Synergy in Knowledge-Based Innovation Systems at National and Regional Levels: The Triple Helix Model and the Fourth Industrial Revolution

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Abstract

Different from national systems of innovation, a knowledge-based economy is grounded in the volatility of discursive knowledge enabling us to specify expectations. Expectations can be improved by testing against observations. Furthermore, expectations can differently be codified; for example, in terms of market perspectives and technological opportunities. The Triple Helix of university-industry-government relations provides first a (neo-)institutional model. However, three functions are recombined at the systems level in each instantiation: wealth generation (by industry), novelty production (academia), and legislation and regulation (government). The Triple-Helix synergy indicator enables us to use the institutional arrangements as instantiations of the knowledge-dynamics and thus to assess the generation of options and reduction of uncertainty in information-theoretical terms. The Fourth Industrial Revolution entails the transition to the reflexive entertaining of expectations in terms of models as increasingly the sources of innovations.

Keywords: triple helix, innovation systems, reflexive turn, expectation, synergy

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Introduction

The Fourth Industrial Revolution (Schwab, 2015) provides a new metaphor replacing older models such as "National Systems of Innovation" (NSI), the "Knowledge-Based Economy" (KBE) and the "Triple Helix of University-Industry-Government Relations" (TH), but hitherto without further theoretical elaboration. The metaphor of NSI emerged in the 1980s; KBE elaborates on NSI from an evolutionary perspective (David & Foray, 2002), whereas the TH can be considered as an institutional elaboration (Etzkowitz & Leydesdorff, 2000). In this study, I propose to further develop the TH into an evolutionary model.

The thesis of NSI combines the claims that innovation is systemic (Lundvall, 1988), that innovation systems are evolving (Nelson, 1993), and that they are organized institutionally, and therefore influenced by and susceptible to government policies at national or regional levels (Freeman, 1987 and 1988; Freeman & Perez, 1988). NSI thus seeks to combine the perspectives of policy analysis, institutional analysis, and (neo-)evolutionary theorizing. However, the metaphor is delusive: innovation is not taking place within administratively bordered nations and innovation is not necessarily systemic.

Sahal (1985, at p. 64), for example, distinguished among (*i*) *material* innovations "that are necessitated in an attempt to meet the requisite changes in the criteria of technological construction as a consequence of changes in the scale of the object," (*ii*) *structural* innovations "that arise out of the process of differential growth whereby the parts and the whole of a system do not grow at the same rate," and (*iii*) *systemic* innovations "that arise from integration of two

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or more symbiotic technologies." As an example of a systemic innovation, the author points to the integration of office automation with computing during the 1950s and 1960s; with a leading role of IBM. More formally, one can distinguish innovations which deconstruct and reconstruct specific relations within a system from changes among clusters of relations at the systems level. The latter can change technological regimes, while specific relations are reconstructed along technological trajectories.

The assumption of NSI that innovation systems would be "national" originated from Freeman's (1987) report entitled "Technology and Economic Performance: Lessons from Japan" (see also: Yamauchi, 1986) about his visit to Japan. NSI and was embraced notably by scholars with a Scandinavian background who feared that specific qualities of their respective national innovation systems might suffer from integration in a larger European framework (Lundvall, 1988). However, the terminology of "national systems" generated resistance among scholars with a background in regions such as Catalonia and Wales claiming regional innovation systems (e.g., Braczyk, Cooke, & Heidenreich, 1998; Cooke, 2002), and at the supra-national level of the European Union where one favors terminology such as the "knowledge-based economy" (Foray & Lundvall, 1996; OECD, 1996).

The knowledge-based economy can be distinguished from a political or market economy as a systemic development made possible as a new regime after the demise of the Soviet Union in 1991 (e.g., European Committee, 2000). In a knowledge-based economy, organized knowledge provides a third coordination mechanism in addition to the market and political control. The focus on organized knowledge production and control (Whitley, 1984 and 2001) as a structural

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dimension of the economy emerged gradually during the late 19th and most of the 20th century. Marx ([1857] 1973, at p. 706) had hesitated whether science-based technological evolution might be an independent source of social wealth more than labor. Sahal (1985, p. 61) cites the young Marx' (1847) *Poverty of Philosophy* where he formulated as follows:

> The landmill gives you society with the feudal lord; the steam mill, society with the industrial capitalist (Marx, 1935, at p. 6).

After extensive study including calculations, however, the older Marx of *Capital I* (1867) concluded 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 repeated 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, Marx envisaged a regime change that would be different from and an alternative for the communist revolution.

Noble (1977, at p. 7) argued that "the major breakthroughs, technically speaking, came in the 1870s." In other words, after the publication of *Capital.* He dated what he calls "the wedding of the sciences to the useful arts" as the period between 1880 and 1920. (Braverman, 1974) 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.)

But the transition is gradual. While WW I has also been characterized as the war of chemistry and WW II as the war of physics, the return to a liberal democracy under peacetime conditions (Bush, 1945) led to a focus on economic models where science and technology were considered first as exogeneous factors of an economy which was conceptualized in terms of the dynamics of production factors such as labor, capital, and land. The component of growth due to technological progress was long held to be a residual factor which could not easily be explained (e.g., Abramowitz, 1956; OECD, 1964; Solow, 1957).

Theorizing about the role of technological knowledge (David & Foray, 1995; Foray, 2004) was elaborated in evolutionary economics by a school of scholars who have been characterized from the perspective of hindsight as "the neo-Schumpeterians" (Andersen, 1994; Freeman & Soete, 1997; Lee, 2013). Schumpeter ([1939], 1964) provided a model of technological change in which he distinguished between innovations as changes in the shape of the production function reflecting the possibility to generate more output from less input, and changes along the production function as factor substitutions (Sahal, 1981). In the Schumpeterian model, the two

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mechanisms stand orthogonally in terms of shifts along or perpendicular to the production function (Figure 1).

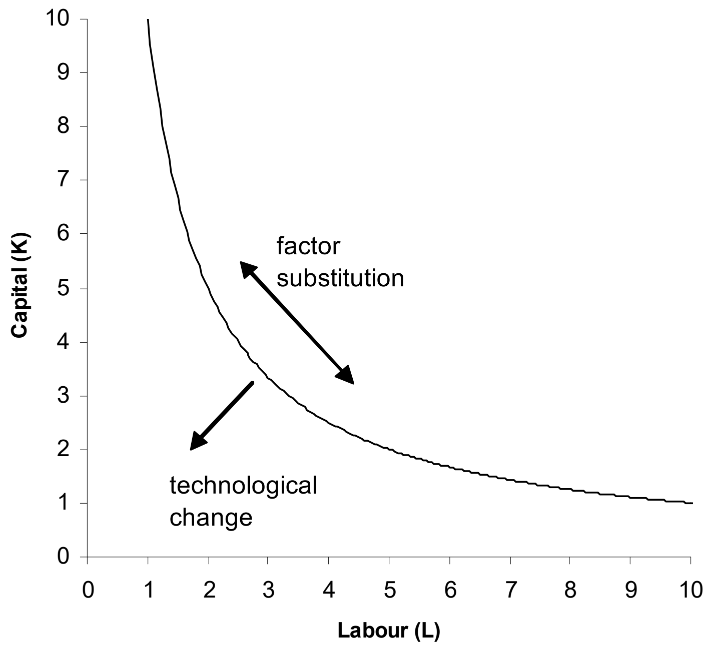

Figure 1: Schumpeter's model of technological change as a shift of the production function towards the origin unlike factor substitution as a shift along the production function.

In Nelson & Winter's evolutionary model (1977 and 1982), two other mechanisms were analytically distinguished: variation along trajectories versus selection mechanisms. These authors (1977, at p. 49) formulated their program of studies 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.)

Freeman & Perez' (1988), furthermore, elaborated a model of structural adjustments at the institutional level *versus* long waves in the technological evolution. This dialectic is reminiscent of Marx's distinction between production forces and production relations.

These various models have in common that *two* dynamics are postulated: adjustment with reference to an equilibrium, and the generation of innovation continuously upsetting the movement towards equilibrium. In processes of "mutual shaping" (McLuhan, 1964) between the two mechanisms, niches can be constructed as temporary and local suboptima. Note that the local suboptima in evolutionary economics are different from the global equilibria assumed in neo-classical economics.

From a dialectics to a trialectic

In the *Epilogue* to *Evolutionary Economics and Chaos Theory: New directions in technology studies* (London: Pinter, 1994), I argued in favor of introducing organized knowledge production as a *third* dynamic into the model in addition to and in interaction with market coordination and institutional control (Leydesdorff & Van den Besselaar, 1994, pp. 186f.). The third dynamic makes the model so "complex" and non-linear that trajectories and regimes, self-organization, emergence, lock-in, etc., can more clearly be defined (e.g., Leydesdorff & Van den Besselaar, 1998; Leydesdorff, 2006).

Henry Etzkowitz contributed a chapter to this edited volume entitled "Academic-Industry Relations: A Sociological Paradigm for Economic Development" (Etzkowitz, 1994, pp. 139-

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151). In this chapter, Etzkowitz described the development of MIT into an entrepreneurial university since the 1930s. In the summer of 1994, Henry and I met again at a workshop in Abisko (Sweden) and discussed a follow-up project which should combine his interest in university-industry relations and my interest in the dynamics of science and technology. In the email conversations following up on our exchanges, we developed the Triple Helix (TH) model of university-industry-government relations (Etzkowitz & Leydesdorff, 1995). This TH model was firmly anchored in both Etzkowitz's interest in institutional dynamics, on the one side, and elaborated on my interest in the operationalization of an evolutionary model of the knowledge-based economy in terms of three (or more) dynamics as different from two, on the other. Whereas a co-evolution in a double helix can stabilize because of "mutual shaping" between the two selection environments, a third dynamic can be expected to upset continuously this tendency toward equilibrium to the extent that such a system becomes unstable. From this perspective, equilibrium needs to be explained.

In an evolutionary theory of innovation, genotypes have to be distinguished from phenotypes (Hodgson & Knudsen, 2011). The genotypes operate as selection mechanisms on the observable (that is, phenotypical) variation. In the (neo-)institutional TH model, the institutional arrangements provide the variation, whereas selection mechanisms are genotypical and deterministic. The genotypes of non-biological systems, however, are not given as DNA—the observable code of biological evolution—but must first be specified (Langton, 1989).

Since non-biological selection is no longer "natural selection," more than a single selection mechanism can be expected to operate: market selection, technological selection, etc. (Oh,

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Phillips, Park, & Lee, 2016). The criteria for selection are based on (potentially different) codes constructed in the communication and developing in functionally different domains (Luhmann, 1995). Using another semantics, one can consider the selection mechanisms also as social coordination mechanisms. In the TH model, we focus on three of them: markets, sciences, and politics.

Nelson & Winter's (1978, 1982) distinction between market and non-market selection mechanisms can thus be generalized to selections in various dimensions. Since the selection mechanisms are not given but constructed, they can be expected to (co-)evolve by adapting to the complexity in the phenotypical variation (Ashby, 1958). With a reference to Hayami & Ruttan (1970), Nelson & Winter (1978, at p. 57) were also aware that selections can operate upon selections and thus drive hyper-selection (cf. Dosi, 1982): the trajectory of a technology provides a historical selection mechanism (stabilization) while developing along a life-cycle; the regime adds evolutionary selection (globalization). One needs a next-order systems perspective to "see" regime changes.

Thus, one obtains a system which is both vertically and horizontally differentiated: vertically, in terms of selections operating upon selections and thereby generating stabilizations and globalizations; horizontally, in terms of different functionalities (academia, industry, and government). However, the resulting construct should not be considered as an existing system; it remains a model as the codes are not biological codes, but codes of communication. Because of this volatility, the selections disturb one another continuously in different directions and at different levels so that the construct cannot be stabilized. One can recombine "infra-reflexively"

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(Latour, 1988) in different directions. Instead of a system, one can thus expect a "fractal manifold" (Ivanova & Leydesdorff, 2015) composed of interacting triple helices. (All higher-order helices can be decomposed in terms of triangles; (Batagelj, Doreian, Ferligoj, & Kejzar, 2014; Freeman, 1992). Such a construct does not "exist" as hardware—in the sense of the Latin *esse*—but we construct it as a model of latent genotypes using the phenotypes that we observe as basis and testing ground for making these inferences.

For example, Freeman & Perez' (1988) above-noted model of structural crises and adjustment mechanisms in the institutional dimension *versus* technological paradigms generating long-term cycles is based on the premise of rapidly falling prices in specific production factors. Each new regime is based on a crucial factor such as oil or, more recently, micro-electronics. In my opinion, it is not the observable micro-electronics as hardware or as a commodity which drives the cycle(s), but the possibility to absorb knowledge in the production system in terms of computer routines and computer power, facilitated and mediated by the use of micro-electronics. The material component of "micro-electronics" opens a window on the knowledge dynamics which itself remains ideational. The surplus of possibilities generated in the knowledge-dynamics can thus be appreciated and exploited.

When the knowledge dynamics is involved as a supra-individual coordination mechanism, "all that is solid, melts into air" (Berman, 1982; Marx, [1848], 1967). But the 19th century "air" is structured during the 20th century as the "hot air" of scholarly discourses de-coding and re-coding the knowledge bases of the economy (Rosenberg, 1982). Unlike air, one can expect this "hot air" to be structured at the above-individual level (Husserl, 1929): that is, as codes of communication. The codes provide the selection criteria; selection environments drive one another: horizontally as triple-helices and vertically because some selections are selected for stabilization, and some stabilizations are selected for globalization.

First, the information in the communications is provided with meaning and thus codified (Leydesdorff, Johnson, & Ivanova, 2018). The codes of the communication can symbolically be generalized. The cybernetic principle holds that the construction is bottom up (*genesis*) in history, but once constructed control (*validation*) tends to be evolutionary and top-down (Simon, 1973). For example, the market is not steered by individual transactions, but by more abstract market forces. The transactions provide the variation. Analogously, the sciences are not developing in terms of individual knowledge claims in manuscripts; the latter have to be validated in the light of theories. Social coordination mechanisms operating above the individual level contain the genotypes of society as the codes of the communications which they both select and enable to be specifically reproduced and proliferated (Giddens, 1984).

Symbolically generalized codes of communications can be considered as the eigenvectors of the communication matrix (Luhmann, 1974; Parsons, 1968). These eigenvectors can be spanned orthogonally shaping a vector-space of possibilities. Although this vector space is generated in terms of relations—action providing variation—the latent dimensions are not relational but based on correlations between distributions of relations. The next-order level can function as the selection mechanism structuring follow-up communications. Without horizontal differentiation, the center of control would tend to the top-level (selection → stabilization → globalization). In

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the fractal manifold of a pluriform society, however, this hierarchical tendency—monopolization—is continuously "broken" by network interactions (Williamson, 1975).

The generation of redundancy op top of the information flow

The TH was first defined in terms of links among universities, industries, and government(s) as institutional relations. However, an essential element of the TH thesis is that the relations among institutions have become knowledge-based and therefore grown into a network. In this constellation, institutions can substitute for each other's functionality to a certain extent. Universities, for example, can take entrepreneurial roles—for example, by creating incubators and science parks—industry can organize academic education and research, and public-private relations between industry and government can be redefined in the light of new technological options. The resulting overlay of relations and communications can develop a dynamic of itself (Etzkowitz & Leydesdorff, 1998). The evolution of these relations, however, is not yet endogenized in the institutionally specified TH model. Under which conditions does the TH dynamic generate a surplus? Note that a TH overlay also generates overhead. Each configuration could have been different and is by definition sub-optimal so that it can almost always be improved.

From an evolutionary perspective, the institutional arrangements provide the retention mechanisms of solutions that have served us hitherto as "best practices." The observable institutions and their relations—the empirical case studies—provide us with a window on the knowledge dynamics in the same sense but in the opposite direction as the micro-electronic

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devices discussed above. The windows on the knowledge-based dynamics open a perspective in the one direction and allow for the import of knowledge at the same time in the opposite direction. Can questions for further research be formulated? Synergy among improving wealth generation in industry, novelty production in academia, and regulation and control by governmental authority may enable the networks (the nations, the regions) to construct competitive advantages by recombining differently coded communications (Cooke & Leydesdorff, 2006). In my opinion, the complexity in the relations among the codes is evolving in the model generating new possibilities of expectations (Andersen, 1994).

The realizations provide the observable variation—which can be measured as information—whereas the not-yet-realized options provide redundancy—that is, possible realizations on top of the actual ones (Figure 2; Brooks & Wiley, 1986, p. 43). The sum of information and redundancy is by definition (Shannon, 1948) equal to the maximum entropy.

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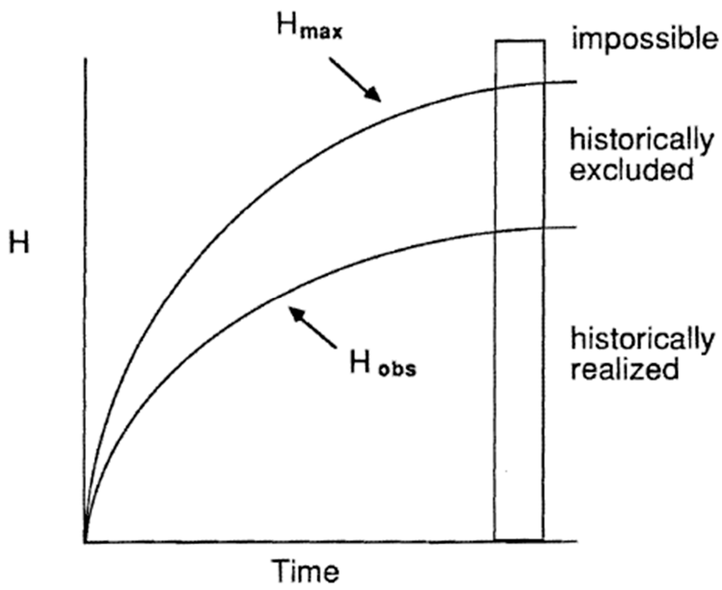

Figure 2: the development of information capacity, information content, and redundancy over time. Source: Brooks & Wiley, 1986, p. 43.

Redundancy is generated in triple-helix relations because of partial overlaps in providing different meanings to the events from political, managerial, and technological perspectives. Patents, for example, are inputs in the economy, but patenting is output from the academic perspective. Thirdly, patents warrant intellectual property against litigation in the court. The patent thus has a different meaning in these various contexts. Following a hypothesis of Herbert Simon (1973), one can assume that there is an alphabet of codes operating. However, knowledge-based innovations emerge from (re-)combinations of technological opportunities, market perspectives, and geographic endowments and constraints (e.g., Arthur, 2009; Mowery & Rosenberg, 1979). The differently coded communications are interacting among institutional carriers. Thus, a second-order dynamic of attributes to (first-order) communications is operating on top of the first-order dynamics of historical developments. The knowledge-based communications incur as possible reconstruction on the historical arrangement that develop

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along the arrow of time. Porter (1997, at pp. 29) assumed that an enormous leap in reflexivity has induced meta-capacities that can evolve faster than realizations at the institutional level.

Redundancy and the further perspective

In Shannon's (1948) *Mathematical Theory of Communication*, information is defined as probabilistic entropy (or uncertainty) and necessarily positive given the coupling to the Second Law of thermodynamics (Krippendorff, 1989). Whereas the Second Law states that uncertainty increases at the global level, pockets of negative entropy can occur locally when distributions resonate. These negative entropies can be considered as redundancies generated on top of the entropy flow as not yet realized options.

Negative information can only be generated in loops of communication generating a next-order layer in a non-linear model. Since redundancy is defined as the complement of the information to the maximum entropy, increases in redundancy lead to decrease of the relative information or, in other words, the uncertainty which prevails. The result is a net reduction of relative uncertainty, as in niches (Geels, 2002). Reduction of uncertainty, furthermore, can be expected to improve the climate for investments (Freeman & Soete, 1997, pp. 242 ff.).

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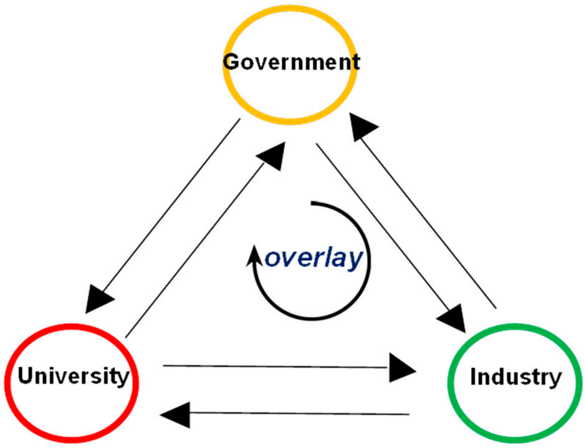	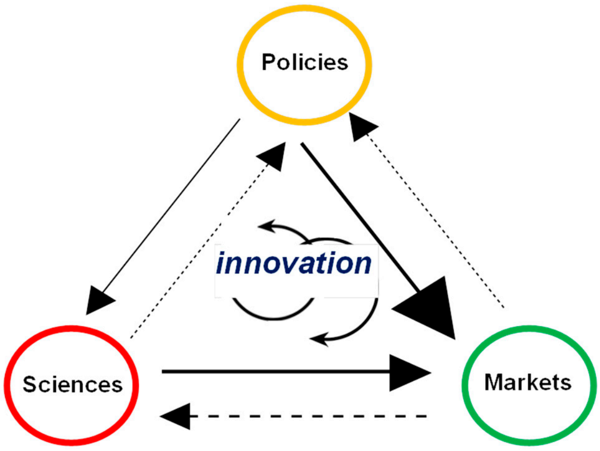
• University-Industry-Government relations • (Inter-)institutional • entrepreneurship (agents) • network analysis; graphs; • historical cases (*phenotypes*); • inductive: ➢ *best practices*; comparative case studies (e.g., Saad & Zawdie, 2011); ➢ Bottom-up (e.g., Li, Arora, Youtie, & Shapira, 2016); ➢ policy analysis (Etzkowitz, 2008; Etzkowitz & Zhou, 2018; 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. Source: (Leydesdorff, Ivanova, & Meyer, 2018)(Leydesdorff, Ivanova, & Meyer, 2018)

Table 1 summarizes the differences between institutional and evolutionary TH models. A first difference is the unit of analysis: in the institutional model this unit of analysis is agency; for example, entrepreneurship. Casson (1997) argued that an institutional perspective on innovation eventually leads to a theory of the firm; in the case of TH theorizing, this perspective is extended with theorizing about the university as a pseudo-firm potentially operating as entrepreneur on relevant (e.g., high-tech) markets (Etzkowitz, 2002).

Innovations are the units of analysis in the evolutionary model on the right side of Table 1. One can expect the relations among the agents to be reconstructed by innovations. Because of these rewrites of the relations, positions based on correlations of distributions of relations are affected. The historical case is one among possible ones; the historical trajectory, one among possible reconstructions. (Yet, these are the ones to which we have access in empirical research.) The range of possibilities has to be hypothesized and this specification is knowledge-based; it can only be improved by developing discursive knowledge. The hypotheses can be tested against observations: Are the cases that happened also significant? The quality of the models thus becomes distinctive for the further development of the economy and therewith for society at large.

In the linear model, innovation was first specified in terms of two dimensions: *technology push* versus *demand pull*. In non-linear models, feedback and feedforward arrows were added to co-determine longer-term developments. Relations were no longer fixed and given, as in a channel between supply and demand (Kline & Rosenberg, 1986). The driving force in one phase may become a dependent variable in a next one (Phillips, 2016). Figure 3 illustrates the feedback and feedforward arrows shaping a non-linear system that operationally develops a third dimension of control mediating between supply and demand.

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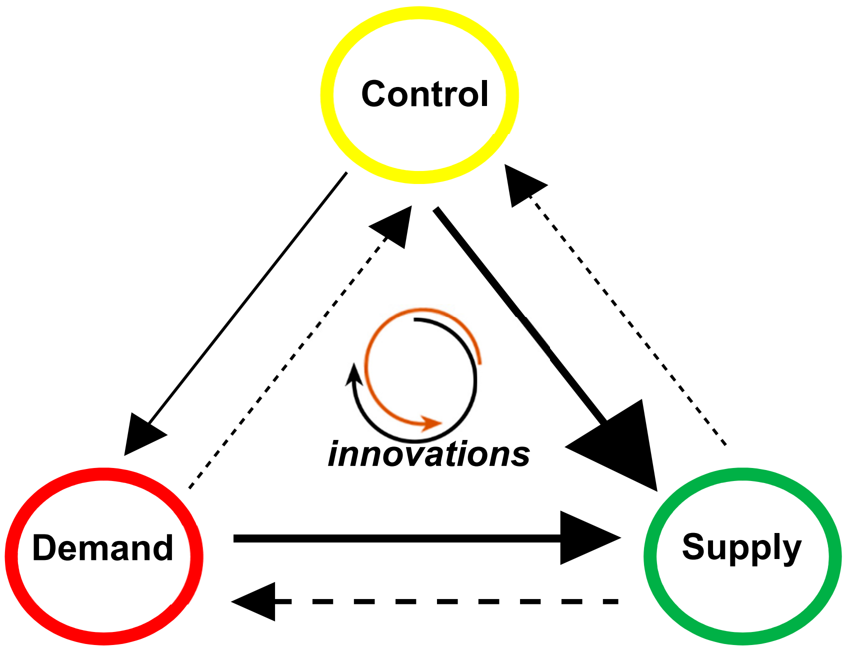

Figure 3: The generalized Triple-Helix model of innovations.
Source: derived from Petersen *et al*. (2016, Figure 1, p. 667)

While each forward arrow in Figure 3 models variation, a reverse arrow represents selective feedback. The process is complex because qualitatively different sources of variation are interacting, and so are the selection mechanisms: cycles can be interrupted, broken, and recombined. Combining a technological opportunity with a market perspective, for instance, may generate an invention, but the market must operate *as a selection environment* before the invention is turned into an innovation.

When three or more feedbacks interact, loops are generated because of the possible transitivity of relations (Bianconi, Darst, Iacovacci, & Fortunato, 2014; cf. (Simmel, 1902a, 1902b)Simmel, 1902a and b). Triads can be either transitive or cyclic (Batagelj *et al*., 2014, pp. 53f.). Whereas transitivity is a relational operation which can thus induce organization and relational hierarchy, the self-organization of markets, technologies and control is based on cycles (Storper, 1997, p.

49). The cycles and the open triangles can develop in parallel (Kontoupolos, 2006). The result is a complex system that is differentiated both horizontally and vertically; both hierarchical and heterarchical (Simon, 1972). The loops may feed forward bringing the system into fruition—that is, structurally providing room for variation—or feed back, leading to lock-in and historical stagnation (Ivanova & Leydesdorff, 2014; Ulanowicz, 2009).

The clockwise and counter-clockwise rotations (depicted in the center of Figure 3) precondition each other, since networks instantiated at the organizational level provide the retention mechanism for the self-organizing dynamics of the codes. Each variant may trigger an avalanche of restructuring. The codes can be expected to adapt to the opportunities provided in the historical layer. As noted, the codes can remain flexible and evolving, since they are not given and directly observable—as in the case of biological DNA—but have the status of hypotheses (Cooke & Leydesdorff, 2006; Distin, 2010). Consequently, one needs a measurement theory for testing assumptions about their interactions and evolution against appropriate data.

The TH indicator of synergy

Entropy statistics (Shannon, 1948; Theil, 1972) enables us to model the trade-offs between variation and selection in the case of three or more analytically different dimensions. Mutual information in three (or more) dimensions can be positive or negative (McGill, 1954; Yeung, 2008; cf. Krippendorff, 2009): when *positive*, this value suggests that the generation of information—that is, historically observable variation—prevails; when *negative*, the generation of redundancy—the complement of the information to the maximum entropy—prevails, and

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uncertainty is reduced. Uncertainty can be reduced to the extent that negative entropy is generated.

One can use the generation of negative entropy—that is, redundancy—as an indicator of synergy and emerging systemness. We applied this information-theoretic approach to studying the knowledge base in a number of country studies (listed in Appendix I and discussed in Leydesdorff & Ivanova [2016]). In these studies, we use firms as the units of analysis and specify three codes as most relevant in innovation systems: (1) firm addresses (ZIP or postal codes) in the geographical dimension, (2) NACE codes developed by the OECD as indicators of the technological capabilities of firms, and (3) size-classes as proxies for organizational formats such as small- and medium-sized firms versus large corporations. ZIP codes, for example, vary over geographical regions; however, in reference to the other two dimensions, the distribution of ZIP codes indicates local constraints operating as a (non-market) selection environment.

A locus of negative information can also be considered as a niche in the entropy flow: more options are available than the realized ones. However, positive values of this indicator (mutual information in three or more dimensions may indicate strength and adaptiveness in terms of past performance, since available options have historically been realized. In such a more mature stage of a cycle, the dynamics of innovation are very different from a configuration where not-yet-realized options prevail (Schumpeter, 1943). Following the distinction between Schumpeter Mark 1 and Mark 2, (Soete & ter Weel, 1999)Soete & ter Weel (1999), for example, distinguished “creative agglomeration” from “creative destruction.” Abernathy & Clark (1995, p. 14) speak of “strategic vectors of industrial development” (see also Suarez & Utterback, 1995).

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Further perspectives

Contrary to the metaphor of Big Data, we argue that the knowledge is not in the data, but in the quality of our handling of the data using models. Using the metaphors of KBE and TH, the data is not "given" in nature (or by God), but previously constructed. For example, the garden of my house in Amsterdam is a current state where previously were meadows and before that only sea. Our knowledge-based capacity to change the "natural" environment is the source of innovations (Von Hippel, 1988). This capacity is stored in books and archives as footprints of codifications of communication. The Fourth Industrial Revolution is not a natural event, but one which has been constructed by preceding Industrial Revolutions. The results challenge us to consider the givens as instantiations of the knowledge dynamics. There is no way back otherwise than by constructing one—and then this road leads also forward.

The crucial step is to consider observations as opportunities for specifying expectations that can be tested against observations. The expectations can theoretically be informed; the interactions among different codifications generate new opportunities as options (Leydesdorff *et al.*, 2018). These options point to the new domains of the Fourth Industrial Revolution. Does this metaphor provide us with a window of opportunities for the formulation of new research questions?

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Appendix I

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