Chapter 5
Evolutionary and Institutional Triple Helix Models

The institutional TH model focuses on relations of universities, industries, and governments in networks. Institutional arrangements develop over time along trajectories. The Triple-Helix metaphor of university-industry-government relations can also be elaborated into a neo-evolutionary model combining the vertical differentiation among the levels (in terms of relations, correlations, perspectives, and horizons of meaning) with the options for horizontal differentiation among the codes (e.g., markets, technologies, politics, etc., operating in parallel). The neo-evolutionary model focuses on the interactions among selection mechanisms (markets, technologies, endowments) at the regime level. The historical and evolutionary dynamics feedback on each other. The relative weights of the historical versus evolutionary dynamics can be measured as a trade-off. Among three or more selection environments, synergy can be generated as redundancy on top of the aggregates of bilateral and unilateral contributions to the information flows. The number of new options available to an innovation system for realization may be as decisive for its survival more than the historical record of past performance.

The "Triple Helix of University-Industry-Government Relations" originated as a research agenda from a confluence of Henry Etzkowitz's longer-term interests in the entrepreneurial university (Etzkowitz, 1983, 2002; cf. Clark, 1998) with my interest in the evolutionary dynamics of science, technology, and innovations as a result of three (or more) different sub-dynamics. Etzkowitz (1994, pp. 139–151) contributed a chapter entitled "Academic-Industry Relations: A Sociological Paradigm for Economic Development" to our—that is, Leydesdorff and van den Besselaar's (1994)—edited volume entitled *Evolutionary Economics and Chaos Theory: New directions in technology studies*. In this chapter, Etzkowitz described the development of MIT into an entrepreneurial university since the 1930s. In the editorial Epilogue to this volume, I argued that more than two interacting dynamics are needed for studying technology and innovation.

The chapter is partly based on: Leydesdorff, Ivanova, & Meyer (2019). The Measurement of Synergy in Innovation Systems: Redundancy Generation in a Triple Helix of University-Industry-Government Relations. In W. Glänzel, H. Moed, U. Schmoch & M. Thelwall (Eds.), *Springer Handbook of Science and Technology Indicators*. Heidelberg, etc.: Springer.

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In the summer of 1994, Etzkowitz and I met again at a workshop in Abisko (Sweden) and discussed a follow-up project combining his interest in university-industry relations with my interest in the dynamics of science, technology, and innovation. In the email conversations that followed, we developed the Triple-Helix (TH) model of university-industry-government relations as a common denominator (Etzkowitz & Leydesdorff, 1995).[1] We agreed about using this title in email exchanges during the month of November 1994.

Etzkowitz and I could find a common ground while the TH metaphor can be elaborated from two different (yet related) perspectives: the (neo)institutional one of relations among universities, industries, and governments, and a neo-evolutionary one of interactions among three coordination mechanisms: wealth generation, novelty production, and governance. The (neo)institutional approach can be combined with social network analysis as a methodology. For example, one can look for the centrality of agents or institutions in the network. In this chapter, I shall elaborate the differences and also discuss the role of transitive and cyclic triads in systems formation.

5.1 Historical Trajectories and Evolutionary Regimes

A knowledge-based economy is different from a political economy by being the result of three instead of two coordination mechanisms operating upon one another. The third coordination mechanism of knowledge production and control (Whitley, 1984)—hitherto considered as external to the economy—is to be "endogenized" into the model of a knowledge-based economy, whereas only the two coordination mechanisms of markets and policies were needed for explaining phenomena in a political economy. Among three coordination mechanisms, however, synergy can be generated as a surplus of options on top of the aggregates of bilateral and unilateral contributions to the information flows. The institutional dynamics in networks generate variations (bottom-up). From a neo-evolutionary (top-down) perspective, the networks can alternatively be considered as retention mechanisms (Freeman & Perez, 1988).

Synergy is a second-order effect among the eigenvectors of a network based on and added to the first-order effects of networks among agents. Relations in a network are the (first-order) attributes of agents at the nodes. However, one can attribute second-order variables to the links (as first-order variables). The attribution of second-order variables to first-order variables implies an orthogonal (90°) change of perspective. In other words, relations in the first layer add up to a configuration. The

[1] Precursors for the Triple-Helix metaphor can be found in Lowe (1982) and Sabato (1975). Peter Healey informed me in March 2004 that he had used this metaphor at a meeting in Mexico in January 1993, but never published it. Note that a Triple-Helix model was the (erroneous) alternative of Linus Pauling for explaining the structure of DNA, as against the Double Helix proposed by James D. Watson and Francis Crick in 1953; Watson and Crick were awarded the Nobel Prize in 1962 (Leydesdorff & Etzkowitz, 2003; cf. Lewontin, 2000). Lewontin (2000) also used the TH metaphor in a biological context.

resulting network has an architecture with main axes. These main axes—principal components—are based on *correlations* among the distributions of relations and non-relations. However, correlations between each two distributions can be spurious on a third as a common factor in the background. For example, the relation between two parents will be changed when something happens to their child. Analogously, when universities file patents in addition to publishing, this may affect the weights of all the collaborative and competitive relations in Triple Helices.

As against the (neo)institutional approach, the (neo)evolutionary model does not focus on relations, but appreciates distributions of relations—including non-relations—evolving in a vector space constructed on the basis of *correlations*. Using the TH indicator, one is able to measure and compare the synergies generated in ranges of *possible* configurations. The quality of specific Triple Helices can then be measured in terms of the opportunities which are generated. In the next chapter (Chap. 6), I elaborate this measurement instrument as the TH indicator using the empirical example of regional and national innovation systems in Italy. Chapter 7 finalizes the empirical part of this study by developing the Triple-Helix synergy indicator to a methodology. A general-purpose computer program for the computation and comparison of synergies among subsets—available at https://www.leydesdorff.net/software/synergy.triads—enables the user to study whether synergy is generated in a complex dynamic in terms of which dimensions and/or at which scale?

5.2 From Dialectics to Triads

Evolutionary economics and technology studies emerged during the 1960s and 70s (Martin, 2012; Rakas & Hain, 2019). Until then, the economy had been analyzed mainly in terms of the dynamics of production factors such as labor, capital, and land. The contribution of technological innovation to economic growth was long held to be a residual factor—that is, the economic growth which remained otherwise unexplained (e.g., Abramowitz, 1956; OECD, 1964; Solow, 1957). In the 1970s, the "black box" of technology, innovation, and the economy (Rosenberg, 1982) was gradually opened by a school of scholars in evolutionary economics who have also been characterized as "neo-Schumpeterians" (e.g., Andersen, 1994; Freeman & Soete, 1997; Lee, 2013).

The reference to Schumpeter points, among other things, to his ([1939], 1964) distinction between technology-driven changes in the form of the production function reflecting the possibility to generate more output from the same economic input because of new technologies, *versus* factor substitutions along a production function based on relative changes in the prices of input factors (Sahal, 1981). Using the Cobbs-Douglas production function, the two mechanisms can be modeled as orthogonal to each other (Fig. 5.1).

Nelson and Winter (1977, 1982) provided a dynamic elaboration of Schumpeter's model in terms of natural trajectories, technological regimes, and selection environments. They added that selection environments can be both market and non-market.

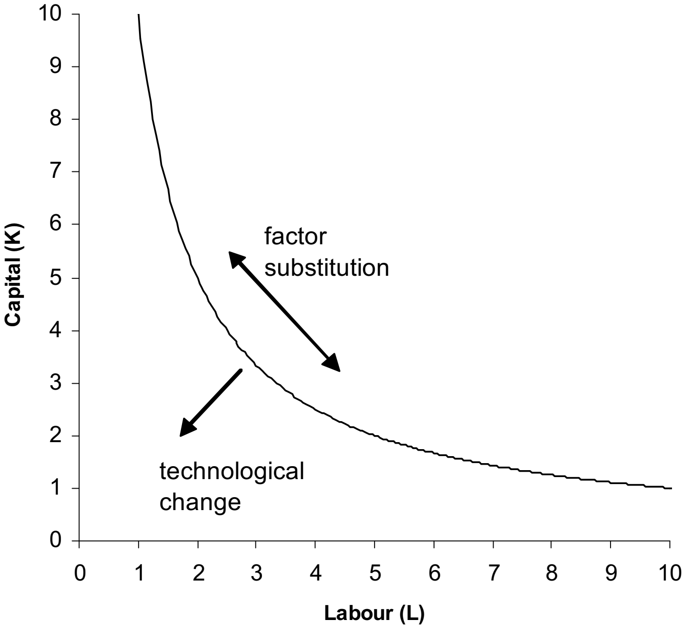


Fig. 5.1 Schumpeter's model of technological change as a shift of the (Cobb-Douglas) production function towards the origin *versus* factor substitution as a shift along the production function

In their evolutionary models, however, firms are the carriers of innovations and trajectories are endogenous to firms as routines (Nelson & Winter, 1982). Regimes (e.g., miniaturization) are assumed to be "natural," and thus not in need of being explained.

A broader perspective on the dynamics of innovation at the level of society was first formulated in Nelson & Winter's earlier (1977) study entitled "In Search of a Useful Theory of Innovation." The authors formulated (at p. 49) as follows:

> We are attempting to build conformable sub-theories of the processes that lead up to a new technology ready for trial use, and of what we call the selection environment that takes the flow of innovations as given. (Of course, there are important feedbacks.)

The feedbacks—provisionally bracketed—are part of a control system which can be managerial or political (Stafford Beer, 1984, 1989). Nelson & Winter chose to focus on *behavior* of firms and not in terms of expectations and opportunities. However, firms are phenotypical and cannot evolve; they can develop a life-cycle in history. Andersen (1992) suggested that the question "what is evolving?" could have been made more focal to the analysis in evolutionary economics (cf. Boulding, 1981). I shall come back to this problem in a later chapter.

Focusing on governmental control and national innovation policies, Freeman and Perez (1988) formulated a dialectical model of long waves in the development of techno-economic paradigms (on the basis of key-factors in the economy) *versus* the need of structural adjustments at the institutional level. Nations (or regions) can, for example, compete in terms of these institutional adjustments. In this model, however, the "key factors" remain external drivers of the innovation dynamics; as "manna from heaven."However, Nelson and Winter (1977, 1982) had called for models that would *endogenize*—i.e., explain—technological innovations and not assume technological developments as a consequence of external factors.

The various models in this neo-Schumpeterian tradition have in common that *two* dynamics are almost always postulated as an evolutionary model: (i) adjustments with reference to an equilibrium—Marx's "exchange value" and Schumpeter's changes in factor prices—and (ii) the generation of innovations upsetting the tendency towards equilibrium—Marx's "use value" and Schumpeter's shift of the production function toward the origin. In the TH model organized knowledge production is considered a *third* dynamic in addition to and in interaction with market coordination and political control. In general, a third dynamic makes a system "complex" and thus potentially non-linear, so that trajectories and regimes, emergence, lock-in, etc., can be specified.[2]

5.3 The Knowledge-Based Economy

Whereas wealth generation and governance are inherent constituents of political economy, the study of the knowledge-based economy includes the additional dynamics of novelty production and innovations. The three selection environments operate with different selection criteria. For example, patents provide legal protection of intellectual property along the governance axis of regulation and legislation, while patents can also be considered as input to the economy or output (like publications) for academia. In sum, the same events—in this case, portfolios of patents—can have different meanings with reference to each of these three selection environments (Fig. 5.2). Furthermore, the trilateral interactions among the bilateral ones can be expected to provide an emerging feedback on the constituent helices and their mutual interactions.

How can interactions among three *bilateral trajectories* shape a phase transition to a *trilateral regime*? In his book entitled *Investigations,* Stuart Kauffman (2000, at p. 258) suggested that "by mere constructive interference" the various trajectories may resonate into a phase transition about which "one can hope" that it will provide evolutionary advantages. However, such an interference remains a coincidence happening in history. Chance processes generate variations; selections are structural—based on criteria—and deterministic.

In the neo-evolutionary version of the TH model proposed here, the next-order regime develops on top of the historical trajectories with another logic that is not historical but evolutionary. The regime first emerges as a feedback harmonizing the

[2]In Leydesdorff & Van den Besselaar (1998), for example, we simulated the emergence of trajectories and regimes within the framework of Schumpeter's production function (cf. Dolfsma & Leydesdorff, 2009; Leydesdorff, 2006).

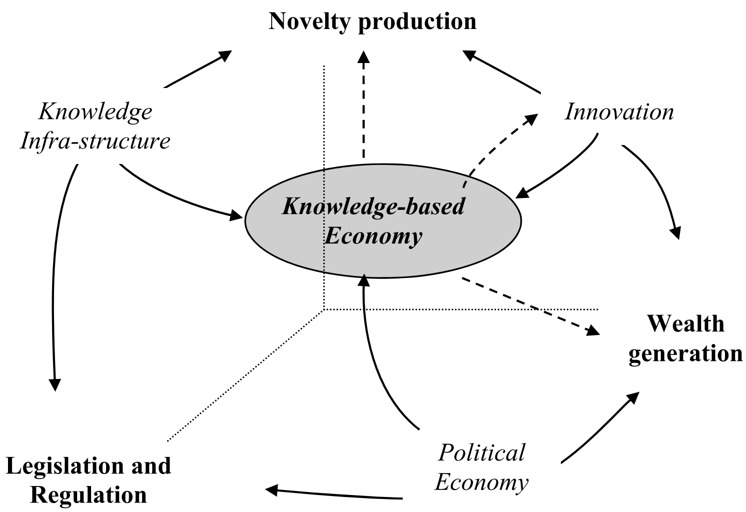


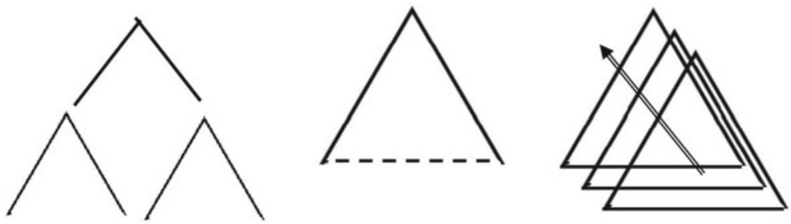
Fig. 5.2 The first-order interactions generate a knowledge-based economy as a next-order system. *Source* Leydesdorff (2010, at p. 379)

trajectories into an innovation *system*—as different from a sum total of sub-systems and with the capacity to process more complexity than the sum of its constituent trajectories. A three-way interaction term is added. However, unlike a "natural" regime—e.g., the cycles of the seasons—a technological regime can continue to interact (in feedback loops) with the trajectories on which it rests. Being not alive, a technological regime can only be reproduced by being reconstructed.

In other words, the regime of a knowledge-based economy does not "exist," but such a regime can be considered as a structure of expectations. The regime adds to the selection pressure by providing the option of globalization at a next-order (that is, relatively global) level. The global dynamics selects on historical stabilizations; stabilizations provide second-order variation and globalization provides second-order selection. In other words, the dynamics of triads are dually layered: both the variations and selection mechanisms can interact.

5.4 Triads and Simmelian Ties in Triple-Helix Configurations

Triads can be either cyclic or transitive (Batagelj et al., 2014, pp. 53f.). Transitive triads—"the friends of my friends are my friends"—are open, while cyclic triads can be closed as a *system* of relations. In general, triads are the building blocks of systems (Bianconi et al., 2014); all next-order forms of organization (quadruplets, etc.) can be decomposed into triads (Freeman, 1996).



Transitive triads can shape hierarchies	Closure of a transitive triad can lead to a cyclic triad	Cycling of the triad generates redundancy and closes the system

Fig. 5.3 Transitive and cyclic triads

Transitive triads are based on relations and can be aggregated into hierarchies (as in a dendogram; see the left-hand panel of Fig. 5.3). Cyclic triads can shape the axes of helices by incorporating potential disturbances generated by relations (the right-hand panel of Fig. 5.3). The cyclic rewrites generate redundancies. The panel in the middle of Fig. 5.3 is intended to illustrate the stochastic possibility of closure in a triad, when more links become available.

University-industry-government relations shape networks in which both dyads (e.g., university-industry relations) and triads can be expected. The sociologist Simmel argued already in 1902 that the transition from a group of two to three is a qualitative one: another awareness of space becomes available. In a triplet, the realization of one or the other relation may make a difference for the further development of the triad *as a system.*

According to Simmel (1902), a dyad remains a private relation; the triad introduces "sociality": each third person can watch the other two and thereby have the advantage of the *tertius gaudens* ("the third who benefits"); that is, the third person may see options in the relations between the other two which s/he can use to her advantage. If the third person actively participates in breaking the tie between the other two, one can consider this as an instance of *divide et impera* ("divide and rule").

The operationalization of these dynamics in terms of social networks was first pursued by Burt's (1992) theory of structural holes. Structural holes in network configurations enable agents to harvest advantages in specific configurations. For example, agents positioned between cliques may provide the only way to move from one cluster to another. Thus, the concept of structural holes is related to betweenness centrality (Freeman, 1978/1979). In the case of a structural hole, an agent between two other agents can induce competition between the latter two and thus reap the benefits; for example, by providing a "weak link" (Granovetter, 1973, 1982).

Krackhardt (1999) argued that Burt's theory of structural holes is about the dynamics of interacting dyads, whereas Simmel had meant to focus on how *triads* contain more capacity than the sum of the interactions among dyads. As Krackhardt formulated:

> In his [Simmel's] view, the differences between triads and larger cliques were minimal. The difference between a dyad and a triad, however, was fundamental. Adding a third party to

> a dyad completely changes them, but […] the further expansion to four or more persons by no means correspondingly modifies the group any further (Simmel, 1950, p. 138).

Krackhardt (1999, p. 186) then defined a "Simmelian tie" as follows:

> Two people are 'Simmelian tied' to one another if they are reciprocally and strongly tied to each other and if they are each reciprocally and strongly tied to at least one third party in common.

A triad of Simmelian ties is cyclic. As transitive triads can shape hierarchies by relating relations into orders, cycles can operate in parallel and thus be hierarchical (Kontoupolos, 2006). In a social system, these processes can occur concurrently and may disturb one another. The self-organizing selection environments tend to *differentiate* horizontally under the selection pressure of the regime, while institutional organization and agency are based on *integrations* among the dimensions at specific moments of time. The loops may bring a system into fruition by adding redundancy—that is, by providing structural room for new options—or lead in the opposite direction to lock-in and historical stagnation (Ulanowicz, 2009).

The constructed "genotypes" are not to be reified into a meta-biology; they remain knowledge-based constructs in a process of being rewritten. This model is "*neo*-evolutionary" because the status of the selection(s) in these environments is different from Darwin's "natural" selection. The selection environments (in the plural!) are knowledge-based; the criteria are socially constructed. The more the "genotypes" can differ in terms of their functionalities, the more complexity can be processed. The analytically expected tendency is towards an orthogonal spanning of horizons of meaning by different codes in the communication. However, this evolutionary process is constrained because one of its subdynamics has to remain on the ground in order to host also the historical variations and stabilizations as among its subdynamics (Bathelt, 2003).

In this TH model, the helices are no longer pictured as wrapped along a common axis, but they are opened up as three dimensions of a vector space (see Fig. 5.2) containing many more options than can be realized. Whereas relations operate historically at specific moments (or during periods) of time, the hypothesized structures operate in a vector space generating redundancies (against the arrow of time).

5.5 The Generalized TH Model of Innovations

In the TH model, the dynamic of *innovations* is first carried by the institutional dynamics among the agents (universities, industries, and governments) whose relations are institutional and observable. However, the dynamics of innovation are based on options provided by interactions *among the communications* of these agents. In network terms, not the nodes but the links operate. This second-order dynamic of interacting communications (links) builds on the first-order dynamic of relations among agents (nodes). It is not the agents who are interacting in the innovative process at this next-order level, but the distributions of their relations and non-relations (e.g., the distribution of competencies or geographical addresses). These distributions cannot be attributed to individual agents! A second-order dynamics among the links is thus overlaid on the first-order one of links among the carriers.

The non-linear model contains the linear one on which it builds as one of its subdynamics (Goguen & Varela, 1979; Maturana, 2000). The loops generate feedbacks on the linear flows or, under specifiable conditions, also feedforwards. What is variable and what is structural (and thus selective) is not prescribed and may change over time. However, a second-order model (of interactions among the attributes of links on top of the interactions among the nodes) can no longer be *micro-founded* on agency (the *homo economicus*), as is required in economic models.

Lundvall (1988) noted this complication for the micro-foundation of his model of national systems of innovation and proposed to "micro-found" the model on "interactions" (that is, links) instead of agency such as entrepreneurship at the nodes. However, Lundvall did not elaborate the second-order interactions among first-order interactions into an evolutionary model of trajectories and regimes. Instead, he advocated a focus on the nation as a common (institutional!) environment allowing for *learning*. Others advocated for using regions or sectors as "innovation systems" (Carlsson, 2006).

In my opinion, a priori delineations of "innovation systems" are begging the question. Whether a system is innovative or not is an empirical question. The delineation of an innovative system may be very different from administrative delineations, and optimal delineations may change over time. The micro-level dynamics is always participating in the systems dynamics, but not necessarily in a foundational role. Even if entrepreneurs were foundational in generating the system historically, the system's dynamics can be expected to change during its further development. After the initial phase, one is no longer able to control non-linear dynamics at the level of individual agency (Callon, 1986; Luhmann, 1997).

Whether an innovation system is national, regional, entrepreneurial, sectorial, or technological cannot be decided *ex ante*. As noted, these remain empirical questions. What is crucial in the TH model is the extension of economic and policy analysis with attention to the cognitive dynamics between discursive and individual knowledge. The objective is to endogenize the cognitive dynamics. However, the delineation of the cognitive, economic, or political system can be different. From the systems perspective of an evolving knowledge base, the observable networks show only the retention at specific moments of time; one can observe the de-selected cases and follow their history. But "history-friendly" simulations (Malerba et al., 1999) and "stylized facts" are not sufficient for the specification of selection mechanisms. Single case studies or comparative studies cannot carry an inference about the dynamics at the systems level. As noted, selections operate on distributions of cases, and not on individual cases.

How can an evolutionary model of innovation with three dynamics be constructed? In non-linear models of innovation, feedback arrows can first be added to the linear models of technology push (from supply to demand) and of demand pull in the reverse direction (from demand to supply). As noted, Nelson and Winter (1977)

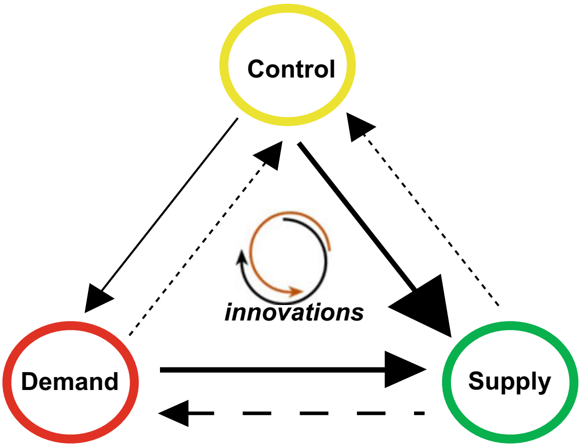


Fig. 5.4 The generalized Triple-Helix model of innovations. *Source* Further development from Petersen et al. (2016, Fig. 1, at p. 667)

mentioned the importance of feedback terms. Kline and Rosenberg (1986) proposed a "chaining model" with such feedbacks. Unlike a linear channel between supply and demand, however, relations based on feedbacks are no longer fixed and given; they become adaptable. When the feedbacks become increasingly important, they may drive the system over a threshold of generating more redundancy than information and induce the need for reconstruction. The control mechanism of feedbacks then becomes another (third) dimension (Stafford Beer, 1984, 1989). The driving force in one phase (e.g., a new technology or a specific market) can become a dependent variable after a bifurcation (Phillips, 2016).[3]

Figure 5.4 illustrates how feedback and feed-forward arrows can interact and thus shape a mechanism of control operating alongside supply and demand. The emergence of a control system follows when the feedback and feed-forward arrows increasingly interact among themselves. When a forward arrow in Fig. 5.4 represents variation, the corresponding arrow in the opposite direction indicates selective feedback. Different sources of variation are interacting, along with the different selection mechanisms. The cycles remain fragile and can be interrupted, broken, reversed in their order, and recombined.

Combining a technological opportunity with a market perspective, for example, may generate an invention. *However, the market has to operate as a selection environment before an invention can be turned into an innovation.* In general, knowledge-based innovations can emerge from horizontal, vertical, or even diagonal (re-)combinations of technological advances, market perspectives, and geographic endowments and constraints (e.g., Arthur, 2009; Mowery & Rosenberg, 1979). Once sufficient triads are closed, a technology can enter the regime phase on the basis of the dynamics among triads.

[3] The mere fact that variables are both dependent and independent over time does not imply that the system is non-linear. The two variables can have linear effects on one another with a perfectly predictable outcome over time (Wouter de Nooy, personal communication, 2 December 2019).

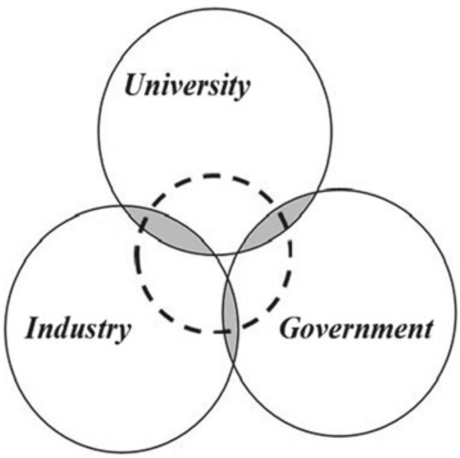
A triangle can be tipped clockwise or counter-clockwise. The two rotations (depicted as cyclic arrows in the center of Fig. 5.4) precondition each other as local organization and global self-organization; networks instantiated at the organizational level provide stepping-stones and retention mechanisms for the self-organizing dynamics of the selection environments; and vice versa, the selection environments can be expected to adapt evolutionarily to opportunities provided in the historical layer.

In Etzkowitz and Leydesdorff (2000), we considered this emerging network of communications among the three subdynamics (the dashed circle in Fig. 5.5) for the first time as a "communication overlay." However, this additional dynamic was not further specified at the time. The overlay provides an emerging (and therefore fourth) selection environment on top of the three institutionally carried functionalities of wealth generation (by industry), novelty production (in academia), and political control (by governments). In summary: the overlay operates on top of and in interaction with the carrying dynamics as another (trilateral) feedback. The possibility of a Quadruple Helix is thus endogenous to a Triple Helix (Fig. 5.6); inductively, all next-order helix-models follow as another recursion of this transition.

If one imagines the dashed circle (in Fig. 5.5) as hovering above the plane, one can envisage the four subdynamics as organized in a tetrahedron (Fig. 5.6). The "hovering circle" of Fig. 5.5 is represented as a fourth circle that in time comes to enjoy a similar status as the other three circles. The arrow of genesis is thus incorporated as a *sub*-dynamic during the morphogenesis of the system. However, the evolutionary dynamic can be expected to overwrite the historical one.

A tetrahedron (Fig. 5.6) can be tumbled in all directions so that all four (that is, three plus one) perspectives can equally become dominant; for example, during the different periods of a cycle. The four resulting communication overlays can operate upon one another and shape a "fractal manifold" (Ivanova & Leydesdorff, 2014). All the hierarchies among them are historical and transient. Co-evolutions in the

Fig. 5.5 "Communication overlay"



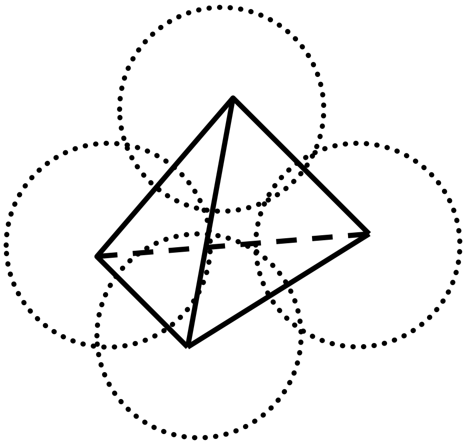


Fig. 5.6 Tetrahedron of three communication systems with an overlay

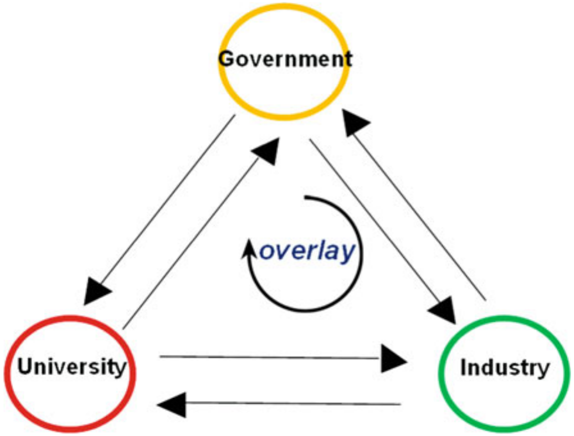
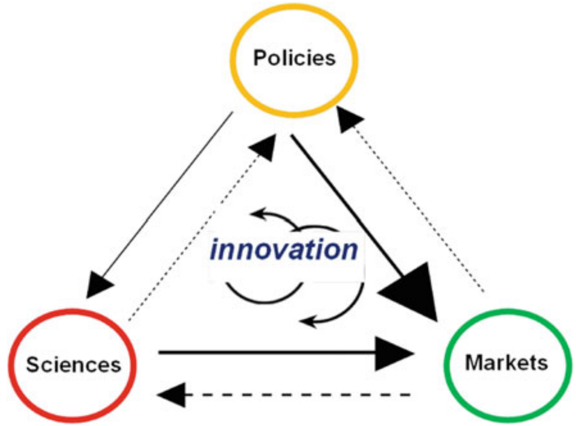
bilateral arrangements along trajectories can be broken open (at all times and scales) by a third perspective along each side of a triangle. The resulting manifold is a scale-free fractal because it develops at a next scale in terms of new, but potentially disruptive opportunities. Since fractals build on fractals, this order of expectations remains fragile, while drifting towards the edge of chaos. Disruptions can be expected to generate avalanches of all sizes (Bak & Chen, 1991; cf. Leydesdorff et al., 2018).

5.6 Institutional and Evolutionary TH-Models

The institutional and neo-evolutionary TH models are related in terms of the topics under study that they seek to explain; for example, the emergence of new options (Padgett & Powell, 2012). The institutional TH model focuses on relations (Storper, 1997; cf. DiMaggio & Powell, 1983). From the neo-evolutionary perspective, however, the relations are first-order attributes to the nodes, whereas interactions among the relations in a triadic (or more-dimensional) configuration can lead to a second-order dynamics among the attributes. Table 5.1 summarizes the differences between the institutional and the neo-evolutionary TH models.

The institutional TH model shares with models in the neo-institutional literature (e.g., DiMaggio & Powell, 1983) a focus on the networked *relations* between and among the institutions. From this institutional perspective, the evolutionary perspective can also be considered as focusing on "institutional logics" (Cai, 2014; Thornton, Ocasio, & Lounsbury, 2012) or as a "categorical imperative" (Zuckerman, 1999). However, these other terms designate similar mechanisms. Let me emphasize that "genotypes" cannot be specified on the basis of historical instantiations of these "genotypes" as phenotypes. Such a confusion might lead to historicism (Popper, 1967).

Table 5.1 Summary of the differences between the institutional and evolutionary TH models

	
• 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)

The institutional and evolutionary models are different in terms of the theoretical perspectives. Most importantly: the units of analysis are agents in an institutional model, and innovations as recombinations in a neo-evolutionary one. As Casson (1997) noted, an institutional model of innovation leads eventually to a focus on entrepreneurship. Indeed, the focus in the literature based on the institutional TH model has shifted gradually from innovations to the study of "academic entrepreneurship" and the "entrepreneurial university" (e.g., Etzkowitz, 2002 and 2016). Typical research questions from this perspective include descriptions of graduates who begin startups; university professors who change their perspective from academic to industrial; or transfer agencies and incubators analyzed in terms of their efficiency. Policy advice about improving institutional conditions can then also be provided. Improving the conditions at one place, however, may have unintended consequences at another since a non-linear dynamic is operating at the next-order (regime) level.

The neo-evolutionary TH model assumes that innovation can be considered as a second-order outcome of interactions among communications. The next-order dynamics are based on interactions among *selection mechanisms* at the system level. From such a neo-evolutionary perspective, one can expect both intended and unintended consequences of any policy specified in terms of the means-ends logic of the linear model. The unintended consequences are likely to outweigh the intended ones. In my opinion, evaluation should focus on these unintended effects because one can learn from them about the non-linear dynamics of innovations operating on top of the linear flows.

The two models differ most importantly in terms of their methodological orientations. While in the institutional model the focus is on networks of relations which can be studied as observable graphs. The neo-evolutionary model is factor-analytic—as opposed to graph-analytic—and based on studying matrices including cases which could have been expected but did not happen. The structural properties of networks develop along axes that provide specific meanings to the information. Since selection is deterministic, selection mechanisms *determine* what in the variation can be considered as a signal and what as noise. In my opinion, the specification of these selection mechanisms (as hypotheses) has theoretical priority.

5.7 The Measurement of Triple-Helix Configurations

The TH indicator (derived in Chap. 4) provides a quantification of the balance between bi- and trilateral relations among universities, industries, and governments (Leydesdorff, 2003; Park & Leydesdorff, 2010; Ulanowicz, 1986). Mutual information among three or more dimensions—follows from the Shannon formulas (see Eq. 4.8; Abramson, 1963; McGill, 1954; Yeung, 2008). The measure T_{123} can be formulated as follows:

$$T_{123} = H_1 + H_2 + H_3 - H_{12} - H_{13} - H_{23} + H_{123} \tag{5.1}$$

It was shown in Chap. 4 that mutual redundancy is equal to mutual information *in the three-dimensional case*: $R_{123} = T_{123}$. In the two-dimensional case, however, $R_{12} = -T_{12}$. The change in the signs may seem confusing—Weaver (1949) considered the Shannon definitions as "bizarre" and counter-intuitive—but in order to maintain consistency with Shannon's information theory, redundancy generated in TH configurations has a negative sign (see Chap. 4 for the relevant derivations).

In the next chapter, I use the TH indicator for testing assumptions about the Italian innovation system; but let me first introduce the indicator here by providing two empirical examples using the tool straightforwardly for descriptive statistics:

1. Taking publications as units of analysis, one can count the institutional addresses of authors provided in the by-lines as "university" {*u*}, "industry" {*i*}, or "government'{*g*} and any of the possible combinations {*ui, ug, ig, uig*} (Leydesdorff, 2003). When for example, an academic and an industrial address co-occur in the by-lines of a single document, this can be counted as a university-industry relation. Thus, one obtains seven categories {*u*,*i*,*g*,*ui*,*ug*,*ig*, and *uig*}; an eighth empty category {0, 0, 0} can also be included. Figure 5.7 shows the results of such an analysis for all the publications in the *Social Scioences Citation Index (SSCI)* and the *Arts and Humanities Citation Index (A&HCI)* with at least one Korean address during the period 1968–2006 (N = 190,196; Park and Leydesdorff, 2010).
2. Using Storper's (1997) metaphor of a "holy trinity of technology, territory, and organization," three variables can be specified as attributes of firms: technological classes, geographical addresses, and organizational formats. One can study the interactions among these three dimensions as indicators of the knowledge base of

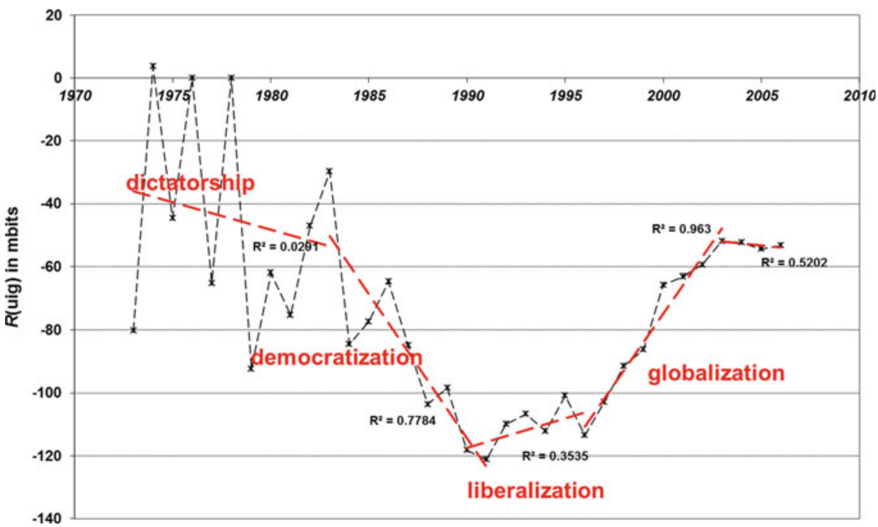


Fig. 5.7 The development of mutual redundancy in South Korean university-industry-government relations during the dictatorship and the periods of democratization, liberalization, and globalization, respectively. *Source* Elaborated from Park and Leydesdorff (2010, at p. 645)

regions and nations. This is introduced here for the case of Sweden and elaborated in the next chapter for Italy.

5.7.1 Synergy in Co-authorship Relations in South Korea

Figure 5.7 shows the long-term development of new options in the social sciences and humanities literature with an institutional address in South Korea, using mutual redundancy as the TH synergy indicator. Publications were first evaluated manually in terms of university-industry-government co-authorship relations. The units of analysis are documents to which different institutional addresses are attributed as academic, industrial, or governmental. Mutual information and redundancy is based on co-occurrences among these three TH categories.[4]

Figure 5.7 shows the results. Whereas the South-Korean system was originally hierarchical and state-controlled, the dictatorial regime relaxed gradually in the 1970s. This tendency was strengthened during the period of democratization during the 1980s. When the status of a more advanced economy was reached, the pendulum in the balance between uncertainty and redundancy generation swung back. Korea entered the world market increasingly, leading to full OECD membership in 1996.

In this later period, internationalization of the research system tended to *uncouple* the self-organizing publication system operating internationally from the national level (Wagner, 2008, 2018). Whereas the discourse in these social-science publications was strongly integrated nationally during the dictatorship, new options became available with democratization. In the more recent period of globalization and internationalization, mutual redundancy consequently decreased in absolute value (or, in other words, became less negative). Communication became more efficient with globalization, or, in other words, less redundant.

The indicator measures a trade-off between institutional retention and self-organized expansion. The example shows that what retention and expansion mean is system-specific. In an innovation system one aims to retain wealth from knowledge, while in a publication system uncoupling from national integration can show the very different dynamic of internationalization.

5.7.2 Synergy in Innovation Systems across Sweden

Retention of wealth from knowledge assumes the development of synergy in TH relations. Which regions or sectors contribute most to the generation of options? I introduce this design here using Swedish firm data as an example, but elaborate further on this methodology in the next chapter for the case of Italy.

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[4] A routine is available at https://www.leydesdorff.net/th/th.exe where one can feed in the values for each of the seven categories and obtain as a result the value of T_{uig}.

The complete set of firm data for Sweden was obtained from Statistics Sweden in November 2011; $N = 1{,}187{,}421$. This micro-data contained address information in terms of 290 units at the lowest (NUTS5)[5] level of municipalities, a technology classification into 21 classes,[6] and nine classes of numbers of employees which allowed us to distinguish between small, medium-sized, and large companies (Leydesdorff & Strand, 2013, p. 1894, Table 5.2).[7] One thus obtains a data array in three dimensions in which each cell value indicates the number of co-occurrences between technological classes, geographical addresses, and size categories. Using the margin totals, one can derive bilateral relations; Eq. 5.1 can be used for the computation of synergy values at different geographical scales (using the NUTS hierarchy of the OECD/Eurostat).

Figure 5.8 shows the results for the 21 counties in Sweden at the NUTS-3 level of so-called counties. I chose Sweden as an example for didactic reasons: the results accord in this case with the literature and with common intuition. Mutual redundancy is largest 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 48.5% of the summed redundancies of the regions at this geographical scale (NUTS-3).

The between-group redundancy (R_0) among the 21 counties can be used as a measure of the synergy among regions.[8] A negative value of R_0 indicates an additional synergy at the next level of national agglomeration among the lower-level units. Although the values in bits of information are sample-specific, one is allowed to compare the indicators as percentages of contribution to the synergy at different levels (Table 5.2).

Table 5.2 (bottom line) shows that the surplus of the national system in Sweden 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

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[5] *NUTS* is an abbreviation for *Nomenclature of territorial units for statistics*, a system developed and maintained by EuroStat.

[6] 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 https://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.

[7] 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 https://www.leydesdorff.net/software/th4. This software computes the TH indicator R_{ijk} and all the two-dimensional and one-dimensional components.

[8] Analogously to the decomposition of probabilistic entropy (Theil, 1972: 20f.), mutual redundancy in three (or more) dimensions can be decomposed into groups as follows:

$$R = R_0 + \sum_G \frac{n_G}{N} R_G \tag{2}$$

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).

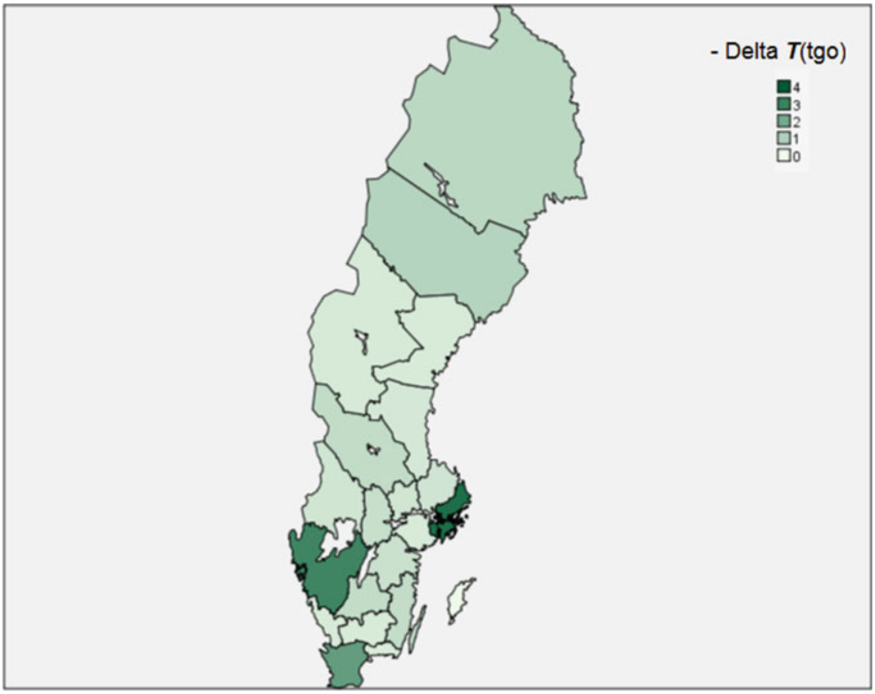

Fig. 5.8 Percentages of contributions to redundancy at the level of 21 Swedish counties (NUTS-3)

Table 5.2 Between-group synergy at different geographical scales in the Swedish innovation system

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

Source Leydesdorff and Strand (2013)

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 indicated. 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 summary, the Swedish national system is organized hierarchically, as indeed is suggested by most of the literature about Sweden.

5.8 Discussion

In a series of studies—usually co-authored with colleagues from these nations—a number of national systems of innovation were thus analyzed and the results were decomposed in terms of both regions and technological sectors: Germany (Leydesdorff & Fritsch, 2006; Ruhrmann et al., under review), the Netherlands (Leydesdorff, Dolfsma, & van der Panne, 2006), Sweden (Strand & Leydesdorff, 2013), Norway (Strand & Leydesdorff, 2013), Italy (Leydesdorff & Cucco, 2019), Hungary (Lengyel & Leydesdorff, 2011), Spain (Leydesdorff & Porto-Gomez, 2019), the Russian Federation (Leydesdorff, Perevodchikov, & Uvarov, 2015), the USA (Leydesdorff, Wagner, Porto-Gomez, Comins, & Phillips, 2019),and China (Leydesdorff & Zhou, 2014).

In the cases of the Netherlands, Norway, Sweden, and China, for example, 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 Germany, however, most of the synergy was found decentralized at the level of the federal states (*Länder*).

In Norway, foreign-driven investments in the marine and maritime industries along the west coast 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 has been 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.

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

Analogous to this relative "foot-looseness" (Vernon, 1979) in the case of KIS, one can also expect uncoupling in the case of high-tech knowledge-based manufacturing. However, the expectation is very different for medium-tech manufacturing, because in these sectors 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 integration within a given region. High-tech knowledge-intensive services, however, may require a laboratory. One would expect medium-tech manufacturing to be embedded and thus to generate more employment than high-tech.

In summary, the various country studies show that patterns can be very different among nations as well as among regions within nations (e.g., Yoon & Park, 2016). Furthermore, one can expect the dynamics to be different at the system's level between the sciences and markets: in publication systems, uncoupling and international (that is, non-localized) orientations 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.

This 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-intensively tend to induce globalization, including volatility. 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. Since the dynamics are complex, the results can be counter-intuitive, and raise further questions. The a priori categories attributed to innovation systems—such as national, regional, etc.—can be considered as hypotheses to be tested and refined.

In a recent study of synergy in the Spanish system, for example, Andalucia as a region (at the NUTS2 level) did poorly in generating mutual redundancy, whereas Seville as the capital of this region (NUTS3) showed a different pattern (Leydesdorff & Porto Gomez, 2019). Indeed, one of the objectives of these studies is to test, revise, and inform the categories used for making assessments. Are regions the appropriate unit of analysis? In the next chapter, I focus on the Italian innovation system using this instrument.

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