepreneurship (Meyer *et al.*, 2014). Academic patenting has been debated in relation to the Bayh–Dole Act of 1980, which changed the intellectual property rights on academic inventions in the USA. Mowery *et al.* (2001), for example, argued that the Bayh–Dole Act has been an important driver of university patenting and licensing activity. The entrepreneurial university has been another starting point for the development of indicators to measure Triple Helix relations (e.g., Liang *et al.,* 2012; Meyer *et al.,* 2003; Ranga *et al.*, 2003). Narin *et al.,* (1997, p. 317) has considered the rapidly growing citation linkages between US patents and scientific literature as "useful evidence in arguing the case for governmental support of science."

Most of the scientometric contributions are method-driven; the TH is used as a metaphor in the theoretical background. Some authors argue for extending the metaphor to four or more helices, including for example the public, or the relation between developed and developing countries (e.g., Carayannis & Campbell, 2010; Park, 2014). The extension of the TH indicator of synergy to more than three dimensions is straightforward (Leydesdorff, Park, & Lengyel, 2014).

8. Concluding Remarks

The Triple Helix has provided a metaphor which can be used in modelling the knowledge-based economy and innovation. The dynamics of a knowledge-based economy are complex

(Leydesdorff, Petersen, & Ivanova, 2017; Luhmann, 1975; Simon, 1962). We have argued that the challenges of modelling are not only theoretical. Systemness can be operationalized and measured in terms of the generation of new options. Without such operationalization, the notion of "system" tends to lead to reification; knowledge-based systems are not given, but constructed.

By using the notion of system analytically, we assume the possibility of emerging systemness. Can synergy be indicated and if so, at which level? From a communication-theoretical perspective, the not yet realized options can be considered as redundancy. Redundancy is developed by providing meanings from different perspectives to the same or similar events. A Triple Helix of university-industry-government relations provides these different perspectives.

In addition to horizontal differentiation among the three helices, we have operationalized vertical differentiation. The vertical differentiation finds its origin in the focus on relations in the neo-institutional model (Padgett & Powell, 2012): the nodes (in this case, the institutions) operate by relating; the relations relate in a second-order dynamics in terms of distributions with reference to possible relations. Meaning is provided from the perspective of hindsight to events invoking horizons of meaning that can be codified differently. The codes are generated by what has also been called institutional logics (Thornton *et al*., 2012) or they can be considered as the eigenvectors in a vector-space (von Foerster, 1960). A three-layered system is thus envisaged: information processing in relations at the bottom; meaning processing in a vector space based on correlations among distributions of relations; and thirdly, an interaction between meaning processing and codes of communication that open horizons in which cognitive distinctions can be constructed.

These cognitive constructs are embedded in social constructions such as networks and institutions. New options are developed through cultural practices. The social structures carry the knowledge-based structures are themselves carried by reflexive agents who infra-reflexively can have access to all three layers (Latour, 1988). Agents are thus able to change structures; the structures mediate in layers of communication which transform events (including actions) into expectations and expectations into discursive knowledge. Construction is bottom-up; control tends to be top-down. As a new selection environment is constructed, the locus of control may also shift. As yet another selection environment, the knowledge base thus transforms the political economy in which it remains under construction.

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