Uncertainty Reduction, Strong *versus* Weak Anticipation, and Innovative Capacities in a Triple Helix Model of the Knowledge-based Economy

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Abstract

The Triple Helix model of university-industry-government relations can be generalized from a neo-institutional model of networks of relations to a neo-evolutionary model of how three (or more) social coordination mechanisms operate as selection environments upon one another. The mutual information among the three contexts (wealth generation, knowledge production, and political control) provides us with an indicator of the knowledge base as a latent structure of a political economy. This structure potentially reduces uncertainty. Using the theory of anticipatory systems, reduction of uncertainty can also be considered as anticipatory capacity. In the computation of anticipatory systems, one distinguishes between weak and strong anticipation. A social system composed of three or more asynchronous selection environments can be expected to generate ranges of options ("horizons of meaning") which in combination with informed decision-making by reflexive agency shape a strongly anticipatory system, that is, a system which co-constructs its own future states. Technological interventions in the natural system take place at specific moments in time, but build upon one another along historical trajectories. The trajectories can be considered as retention mechanisms that enable us to reach new positions from which new possibilities can be envisaged. The communicative competencies of the carriers of the differentiated communication systems, that is, their capacity to translate among horizons of meaning, limit the further development of the knowledge base of an economy historically.

Keywords: knowledge-based economy, anticipation, probabilistic entropy; triple helix; innovation

Introduction

How can an economy based on something as volatile as knowledge be sustained? How does a knowledge-based economy differ from a market-based or political economy? Markets and political (e.g., national) systems can be considered as providing different kinds of subdynamics to the social system. Markets, for example, function mainly to clear imbalances in the system, while political institutions, among other things, regulate markets. Organized knowledge production adds yet a *third* coordination mechanism to the social system (Whitley, 1984). Innovations based on new technologies can upset the equilibrium-seeking dynamics of the market (Schumpeter, 1939; Nelson & Winter, 1982).

When three subdynamics interact, a non-equilibrium dynamics can be expected (May, 1976; May & Leonard, 1975; Sonis, 2000). In such a complex dynamics, historical events may change the system in which they emerge. Therefore, an independent (steering) variable at one moment in time can become a dependent variable at a next moment. In this sense, the complex dynamics can be considered as self-organizing; it is no longer organized nor can it be organized from a specific (e.g., political) perspective without generating unintended consequences. Consequently, economic and political mechanisms do not control, but provide feedbacks that enable and constrain the development of scientific and technological knowledge. The three coordination mechanisms (markets, policies, and discursive knowledge) operate upon each other as selection mechanisms using their respective criteria for the selection.

In other words, the knowledge-based economy can be explained by using a model of three interacting structures of communication which select upon each other. The communications are differently codified in each respective domain (Luhmann, 1984; Foray, 2004). For example, the market communicates in terms of prices and quantities. Scientific communication focuses on truth-finding and puzzle-solving (Simon, 1969). Three interacting mechanisms can also be modeled as a triple helix (Leydesdorff, 1994; Lewontin, 2000).

The Triple Helix model

"The Triple Helix of university-industry-government relations" can first be considered as a network of institutional relations (Etzkowitz & Leydesdorff 2000). However, these institutional networks provide only a knowledge infrastructure to knowledge-based systems. The latter operate in terms of exchanging different expectations. A knowledge infrastructure can also be considered as an evolving retention mechanism of the fluxes of communication in a diversified system of communicative interactions. The institutional layer provides a specific organization to the interactions among functionally different communication structures.

Beyond the institutional layer, the Triple Helix model can be extended to a neo-evolutionary model of how three selection environments can be expected to operate upon one another in terms of functions. As noted, three evolutionary functions can be expected to prevail in a knowledge-based economy: economic wealth generation, organized knowledge production, and political control. Differentiation among these communication structures is functional insofar as it enables the system to process more complexity. However, the functions have to interact at the systems level for the reproduction of the system. The interactions serve the system's integration. In other words, differentiation and integration evolve as two sides of the same coin because both mechanisms operate in empirical configurations.

Although historically building upon the institutional layer, the functional layer is evolutionarily leading by providing meaning to—that is, selecting from—the institutional layer. The reflections open windows on other possible arrangements. The historical realizations no longer correspond one-to-one to specific functions, since hybrid arrangements can be constructed with competitive advantages (Gibbons et al. 1994; Cooke & Leydesdorff 2006). Whereas the system builds up bottom-up and historically, the functional layer of interacting communications operates within it by providing a variety of meanings to the historical events from the perspective of *hindsight* and with reference to horizons of possible meanings (Husserl 1929). A knowledge base, for example, enables us to consider possible futures in the present by using models which use the historical events as data among other possible data. Thus, the anticipatory capacities of the system are strengthened.

Methodologies

In my opinion, two bodies of theory from mathematical biology can be made most relevant for the modeling, simulation, and measurement of a knowledge-based economy: first, Rosen's (1985) theory of anticipatory systems, elaborated more recently into the computation of anticipatory systems (Dubois, 1998); and second, the mechanism for reducing uncertainty in niches provided by Ulanowicz's (1997) ascendency theory.

Following McGill (1954) and Abramson (1962), Ulanowicz (1986) noted that the mutual information in three (or more) dimensions provides us with a measure of *reduction of uncertainty* at the systems level. By elaborating on the Shannon formulas,[1] the mutual information (or transmission T), for example, in a network of coauthorship relations among (u)niversities, (i)ndustries, and (g)overnment agencies, can be measured using the following formula:

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[1] The uncertainty in a distribution according to Shannon (1948) is $H_i = \Sigma_i\, p_i \ \log_2 p_i$. It can be shown that the mutual information in two dimensions cannot be negative (Theil, 1972).

$$T_{uig} = H_u + H_i + H_g - H_{ui} - H_{ug} - H_{ig} + H_{uig} \quad (1)$$

In this equation, H_{ui}, for example, stands for the uncertainty in the two-dimensioanl distribution of papers with university or industrial addresses (independently of their status in the third dimension g). Whether the mutual information in the three relevant dimensions (T_{uig}) is positive or negative depends on each empirical configuration. T_{uig} can thus be considered as a (negative) measure of the synergy or fine-tuning among the dimensions of a configuration. The measure is negative because at issue is whether the prevailing uncertainty is *reduced* by a configuration.

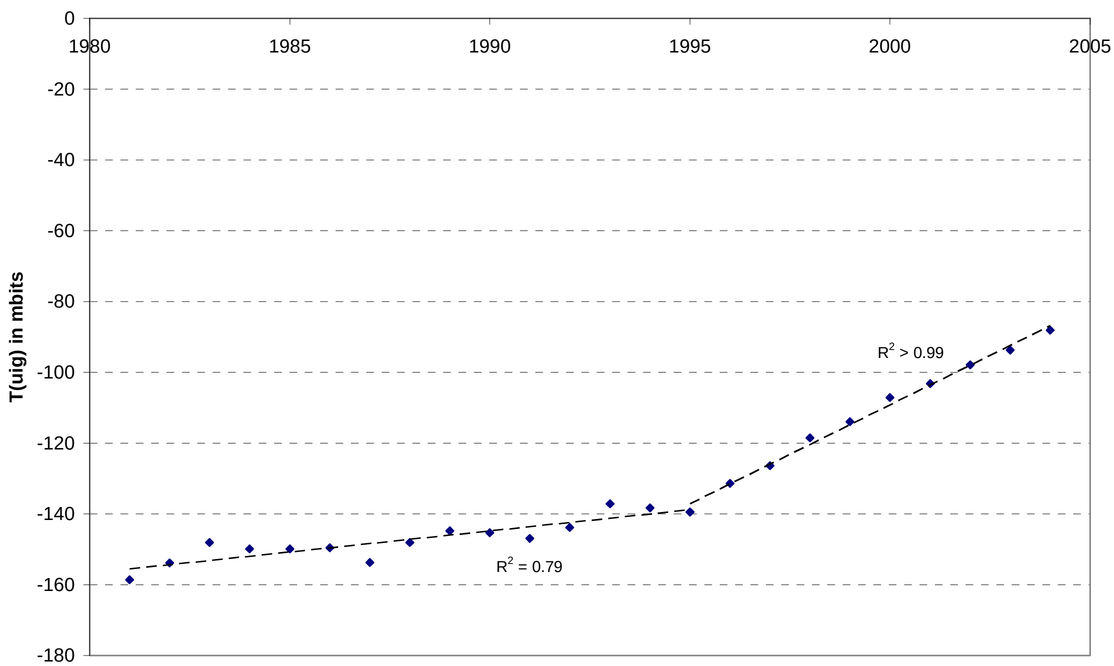
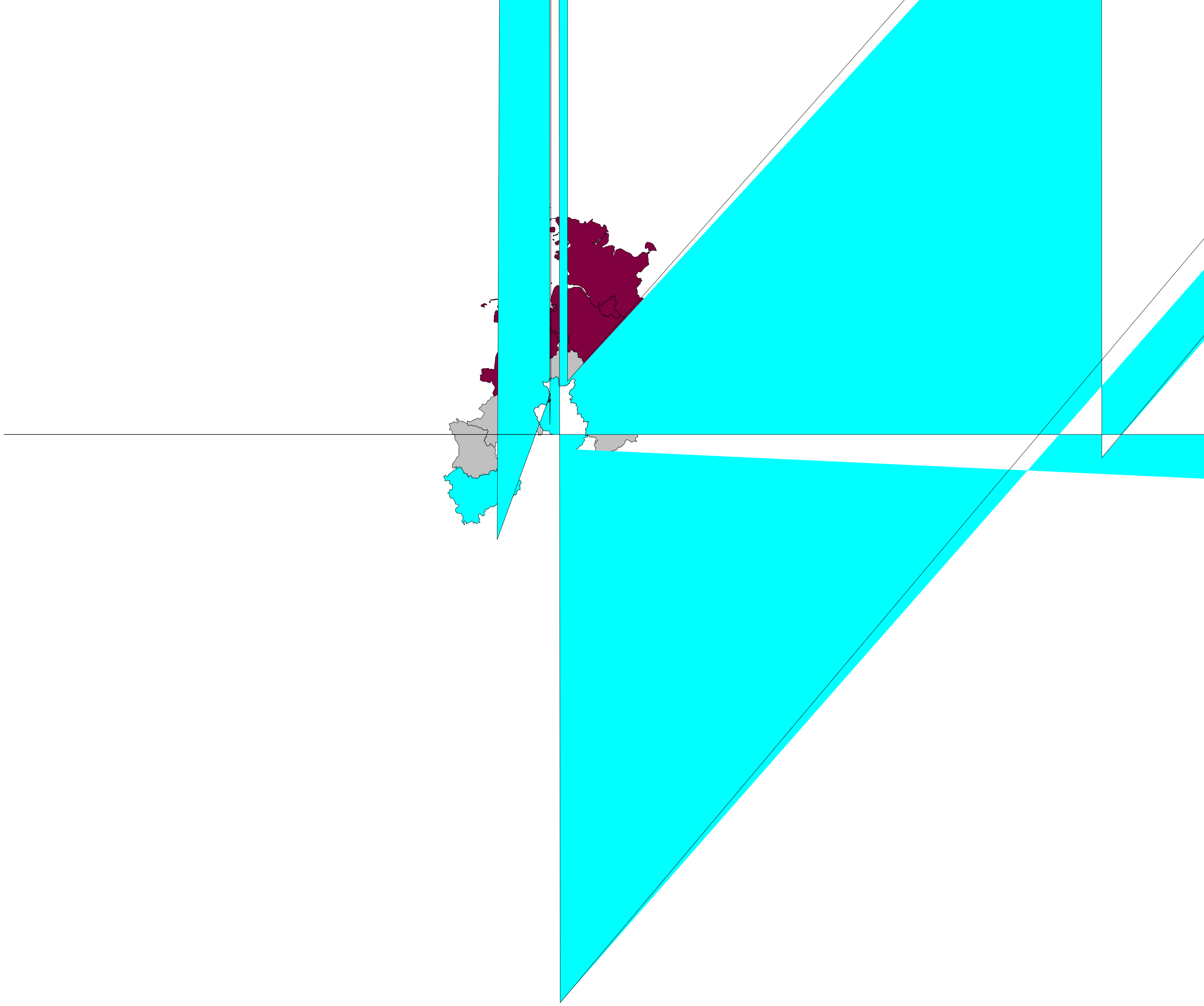


Figure 1: The mutual information in three dimensions of Japanese articles with addresses in university, industry, and government establishments, and their co-authorship relations.

Using this measure, Sun *et al.* (2007) showed that the synergy in coauthorship relations among universities, industries, and governmental agencies in Japan eroded increasingly after 1994 (Figure 1). The Japanese national system of coauthorship relations has become internationalized ever since. Taking this international dimension into account as a fourth dimension, however, an increasing reduction of uncertainty could be found after 1994. Thus, the Japanese system of inter-sectorial publications has become less integrated at the national level, since international coauthorship relations both within and across sectors have become more important (Wagner & Leydesdorff, 2005). This conclusion has important implications for national science policies aimed at stimulating university-industry relations within a national framework: the national system of innovations (Lundvall, 1992; Nelson, 1993) is no longer a unique system of reference for science, technology, and innovation policies (Wagner, 2008).

Figure 2 extends the scientometric analysis with an economic example (Leydesdorff & Fritsch, 2006). In this case, 41 German regions were compared in terms of the synergy among distributions of technologies (indicated by OECD classifications), firm sizes, and geographical locations. The reduction of uncertainty was largest in metropolitan areas like Munich, Frankfurt, and Hamburg. However, the Berlin region is indicated as hardly a knowledge-based economy.



Note that my argument is mainly methodological: however imperfect these proxies may be, the systemic synergy among three (or more) dimensions can be indicated by their mutual information. The knowledge base of an economy can thus be considered as a configurational property (Jakulin & Bratko, 2004): none of the participating actors (including government) can shape it intentionally since these actors are embedded in networked systems with dynamics of their own. However, the measurement results can inform us that some parts (regions, sectors) of the economy are more knowledge-based than others (Bathelt, 2003). Thus, the problem of the measurement of the knowledge base of an economy can be made tractable (Carter, 1996; Foray & Lundvall, 1996; Godin, 2006).

Weak and strong anticipation

Because the second law of thermodynamics is equally valid for Shannon's probabilistic entropy (Georgescu-Roegen, 1971; Theil, 1972), reduction of uncertainty would indicate a local reversal of the entropy flux along the arrow of time. This idea of a local niche containing less uncertainty than the global development can be provided with an interpretation using the theory of anticipatory systems: the knowledge base of an economy works as an anticipatory mechanism by making representations of (and predictions about) the future available in the present, that is, as a feedback against the arrow of time (Coveney & Highfield, 1990).

Robert Rosen (1985) defined an anticipatory system as a system which entertains a model of itself. The model advances on the system which it models, and looks back upon this system from the perspective of a future state. One can also formulate that a model provides meaning to the modeled system from the perspective of hindsight. Dubois (1998) modeled this advancement along the time axis by changing the time subscripts in the relevant equations accordingly. He proposed to consider equations based on this change in the time order as *incursive,* that is, different from the differential (or difference) equations that are used for *recursive* simulations along the arrow of time.

For example, let us consider the logistic equation that can be used for modeling the growth and decline of a population over time. Its recursive formalization reads as follows:

$$x_t = ax_{t-1}(1 - x_{t-1}) \tag{2}$$

The second term of the equation $(1 - x_{t-1})$ can be considered as a selection term by the environment of the system. As the system grows, this feedback becomes increasingly important, leading eventually to the well-known sigmoid curves of systems development. (The parameter a is the so-called bifurcation parameter: the development of this system leads to oscillations for $a \geq 3$, and increasingly to chaos for $3.57 \leq a < 4$.)

$$x_t = ax_{t-1}(1 - x_t) \tag{3}$$

Equation 3 provides the incursive equivalent of Equation 2. Note the different time subscript in the second term $(1 - x_t)$. In this model, the next state develops in relation to its previous state (x_{t-1}), but the feedback $(1 - x_t)$ operates in the present. The new model is pertinent to our subject: a technology, for example, can be expected to develop on the basis of its previous state, but the new technology has to compete in the present under selection pressure on the market.[2]

Unlike the recursive version of the logistic equation, the *incursive* system tends to a steady state for all values of a,[3] and never becomes chaotic (Leydesdorff, 2005 and 2008). In other words, anticipation reduces uncertainty like a filter on the noise (Brown & Michael, 2003; Borup *et al*., 2006; Van Lente, 2006). One can further distinguish between weakly and strongly anticipatory systems, and accordingly write incursive and hyperincursive equations. Unlike a weakly anticipatory system, a strongly anticipatory one co-constructs its own next states because more than a single option is possible using a *hyperincursive* equation, that is, a configuration in which only future states—expectations—are considered as drivers of the development.

Consider the following hyperincursive formulation of the logistic equation:

$$x_t = ax_{t+1}(1 - x_{t+1}) \tag{4}$$

[2] Leydesdorff & Dubois (2004) showed that this incursive formulation of the logistic equation can be derived for anticipatory systems which, like social systems, are based on aggregation and interaction.
[3] $x_t = ax_{t-1}(1 - x_t)$; $x_t = x_{t-1} \rightarrow x = (a - 1)/a$.

In words: the next state of this system is dependent on its own next state and the next state of its selection environment. An example of such a system is provided by what is called "double contingency" in sociology: *Ego* operates in relation to *Alter* in terms of one's expectation that the other also operates in terms of expectations (Parsons, 1968; Vanderstraete, 2002). Analogously, market perspectives and technological options can be mutually adjusted in decision-making processes at higher levels of aggregation (like in corporations and government agencies).

Let us develop Equation 4 analytically as follows:

$$x_t = ax_{t+1}(1 - x_{t+1})$$

$$x_t = ax_{t+1} - ax_{t+1}^2$$

$$ax_{t+1}^2 - ax_{t+1} + x_t = 0$$

$$x_{t+1}^2 - x_{t+1} + x_t / a = 0$$

In general, the latter equation has two solutions:

$$x_{t+1} = ½ \pm ½ \sqrt{[1 - (4/a)\, x_t]} \qquad (5)$$

Because the value of x can only vary between zero (no system) and one (no environment), the curve for $x_t = 1$ [that is, $x = 0.5 \pm 0.5 \sqrt{(1 - (4/a))}$] sets limits to the possible values that can be reached by this hyper-incursive system. This curve is penciled into Figure 3. The figure shows additionally on the left side (for $a < 4$) the well-known bifurcation diagram of the logistic equation, and the curve for the steady state of the incursive equation [$x = (a-1)/a$; see footnote 2 for the derivation].

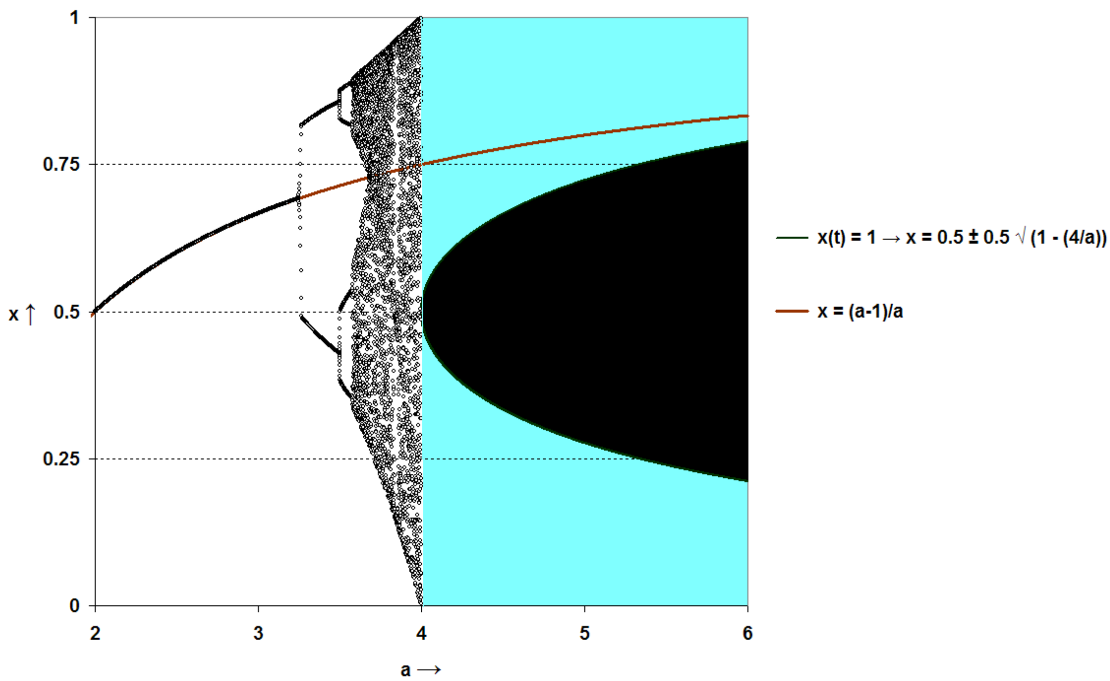


Figure 3: The social system as a result of hyper-incursion.

For $a \geq 4$, two sets of expectations are generated by the hyper-incursive system at each time step depending on the plus or the minus sign in the equation. After N time steps, 2^N future states would be possible. Thus, this social system of expectations continuously needs another mechanism for choosing between options. Otherwise, the system would rapidly become overburdened with uncertainty.

Decisions have to be made by reflexive agency, that is, in the layer of historically-rooted, but weakly anticipatory systems. In other words, a strongly anticipatory system is generated by the coupling of the hyper-incursive social system providing ranges of possibilities with an incursively operating layer of weakly anticipatory systems, that is, historically contingent agents who are able to entertain models reflexively. Insofar at these two layers of expectations drive each other, a future-oriented knowledge base can increasingly be shaped.

Under what conditions can a social system develop hyperincursivity, that is, be driven in terms of interacting expectations? Incursivity or weak anticipation is possible for systems like human minds that are able to entertain models. Hyper-incursivity assumes that a system is able to entertain models of models in different dimensions. Our minds are able to entertain different models sequentially, but not synchronously (without becoming confused). The functional differentiation among coordination mechanisms in the Triple Helix model of the social system provides interfaces where different models can be modelled in terms of each other. The market, for example, entertains a model of different technologies by mapping them in terms of their respective prices, and competing technological developments anticipate on future markets in terms of specifications (Saviotti, 1996; Frenken, 2005). This anticipatory mechanism operates transversally as synchronization between functionally different selection environments with their own respective dynamics.

While all (Rosen-type) anticipatory systems continue to provide meaning along a longitudinal axis, the internal differentiation of the social system thus allows additionally for a decentralized layer of models of models. When various models can be entertained and interfaced, the social system is provided with a horizon of possible meanings and thus opens itself as an intentional system at a level beyond individual psychologies (Husserl 1929; Author 2006, 2009). Note that in a pre-modern system, integration into a cosmological order is expected to prevail over functional differentiation at the level of society (Luhmann 1984).

Interactions among hyperincursive, incursive, and recursive opertions

How are the three layers—the hyperincursive knowledge base of the social system, the incursive layer of psychological systems, and the historically developing biologies—related? Note that the logistic equation and its hyper-incursive formulation are symmetrical in t: the logistic curve (Eq. 2) refers exclusively to $(t - 1)$, and the hyper-incursive equation derived from it (Eq. 4) exclusively to $(t + 1)$. Because of this symmetry in the formulas, both systems can be expected to reach a limit value for $a = 4$.

The weakly anticipatory system—that is, the one that is able to entertain models—is modeled in Figure 3 as a line, $x = (a - 1)/a$, which crosses this divide between the two others (at $a = 4$). However, the social system can also have real values in the biological domain ($a < 4$), but only if the term under the root in Equation 4 is positive, that is, if $x_t \leq a/4$. This condition is always met for $a \geq 4$, but sets a borderline to the possible penetrations of the strongly anticipatory (social) system into the historical variation.

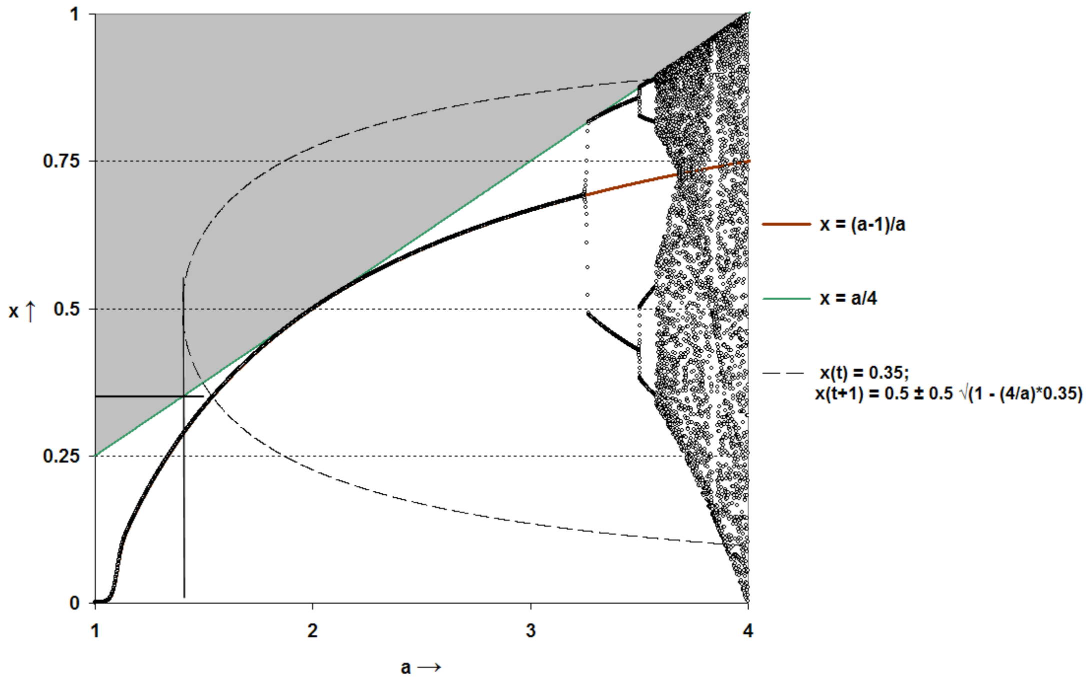


Figure 4: Possible penetrations of the social system into the historical variation ($a < 4$).

In Figure 4, this limitation is elaborated for $a = 1.4$ and $x_t = 0.35$. Since at a next step $x_{t+1} = 0.5$ and is therefore larger than $a/4$ (= 0.35), the strongly anticipatory system would no longer be able to proceed. In general, the strongly anticipatory system can reconstruct the historical variation (e.g., technologically), but only at specific moments of time. While the relations between incursive agency and hyper-incursive social development can be considered as based on mutual reflections and therefore a coevolution of expectations, the technological reconstruction of nature by the strongly anticipatory system takes place as specific interventions. Although the artifacts may contain models, only psychological and social systems are able to entertain and change models reflexively (Luhmann, 1984; Van Lente & Rip, 1998; cf. Latour, 1993).

The social system can be strongly anticipatory insofar as it contains two anticipatory mechanisms operating upon each other: the longitudinal providing of meaning, as in all anticipatory (sub)systems, and the transversal entertaining of models between its differently codified subsystems of meaning-processing (Leydesdorff, 2009). The knowledge base of an economy can thus be conceptualized as a specific arrangement among communication systems at the level of the social system that allows for both differentiation and integration.

Differentiation is needed in order to process increasing complexity. Uncertainty, however, has to be reduced by replacing "natural" or previous solutions with other possible ones. This requires informed choices at interfaces among ranges of possibilities. These informed decisions integrate the system and shape trajectories in real time. The trajectories enable us to reach new positions, and new positions allow for the perception of new possibilities. The communicative competencies of the carriers of the differentiated communication systems, that is, their capacity to translate among horizons of meaning thus limits the further development of the knowledge base of an economy historically.

Summary and conclusions

The measurement of the knowledge-based economy was placed on the research agenda by the Organization of Economic Cooperation and Development OECD in 1996 (OECD, 1996). Hitherto, the efforts of this organization were focused on reorganizing existing indicators (Godin, 2006). These efforts have been largely unsuccessful because a knowledge-based economy can be considered as a second-order interaction effect at the systems level.

In a political economy, two social coordination mechanisms (markets and politics) interact. As organized knowledge production becomes increasingly available as a third coordination mechanism in a differentiated society, two more interactions are feasible: the shaping of (e.g., national) knowledge infrastructures and the innovative dynamics in the economy. The knowledge-based economy can be considered as a possible resonance among these three interaction effects which can no longer be attributed to any of the composing elements of this complex interaction; it generates an independent source of feedback (Figure 5).

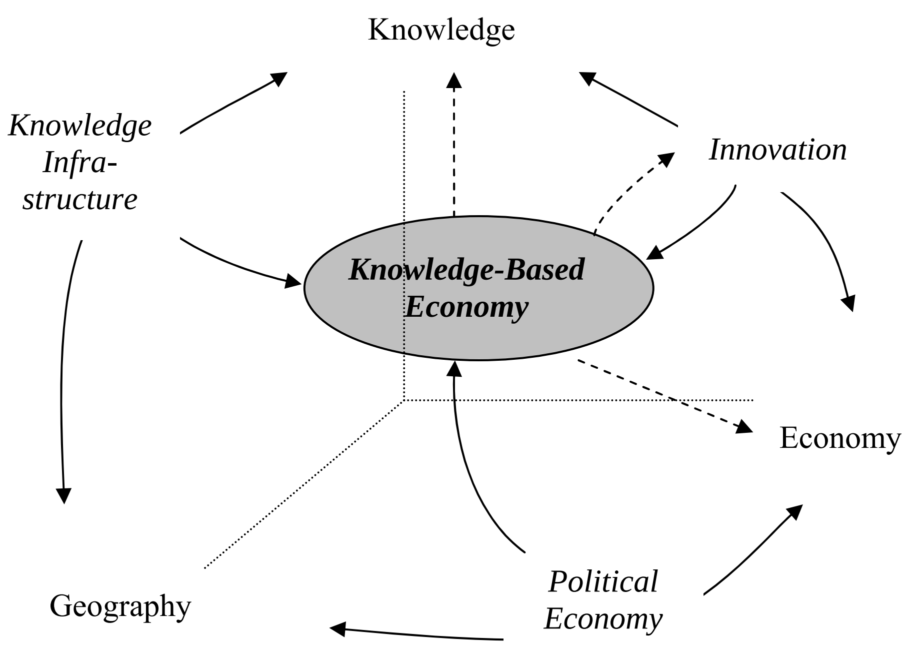


Figure 5: First-order interactions among different social contingencies can generate a knowledge-based economy as a next-order system.

In other words, the emerging feedback operates top-down, while historically this evolutionary subdynamic continues to be constructed bottom-up (Ashby 1958; Maturana & Varela 1980). The reduction of uncertainty in a knowledge-based economy remains an empirical question. It can be measured as mutual information in three or more dimensions (Jakulin & Bratko 2004). I provided examples of empirical measurement efforts for the cases of Germany and Japan. The proposed measure is very general and results can be decomposed in great detail (Theil 1972).[4]

The reduction of uncertainty in a local environment can be considered as a feedback against the axis of time. While historical developments continue along trajectories following the arrow of time, reflexive agency is able to exploit this next-order feedback from the social system of expectations for envisioning future states of the systems. When knowledge production is socially organized in scientific and technological discourses, hyper-incursive mechanisms can be developed at the level of the social system. Technological interventions by the social system in the "natural" variation become increasingly possible in a configuration which reduces uncertainty. The hyperincursive routines can be coupled onto the incursive mechanisms of decision-making agents in a techno-economic coevolution which drives its *autopoiesis* as a strongly anticipatory system. Unlike Darwinian evolution, these evolutionary dynamics of expectations operate by reconstructing historical developments from the perspective of envisaged possibilities.

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[4] Unlike co-variance analysis among three or more variates, information-theoretical measures are yet dimensionless and allow for comparisons among (quasi-)experimental results which differ in their metric. In the case of co-variance analysis, the assumptions (e.g., about the shape of the distribution) are more restricted, and the results more difficult to interpret (Garner & McGill, 1956: 228).

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