Qualitative and Quantitative Analysis of Scientific and Scholarly Communication

Loet Leydesdorff

The Evolutionary Dynamics of Discursive Knowledge

Communication-Theoretical Perspectives on an Empirical Philosophy of Science

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ISSN 2365-8371 ISSN 2365-838X (electronic)
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication
ISBN 978-3-030-59950-8 ISBN 978-3-030-59951-5 (eBook)
https://doi.org/10.1007/978-3-030-59951-5

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Acknowledgements

I am grateful to Staša Milojević, Rob Hagendijk, Gaston Heimeriks, Inga A. Ivanova, Caroline S. Wagner, Iina Hellsten, Henry Etzkowitz, Mark W. Johnson, Han Woo Park, Wouter de Nooy, Lutz Bornmann, Joseph Brenner, Franz Hoegl, and Margaret Traudes for comments on previous drafts. I thank Gene Moore for providing feedback on the English.

Chapters are often based on coauthorships and other forms of collaborations: I am grateful for the collaboration with Iina Hellsten and Collin Grant (Chapter 1), Paul Wouters (Chapter 2), Piet Strydom (Chapter 3), Mark W. Johnson (Chapter 4), Alexander M. Petersen (Chapters 4 and 5), Inga A. Ivanova (Chapters 4, 5, and 7), Henry Etzkowitz and Han Woo Park (Chapters 4 and 5), Martin S. Meyer, and Wolfgang Glänzel (Chapter 5), Petra Ahrweiler (Chapter 5), Øivind Strand (Chapter 5), Ivan Cucco (Chapter 6), Katy Börner and Andrea Scharnhorst (Chapter 7), Daniel M. Dubois (Chapter 8), Franz Hoegl (Chaper 9). I thank the Amsterdam School of Communication Research (ASCoR) and the Foundation for the Study of Science Dynamics for supporting the publication of this study.

Contents

Chapter 1
Knowledge-Based Innovations and Social Coordination

Three themes have been central to my research program: (1) the dynamics of science, technology, and innovation; (2) the scientometric operationalization and measurement of these dynamics; and (3) the Triple Helix (TH) of university-industry-government relations. In this introductory chapter, I relate these three themes first from an autobiographical perspective to (*i*) Luhmann's sociological theory about meaning-processing in communications with (*ii*) information-theoretical operationalizations of the possible synergies in Triple-Helix relations, and with (*iii*) anticipation as a selection mechanism in cultural evolutions different from "natural selection." Interacting selection mechanisms can drive the development of redundancy; that is, options that are available, but have not yet been used. An increasing number of options is crucial for the viability of innovation systems more than is past performance. A calculus of redundancy different from and complementary to information calculus is envisaged.

1.1 The Spring of "1968" in Prague, Paris, and Amsterdam

On 21 August 1968, the Soviet Union and its allies invaded Czechoslovakia. In that year I was a third-year student and went to Prague to attend discussions. During this summer, Prague had become a meeting place for intellectuals. I left Prague the day before the Russian invasion. Earlier that year, I had been in Paris in March, shortly before the student revolt in May; and since 1967 I had been attending meetings of the Critical University in Amsterdam on Sunday evenings. The various discussions

This chapter is partly based on: Leydesdorff (2010). Luhmann Reconsidered: Steps towards an empirical research program in the sociology of communication. In C. Grant (Ed.), *Beyond Universal Pragmatics: Essays in the Philosophy of Communication* (pp. 149–173). Oxford: Peter Lang.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*, Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_1

focused on the changing role of science and technology in the dynamics of capitalism from neo-Marxist and other perspectives.

In the *Action Program* of the Communist Party of Czechoslovakia (published on April 5, 1968), the Central Committee of the Party formulated its reform program as follows:

> […] it will be necessary to prepare the country for joining the scientific-technical revolution in the world, which calls for especially intensive cooperation of workers and agricultural workers with the technical and specialized intelligentsia, and which will place high demands upon the knowledge and qualifications of people, on the application of science. (ČSSR, 1968, at p. 3)

Why were these words considered as such a serious threat to the Soviet system that the Russian orthodoxy thought they had to send in the army? The Czechoslovak government had repeatedly stated that it did not intend to change existing alliances. The reasons for the invasion were mainly ideological.

The issue of "the scientific-technical revolution" has a long history in Marxist ideology. In a footnote to *Capital I* (at p. 393, note 89), Marx himself speculated: "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 would fall away*" (Marx [1857] 1973, p. 709; italics in the original). In other words, Marx had envisaged another possible regime change to a knowledge-based economy that is different from and potentially an alternative to the communist revolution.

In *Grundrisse: Foundations of the Critique of Political Economy,* Marx ([1857] 1973) elaborated on this question as follows:

> Nature builds no machines, no locomotives, railways, electric telegraphs, self-acting mules etc. These are products of human industry; natural material transformed into organs of the human will over nature, or of human participation in nature. They are *organs of the human brain, created by the human hand;* the power of knowledge, objectified. The development of fixed capital indicates to what degree general social knowledge has become a *direct force of production,* and to what degree, hence, the conditions of the process of social life itself have come under the control of the general intellect and been transformed in accordance with it. To what degree the powers of social production have been produced, not only in the form of knowledge, but also as immediate organs of social practice, of the real life process. (at p. 706).

Note that Marx proposed "the development of fixed capital" as an empirical indicator of the transformation from political to a knowledge-based economy.

During the period 1850–1870, Marx spent most of his time studying in the Library of the British Museum (Higgins, 2017). Among other things, he had set himself the task to study the possibility that science and technology had become sources of societal wealth more than labour. (A model with two independent variables was not available in his time.) On the basis of his calculations, however, he rejected this hypothesis and concluded that the main contradiction at the time remained the one between capital and labour (e.g., *Capital III* [1894]; 1972, Chap. 5, p. 90 ff.).

In his time, Marx witnessed the prelude to the emergence of a knowledge-based economy. For example, William Henry Perkin's research on dye-stuffs in England during the late 1850s developed into an industry in Germany (Beer, 1959; cf. Braverman, 1974, pp. 161f.; Etzkowitz, 2008, p. 25). However, *Capital* I (1867) was written in a key period of the shaping of nation-states with their respective *political* economies. The unifications of Germany and Italy in 1870, for example, followed upon the Meji Restoration of Imperial Rule in Japan in 1868, the end of the American Civil War in 1865, and the Commune de Paris in 1870.

For example, Noble (1977, at p. 7) argued—with a focus on the USA (Thomas Edison)—that "the major breakthroughs, technically speaking, came in the 1870s." He dated "the wedding of the sciences to the useful arts" as the period between 1880 and 1920, that is, *after* Marx's period of studies. Braverman (1974) used the term "scientific-technical revolution" for this same period (1870–1910) when he described 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.)

In summary, the *Action Program* of the Czechoslovak Communist Party reopened a debate within Marxism by suggesting the possible transformation of the communist state into an open society oriented to science, technology, and innovation, while guided by a socialist inspiration (*fraternité*). A think-tank at the Academy of Science of Czechoslovakia under the leadership of Radovan Richta formulated this possibility as follows:

> The productive forces should not be seen in the narrow and unhistorical pattern that stabilized under the impression of industrialization (and in general accepted these conditions)—that they conceived of them merely as the sum of the means of labor and the labor force—but in the broad Marxian sense as a rich and variable multiplicity of production forces of the human kind—thus including the social combination and science, the creative faculties of man and the forces of nature which he has appropriated. (Richta et al., 1968, pp. 20f.; cf. Richta, 1963)

The invasion of 1968 led to decades of stagnation. It would take until 1989, before Alexander Dubček, the Secretary-General of the Communist Party, who led the reforms during the Spring of 1968, could be democratically elected as chairperson of the federal parliament of Czechoslovakia. Might Czechoslovakia have found a way to realize a new form of Euro-communism if the Soviets had not intervened?

1.2 Science and Technology Policies in the West

In the very different context of western democracies, the changing role of science and technology (S&T) in society was placed on the agenda of the Organization of Economic Co-operation and Development (OECD) in Paris—after its transformation in 1962 from an organization for distributing Marshall help into a think-tank for the development of science, technology, and innovation policies (Elzinga, 2012).

The economic issue in the background was the so-called "residual factor" or, in other words, the realization that the continuation of post-war growth could not be explained in terms of the increased productivity of the traditional production factors (Solow, 1957; OECD, 1964). Was this residual factor a reflection of scientific and technological developments? For science-policy purposes, however, one needed to understand the role of S&T in society beyond labeling it as "residual."

An elaboration of other theoretical perspectives had become urgent after the Soviet launch of the first Sputnik in 1957. Sputnik I came as a surprise, and was perceived as a challenge not only to the U.S. but also to capitalism and democracy as economic and social systems. The President's Science Advisory Council and other mechanisms such as the Advanced Research Projects Agency (ARPA) in the Department of Defense were established to insure U.S. technological competitiveness in the military and space arenas (Eisenhower, 1965; York, 1970). During the 1960s, the OECD took the lead in developing and coordinating S&T policies among the member states. Science policies in these countries were shaped during the late 60s and early 70s (OECD, 1963, [3]1976, 1971; Weinberg, 1963).

In the Netherlands, for example, the first minister for science policy was appointed in 1971; in Sweden, S&T policies were initiated since 1965 (Elzinga, 1980). Initially, these S&T policies were narrowly confined to budget allocations; but the so-called "Harvey Brooks Report" of the OECD (1971)—entitled *Science, Growth, and Society: A new perspective*—addressed the relations between science, technology, and society more broadly. For example, "policy for science" and the use of "science in policy" were distinguished.

In 1973, a left-wing government came to power in the Netherlands with the program of democratizing *knowledge*, power, and income. The science-policy component of this program was elaborated into a system of sectorial councils including citizen representatives.[1] The focus on external democratization led, among other things, to the development of science shops at Dutch universities and thereafter elsewhere (Leydesdorff, 1980; Leydesdorff & Ward, 2005). The issue was to articulate and democratize the demand for knowledge and innovations from perspectives other than those of the state and large industries with their own R& D facilities (Sclove, 1995).

1.3 Science Studies: The Sociological Perspective

At the Critical University in Amsterdam, discussions were pursued mainly in terms of the debates about "critical theory" in neo-Marxism (Habermas, 1968b; Marcuse, 1964) and euro-communism (e.g., Althusser, 1965, 1975) as an alternative to, for example, the "new industrial state" (Galbraith, 1967). We discussed among other

[1]Brief van de Minister voor Wetenschapsbeleid, *Nota Sectorraden Wetenschapsbeleid*. Den Haag: Tweede Kamer, zitting 1977, 14623, nrs. 1–3.

things Marcuse's (1964) technocracy thesis in *One-Dimensional Man* and Habermas' (1968a and b) critique of this analysis. Marcuse's (1955) book *Eros and Civilisation*, for example, related the critical tradition of the *Frankfurter Schule* with the counter-movements of the late 1960s such as the anarchistic "Provo" movement in Amsterdam (cf. Hollak, 1966).

Against Marcuse, Habermas (1968a, b) argued that technocracy and bureaucratic rationalization are not "natural forces," but theoretical constructs that can be considered at most as tendencies when operating in society.[2] In Habermas' opinion, it would be mistaken to consider "rationalization" as a single force; one can for example distinguish *technical* (means-ends) rationality from *practical* rationalization:

> Above all, it becomes clear against this background that *two concepts of rationalization* must be distinguished. […] *Rationalization at the level of the institutional framework* can occur only in the medium of symbolic interaction itself, that is, through *removing restrictions on communication.* Public, unrestricted discussion, free from domination, of the suitability and desirability of action-orienting principles and norms in the light of the socio-cultural repercussions of developing subsystems of purposive-rational action—such communication at all levels of political and repoliticized decision-making processes is the only medium in which anything like "rationalization" is possible. (p. 118)

As is well known, Habermas further developed a distinction between systemic and "life-world" dynamics in his studies of the transformation of the public sphere (*Strukturwandel der Oeffentlichkeit;* Habermas, 1974) and then in the *Theory of Communicative Action* (1981). Less well known is his extensive study entitled *Erkenntnis und Interesse* (Habermas, 1968b; translated as *Knowledge and Human Interests*) about three knowledge interests—rationalities—operating in the different sciences.

The three "knowledge interests" distinguished by Habermas (1987 [1968b]) were: (*i*) the *technological* one of the natural sciences, (*ii*) the historical-hermeneutical one of *understanding* in the humanities, and (*iii*) an *emancipatory* interest in social change on the basis of reflection and critique. According to the author, one can expect scholars working in these three domains to develop different criteria for "objectivity": nomothetical, hermeneutic, and ideology-critical, respectively. From this perspective, a sociology of science should not focus only on the micro-organizational differences between disciplines, but also explore their relations with these macro-socio-epistemic drivers. As a member of the *Frankfurter Schule*, Habermas, however, remained at this stage neo-Marxist: he questioned the room for unrestricted discussion ("*Herrschaftsfreie Diskussion von allen mit allen*") from the perspective of the critical tradition (Horkheimer & Adorno, 1969 [1947]).

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[2] In the French discussion, Althusser (1974) would analogously formulate a "self-critique" arguing for a "coupure épistémologique" (an epistemological turn) by turning away from an objectivistic analysis of class structures (e.g., Althusser, 1970; Poulantzas, 1968) towards a focus on historical processes of change.

1.4 The Habermas-Luhmann Discussion

The relation between the micro-sociological and macro-sociological analysis of science, technology, and innovation has been core to my research interests. However, Habermas' theorizing evolved increasingly in a normative direction given his claim of counterfactual openness in the discourse (e.g., Habermas, 1987 [1985]). In this context, it was an eye-opener to read Luhmann's objections against Habermas' arguments in the so-called "Habermas-Luhmann discussion" (Habermas & Luhmann, 1971).

In addition to elaborating on the perspective of Parsons' (1937; 1951) social-systems theory, Luhmann (1980; cf. 1971, at p. 344 ff.) argued that (*i*) dominance is structurally present in discussions; discussions cannot be "unrestricted"; (*ii*) Habermas' appeal to "rationality" might easily be used as a sanction against contributions deemed undesirable and therefore labeled as "irrational"; (*iii*) language structures discussions; and (*iv*) time constraints set inevitable limits to the discussions.[3] According to Luhmann, "critical theory" as advocated by Habermas had increasingly become *irrelevant* since outdated. As he put it:

> The portrayal by Habermas is consistent and true. Only the relevance of the analysis and vocabulary can be denied. It is not a goal, but an important aspect of sociological system theory that it uses a concept of action that no longer allows a fundamental separation of practice and technology. (1971, p. 293; my translation)

Against Habermas' analysis, Luhmann (1971, p. 21) proposed to abandon (neo-Marxist) historicism—that is, drawing "lessons from history"—and turn to constructivism:

> What can no longer be presupposed (e.g., "historical facts", L.) will have to be brought forth in the construction of our basic categories. […] Their suitability will have to be judged using different criteria, i.e., no longer from the point of view of the accurate repro-duction of what is simply pregiven and waiting to be discovered, but from that of grasping and reducing this contingency of possible worlds. As the basic category for describing how this is accomplished in consciousness and communication (and not merely physically or organically) I suggest the concept of *meaning*.

Note that both Habermas and Luhmann called for a theory of meaning as foundational to sociology. However, Habermas elaborated this theory in terms of communicative *action*, whereas Luhmann theorized communication *structures*. In Marxism, action provides a way to change structures, but this relation between action and intended changes had become less obvious given the increased complexity of an increasingly knowledge-based economy. Reflexive systems can adapt innovatively and be resilient against external steering. Luhmann formulated this at the time as follows:

> Social structures do not take the form of expectations about behavior (let alone consist of concrete ways of behaving), but rather take the form of expectations about expectations. (1990b, p. 45 [1971, p. 63])

[3] I have summarized Luhmann's argument in Dutch in Leydesdorff (1977).

From this perspective—that is, focusing on the dynamics of expectations—"action" is no longer an *explanans* (Giddens, 1979; Latour, 1983 and 1988), but action needs to be explained in relation to structures. However, expectations are not obviously observable. The specification of structures of expectations operating selectively and thus potentially interacting requires a theory at the macro-level (such as Marxism). However, Luhmann turned for the elaboration of a structuralist perspective to Parsons' (1951) concept of *double contingency* in interhuman relations.

Double contingency means that each of us (*Ego*) expects the other (*Alter*) to entertain expectations as we entertain them ourselves. This second contingency among expectations comes on top of the first contingency of empirical processes in the physical and biological conditions. Sharing of meaning and communication of information enable us reflexively to entertain and develop structures in our communications. Note that this approach is sociological and not linguistic: communications can be mediated symbolically providing meaning to reflections.

I agree with Parsons and Luhmann that double contingency can be considered as the micro-operation of the social system. This basis is not grounded in observable behavior, but in reflexive communications. I shall show in a later chapter that the coding of the communications adds a hyper-reflexive layer at the supra-individual level. From this perspective, both actions and texts are part of a first contingency; they are historical and observable. From an evolutionary perspective these observables in the first contingency provide the variation. However, inter-human communications develop *evolutionarily* in terms of selection mechanisms. Selection criteria are not immediately and unambiguously observable. As Luhmann (1995, at p. 164 [1984, p. 226] formulated: "*communications cannot be observed directly, only inferred.*" (italics in the original).

In other words, interactive rationality, which Habermas distinguished from means/ends rationality, is shaped in terms of *meanings* provided and shared among humans reflexively. Providing meaning to information can be considered as the selection of a signal from the noise. Not all information is meaningful; and one or more selections can be involved. However, the selection mechanisms cannot be inferred from the observable variation. Unlike variations (which are phenotypical), selection is "genotypical"—a system's property—and may also be deterministic. Habermas' assumption that the social system of communications can be considered as unrestricted ("*herrschaftsfrei*") specifies a counterfactual; somewhat comparable to "all men are born equal." However, normative assumptions are not sufficient for understanding the complex dynamics under study. We need research programs!

1.5 "Wertfreiheit"

The distinction between different rationalities (e.g., technocratic or capitalist rationalities) potentially operating upon one another—but not necessarily in a single Marxian dialectics—finds its origin in Max Weber's work and relates directly to

Weber's Marx-critique or, more generally, his critique of *historicism*.[4] According to Weber, values are ideal-typical constructs: they operate in history as coordination mechanisms. The *Sinn der Wertfreiheit*—the commitment to value-freeness—in the social sciences serves our ability to study these values without an a priori commitment to them. Value-freeness is an epistemic condition for the objectivation of "*verstehende Soziologie*" (Weber, 1913). Without *Verstehen* ("understanding the meaning of action from the actor's point of view") the sociological analysis remains substantively empty. Human agency is "intentional" (Searle, 1983). Both understanding and explanation are needed in the sociological analysis.

For explaining the status of values, Weber used the metaphor of the Greek Gods who operate above human history, but are present within it. History is then considered as a *Kampfplatz* (battlefield) of *völlig unaustragbare* (completely incompatible) values (e.g., Weber, 1919, at p. 608f.). Weber (2015 [1904], at p. 203 ff.) opposed (among others, Marx's) historicism. He explained the analytical tension between sociological analysis and historical studies as follows:

> In the interest of the concrete demonstration of an ideal type or of an ideal-typical developmental sequence, one seeks to make it clear by the use of concrete illustrative material drawn from empirical-historical reality. The danger of this procedure, which in itself is entirely legitimate, lies in the fact that historical knowledge here appears as a servant of theory instead of the opposite role. It is a great temptation for the theorist to regard this relationship either as the normal one or, far worse, to mix theory with history and indeed to confuse them with each other.

Seeking to understand the system's dynamics, Luhmann's (1971: 291 ff.) program of studies was radically anti-historicist, as when he formulated, for example, as follows:

> Our flight must take place above the clouds, and we must reckon with a rather thick cloud cover. We must rely on our instruments. Occasionally, we may catch glimpses below of a land with roads, towns, rivers, and coastlines that remind us of something familiar, or glimpses of a larger stretch of landscape with the extinct volcanoes of Marxism. But no one should fall victim to the illusion that these few points of reference are sufficient to guide our flight. (Luhmann [1984, pp. 12–13]; 1995, p. 1).[5]

Note that the "volcanoes of Marxism" (e.g., Habermas?) are considered "extinct." From a systems perspective, history can be considered as *morphogenesis* (Archer, 1982 and 1995). The historical events provide variation, but the systems dynamics are structural: they operate in terms of selection mechanisms (Hodgson & Knudsen, 2011). From Luhmann's perspective, Weber's values are not Greek Gods, but the results of resonances among interhuman intentions and communications. These structures, operating like "Greek Gods" in the background, also need to be explained.

In my opinion, Luhmann's contributions to the Habermas-Luhmann discussions were very rich, and they are important for the argument to be developed in this

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[4] Popper's (1957) term "historicism" is not used by Weber.

[5] The metaphor of the airplane flying on the basis of instruments is taken from Maturana (1978, p. 42). The flight metaphor refers also to the Preface of Hegel's (1820) *Rechtsphilosophie* where he wrote that "the owl of Minerva begins its flight only with the onset of dusk."

study about the dynamics of discursive knowledge as systems of rationalized expectations. However, I will use Luhmann's proposals without orthodoxy, and change them when necessary, in my opinion. I will also emphasize some aspects differently from the scholarly reception of Luhmann's work in Germany and elsewhere. My main purpose is to operationalize this sociological theory and to proceed to the measurement (Leydesdorff, 1995).

At the time of the debate with Habermas,[6] Luhmann (1971, p. 34; 1990a, b, p. 27) was ahead of his time when he drew the following conclusion about the dynamics and evolution of meanings:

> The function of meaning then does not lie in information, i.e., not in the elimination of a system-relative state of uncertainty about the world, and it cannot, therefore, be measured with the techniques of information theory. If it is repeated, a message or piece of news loses its information value, but not its meaning. Meaning is not a selective event, but a selective relationship between system and world—although this is still not an adequate characterization. Rather, what is special about the meaningful or meaning-based processing of experience is that it makes possible *both* the reduction and the preservation of complexity; i.e., it provides a form of selection that prevents the world from shrinking down to just one particular content of consciousness with each act of determining experience. (1990, p. 27)

In addition to this quest for the specification of social selection mechanisms potentially different from "natural selection," the long-term program of theory construction was at the time formulated as follows:

> No matter how abstractly formulated are a general theory of systems, a general theory of evolution, and a general theory of communication, all three theoretical components are necessary for the specifically sociological theory of society. They are mutually interdependent. […]
>
> The decisive questions now become: How are these various theories related to one another? What unifies them? How must a theory that integrates them be constructed? (Luhmann, 1975, at p. 96; 1982a, b, at p. 261.)

This program was ambitious; further research questions were supposed to follow. However, the program never took off in terms of empirical methods. For example, Luhmann's conclusion that "meaning cannot be measured with the techniques of information theory" (1990a, b, p. 27) was, in my opinion, too hasty. As I shall show, information theory can be extended with a theory of redundancy which enables us to estimate the imprint of meaning processing on information processing, and thus to take steps toward the operationalization of this program of studies.

[6]Habermas ([1985] 1987) revised his critique of Luhmann's program after almost two decades, as follows:

As Luhmann's astonishing job of translation demonstrates, this language can be so flexibly adapted and expanded that it yields novel, not merely objectivating but objectivistic descriptions even of subtle phenomena of the life-world. […].

As a result, the critique of reason carried out as a critique of metaphysics and a critique of power, which we have considered in these lectures, is deprived of its object. (p. 385).

1.6 Meaning and Information

Meaning is provided to events and information with reference to "horizons of meanings." Providing meaning to information can be considered as the selection of a signal from noise. The result is "meaningful information." The additional dimension of other possible meanings potentially resounding in each local selection makes the selection dynamics of processing meaning internally structured and non-linear, with the noted potential of preventing "the world from shrinking" by selections. As against Darwin's "natural" selection, cultural selection may add options to a system and thus *not* reduce complexity. I shall argue below that the sharing of meanings among human beings can generate redundancy by operating as a feedback against "the arrow of time" differently from the generation of uncertainty—that is a consequence of Shannon's (1948) proposal to operationalize information as probabilistic entropy.

New options can be added when the codes of the communications—the horizons of meaning—interact as control mechanisms *in addition to and in interaction with* the observable interactions at the level of the data. Both vertical and horizontal differentiations are then possible (Simon, 1973) and can operate upon one another. However, selections cannot operate without variation.

In my opinion, the variation-generating mechanisms were insufficiently specified by Luhmann, who posited, with reference to Bateson (1972), that "all information has meaning" (Luhmann, 1995, p. 67). Information, however, is empirical and contains uncertainty. In Shannon's (1948) information theory, information is yet-meaningless uncertainty or, in other words, (potentially random) variation. The specification of system(s) of reference is needed to provide this yet-meaningless information with meanings. Luhmann's specification of variation, however, is only in terms of frictions and irritations. Consequently, "information" cannot be measured from this perspective (cf. Baecker, 2017). However, I shall argue that the relations between (Shannon-type) information-processing and meaning-processing can further be clarified by extending information theory with a calculus of redundancy.

When different perspectives provide different meanings to the same information, one can expect redundancies in the overlaps among perspectives. In information theory, redundancy is defined as the complement of the information given the maximum information capacity—that is, the total number of options. Redundancy provides a measure for the options that were hitherto *not* realized historically but which *could have been* realized (Brooks & Wiley, 1986). (*Adding* redundancy adds also to the maximum information content, while the latter is equal to the sum of information and redundancy.)

Whereas Shannon-type information—$H = -\Sigma_i p_i \log_2(p_i)$—is (by definition) positive, selective feedbacks can be measured as *negative* bits or, in other words, as redundancy. The *sharing of meanings* on top of but different from the *communication of information* can generate synergy under specifiable conditions. Synergy enlarges the number of options at the above-individual level. In my opinion, this dynamic of adding options provides an operationalization of Luhmann's (1990a, b, p. 27) call for the specification of a "selection that prevents the world from shrinking."

I shall distinguish between (*i*) redundancy as the not-yet-realized options at each moment of time and (*ii*) the *generation* of redundancy as new options resulting from the synergy in the interactions among codes in interhuman communications. The latter redundancy operates upon the former, which is by definition at each moment the complement of the information to the maximum entropy.

Interpersonal intentionality can be expected to encompass both information in the first contingency of historical observables and redundancy in the second contingency of expectations. The two have to be unraveled analytically. I shall argue that historical and evolutionary processes operate as feedbacks on each other but with opposite signs. Note that interpersonal communication can be considered as intentional; however, the word "intentional" has a meaning at the supra-individual level different from individual intentionality.

The net result of the interactions between information and meaning processing can be measured in bits of information (Leydesdorff & Ivanova, 2014; Leydesdorff, Johnson, & Ivanova, 2018). If this net result is positive, historical realization in organizational formats prevails; if it is negative, self-organization of the communications is indicated changing and overwriting organizational shapes.

Self-organization means that the communication dynamics is guided by a code in the communications which tends to take over control from agency in terms of determining what can be communicated in specific communications. For example, scholarly discourse is coded differently from political discourse or market transactions. When the codes are not observable, they can be hypothesized and these hypotheses can be operationalized and tested. The possible interactions among codes are probably limited. For example, one cannot legitimately pay for the truth of a statement.

In summary: socio-cultural evolution has a complex dynamic of organization and self-organization that is different from biological evolution. For example, there can be trade-offs between selection mechanisms. Biological selection is based on genotypes that are *hard-wired*, historically present, and thus observable (e.g., as DNA). The "genotypes" of cultural evolution are codes of communication which can further be developed *because they are not hard-wired*. They are structures of expectations operating at a level above the hardware. Interactions among the codes can be positive or negative given historical constraints. Information theory enables us to measure whether new options (redundancies) are being created, to what extent, and in which relations.

In other words, the relations between evolutionary theory and systems theory can further be specified *using communication theory*. Increasingly, it has been my program of studies to relate these Luhmann-inspired ideas about meaning-processing with an information-theoretical operationalization (Leydesdorff, 1995; Shannon, 1948; Theil, 1972) and, thirdly, with the anticipatory mechanisms involved in the cultural evolution of expectations and meanings in the second contingency (Dubois, 2003; Luhmann, 2002a; Leydesdorff & Franse, 2009; Rosen,1985). The essays underlying this book were collected and reorganized in order to illustrate this progression: the questions are often Luhmann's; the answers are sometimes mine. Let me first distance myself from Luhmann and then return to the autobiographic narrative.

1.7 "Luhmann Reconsidered"

In my opinion, Luhmann's contributions have been obscured by attempts in his later work—mainly in the 1990s—to develop an overarching philosophy of observation on the basis of Spencer Brown's (1969) *Laws of Form*. The focus on Spencer Brown's very abstract and mathematical ideas has led to theoretical discussions among some of Luhmann's leading followers, but hardly to empirical research and the testing of theoretical claims. In my opinion, Shannon's mathematically theory of communications provides a much more fruitful methodology, because this theory—based on probabilities—provides instruments for the measurement (e.g., Theil, 1972). At the interface between Luhmann's sociological theory of communication and Shannon's mathematical theory of communication puzzles can be formulated that ask for empirical research, modelling, and simulation (Leydesdorff, 1995).

For example, I mentioned above the puzzle (raised by Luhmann already in 1971) of specifying social selection mechanisms other than "natural selection." Although Luhmann placed this and other puzzles on the agenda, he refrained from the elaboration and testing of these ideas as hypotheses. The theorizing thus tends to become a closed and highly codified artifact despite the empirical intentions. The focus on naturalistic "observations" brings the risk of historicism; without specification of "expectations" testing and therefore refutation become impossible. Differences are not yet significant because they are meaningful.

In a critical reflection on Luhmann's *œuvre*, Gumbrecht (2006; 2019) proposed to distinguish among Luhmann I, II, and III as follows:

1. "Luhmann I" (mainly—but not exclusively—in the 1970s) denotes the contributions to the Habermas-Luhmann discussion about the premises and construction of sociology as a theory of society.
2. During the 1980s, "Luhmann II" incorporated Maturana & Varela's (1980) theory of *autopoiesis*; that is, self-organization (Luhmann, 1995 [1984]). In my opinion, this program of studies begins with the publication of *Liebe als Passion* in 1982 (Luhmann, 1982b—translated as *Love as Passion* (Luhmann, 1986a)—includes the foundational study *Soziale Systeme* (Luhmann, 1984)—*Social Systems* (Luhmann, 1995)—and culminates in *Die Wissenschaft der Gesellschaft—The Science of Society*—published in 1990. Because of its specific focus on science as a communication system, the last book is most relevant for this study.
3. "Luhmann III" denotes the philosophy of observation which Luhmann developed during the 1990s in order to provide his work with a fundament in an axiomatic system to be derived from Spencer-Brown's (1969) *Laws of Form*.

"Luhmann I, II, and III" are not necessarily consecutive although there is a pattern of development. I agree with Gumbrecht that "Luhmann III" is problematic: following Spencer-Brown (1969) and other scholars in cybernetics (e.g., Baecker, 1999; Kauffman, 2003), Luhmann accepted in the early 1990s—on the basis of discussions with Von Foerster and Baecker—that a distinction that is identified can be considered as an *observation.* In the social sciences, however, the identification of a distinction specifies only an observational category—an empty box—and not yet an observation.[7]

In biology, a predator can observe its prey after distinguishing and identifying it in its environment. In the social sciences, observed values to be filled into the empty boxes thus generated have still to be determined empirically, for example, by measurement (De Zeeuw, 1993). The status of observations thus is different: not the observations, but observational categories are generated by distinctions and identifications. Observations are the results of the measurement and can be tested for their statistical significance.

"Luhmann II" provides another, and, in my opinion, most creative and original part of his *œuvre.* Crucial to the theory of that time is a *sociological* specification of the *autopoiesis* model of Maturana & Varela (1980 and 1984) in a series of studies. The autopoiesis model—*autopoiesis* is the word for self-organization in classical Greek—combines structure and action and thus allowed Luhmann to bridge the gap between Parsons' structural functionalism and symbolic interactionism in sociology (Grathof, 1978; cf. Giddens, 1981, p. 167). The communication structures are reproduced and changed by interactions which are *carried* by agents. However, the biological model of *autopoiesis* cannot be applied to inter-human communications without modifications. As Luhmann (1986b, p. 172) put it:

> [...] living systems are a special type of systems. However, if we abstract from life and define autopoiesis as a general form of system-building using self-referential closure, we would have to admit that there are non-living autopoietic systems, different modes of autopoietic reproduction, and general principles of autopoietic organization which materialize as life, but also in other modes of circularity and self-reproduction. In other words, if we find non-living autopoietic systems in our world, then and only then will we need a truly general theory of autopoiesis which carefully avoids references which hold true only for living systems. But which attributes of autopoiesis will remain valid on this highest level, and which will have to be dropped on behalf of their connection with life?

[7]Luhmann (II) had up until that time (that is, approximately 1990) worked with two major distinctions: (*i*) system and environment, and (*ii*) (individual) "consciousness" and inter-human "communication." In his 1990 book about the *Science of Society,* Luhmann explicitly objected to this reduction of sociological reasoning to observing as the basic concept of sociological analysis by formulating as follows:

> It would perhaps be possible to abandon the idea of a human subject and only use the words "observers" and "observations." However, such semantic changes do not lead anywhere as long as there is only one way to identify the observer, namely as a human being. (p. 14; my translation)

As noted, human beings ("consciousness systems") were not Luhmann's subject of study except in their relation to communications. As stated above, "action" needs to be explained.

A sociology based on the "autopoiesis" of communications can be considered as a form of *radical constructivism* (Knorr-Cetina, 1989). As against other forms of constructivism, the focus is on the *constructedness* of the constructs and not on the constructing agency (Luhmann, p. 515 ff.; cf. Latour, 1983). In science and technology studies (STS), however, the focus has been mainly on explaining macro-structures in terms of micro-sociological agency (e.g., Knorr-Cetina, 1981; Krohn et al., 1990; Latour & Woolgar, 1979; Latour, 1996; cf. Leydesdorff, 1993; Luhmann, 1995). From this perspective, one can consider Luhmann's approach as a paradigm shift from the Latourian approach prevailing in STS (Nowotny, 1990; cf. Wagner, 1996). I return to this issue in Chap. 3.

1.8 Codification

The *meaning* of a communication is a second-order variable attributable to the communications. The latter are first-order attributes of communicating agents. Meanings originate from communications and feedback on communications. When selections can operate upon one another, a complex and potentially non-linear dynamics is generated. In other words: communications are provided with meanings in a layer other than agency. Meanings are based on reflections; they are attributes of the links and not of the actors at nodes in networks, and are therefore by their nature *inter*-subjective (Fig. 1.1). The communicators—Luhmann used the word "consciousness" for individuals—provide variation to systems of communication.

The codes coordinate the communications by discarding the noise on the basis of selection criteria. These coordination mechanisms are not "given" or directly observable. The theoretical task is to specify the selection mechanisms in terms of specific codes. The codes in the communications are structural and therefore *determine* the selections. For example, one can say different things in a courtroom,

Communications with communicators	Communications	Communications with codes of communication operating as coordination mechanisms

Fig. 1.1 Communications can be considered as attributes of communicators, but they can also be considered as second-order units of analysis to which codes of communication can be attributed

in parliament, in a newspaper, or in a class, because of differences in the codifications in the language given respective settings.

Codes developed in the communication provide criteria for the selections and thus coordinate the system in which they emerge. Codes, however, have to be constructed as a further refinement of language in a historical process before the logic of the selection can take control over the logic of variation in the communication from which the codes emerged. This emerging order builds on support structures that have to be reproduced; for example, in terms of carrying institutions.

1.8.1 Husserl's "Intersubjective Intentionality"

Luhmann elaborated on three disciplinary backgrounds for the specification of selection mechanisms in interhuman communications: (*i*) Husserl's (1929) "intersubjective intentionality" in the philosophical background; (*ii*) Parsons' (1963a, b; 1968) "symbolically generalized media of communication" for the sociological operationalization; and (*iii*) Maturana's (e.g., 1978) "autopoiesis" or self-organization theory for the dynamic model.

First, Luhmann's *œuvre* can be considered as an attempt to operationalize Husserl's philosophical concept of "intersubjectivity" sociologically in terms of inter-human communications (Luhmann, 1995; cf. Knudsen, 2006). Luhmann was fascinated by Husserl's philosophy. For example, Paul (2001, at p. 374) described this commitment to Husserl's philosophy as follows:

> […] one can hardly overestimate the importance of Husserl's phenomenology for Luhmann (1996). I can distinguish two levels of influence. First, Luhmann extends Husserl's project, bequeathing legitimacy not only on reflection or conscious action but also on the *experience* of the world. Second, his analyses of the constitution of the social follow directly upon the problem posed by Husserl as to whether and, if so, how, intersubjectivity can be understood.

Meanings can be shared in a non-linear dynamic co-evolving as a feedback on the underlying flow of information. As Luhmann (2002a, at p. 53 ff.) formulated:

> A variant of operative constructivism […] is presented today under different brand names: for instance, formal calculus; second-order cybernetics; the theory of closed, "autopoietic" systems; or radical constructivism. Its disciplinary provenance is very heterogeneous, ranging from mathematics to biology and neurophysiology to the theory of automata and linguistics. […]
>
> But how would it be if one could successfully show that Husserl already uses this theory, except that, with concepts such as "subject," "spirit," or "transcendental phenomenology," he places it within a tradition that already in his time had little chance of a future. […] I believe that this is possible if one […] distinguishes whether systems are constructed on the basis of intentional acts of consciousness or on the basis of communication.

In the fifth of his so-called *Cartesian Meditations*, entitled "Uncovering of the Sphere of Transcendental Being as Monadological Intersubjectivity," Husserl (1929) addressed the intersubjective level. He formulated (at p. 182)[8] that “the intrinsically first being, the being that precedes and bears every worldly Objectivity, is transcendental *intersubjectivity* […].” However, Husserl added that “we must forego a more precise investigation of the layer of meaning which provides the human world and culture, as such, with a specific meaning and therewith provides this world with specifically ‘mental’ predicates” (1929, at p. 138; my translation). In contemporary wording: Husserl noted that he had no instruments (methodologies) beyond his “transcendental apperception” of intersubjectivity.

Luhmann proposed using semantic resources from the other two traditions (Parsons’ structural-fuctionalism and Maturana’s theory of *autopoiesis*) for the operationalization of the interpersonal domain in terms of communications. Communications build on communications and can thus shape patterns. The recursively repeated patterns of communications shape forms that code the communication increasingly in specific directions as they emerge. After their emergence the codes can begin to shape the room for further communications in feedback loops; analogously to the mechanism of preferential attachment (Barabási & Albert, 1999) or cumulative advantages (de Price and Solla, 1976; cf. Arthur, 1989).

For example, money can be considered as such a communication-facilitating code. It enables us to accelerate economic transactions: one can pay the price of a commodity instead of having to bargain on the market. Credit further speeds up monetary transactions; credit cards enable us to shop worldwide. These codes of communication operate within *and* on top of the communications from which they emerge endogenously. The codes are part of the communication, but their logic of control is different from that of the historical developments in the communications. While the communication develops historically along *trajectories*, the emerging codes operate as feedbacks from the next level of a *regime*. The regime exerts selection pressure on the trajectories.

As in the case of money, the mechanisms of scientific communication, for example, have become internally structured by using more than a single code:[9] the “context of justification” operates as a selection mechanism on outcomes of the “context of discovery” (Popper, 1935 [1959]). The context of justification can be considered as a “self-organized”—and therefore endogenous—control system of the communication among scholars (Merton, 1942). The context of discovery provides the larger environment in which knowledge can be generated. On the basis of this production process, knowledge claims are formulated, for example, in manuscripts. The manuscripts can be reviewed in the context of justification and then selectively codified before possibly becoming part of the archive of science.

This evolutionary dynamic of scholarly discourse has become part of the self-understanding of the sciences (e.g., Hempel & Oppenheim, 1948). Communications are *not grounded, but anchored* by codes. Using Neurath’s (1932/33, p. 206) well-known metaphor: “The ship has to be rebuilt while a storm is raging on the open sea.” Popper (1935) formulated, as follows:

[8] Husserl (1929 [1960]), at p. 156 in the English translation.

[9] Luhmann insists that codes are binary and unique.

> The empirical basis of objective science has thus nothing 'absolute' about it. Science does not rest upon solid bedrock. The bold structure of its theories rises, as it were, above a swamp. It is like a building erected on piles. The piles are driven down from above into the swamp, but not down to any natural or 'given' base; and if we stop driving the piles deeper, it is not because we have reached firm ground. We simply stop when we are satisfied that the piles are firm enough to carry the structure, at least for the time being. (p. 111)

The codes can be the unintended results of repeating patterns of communication; the logic of the codes is intersubjective, while individual intentions are subjective. The patterns develop in terms of selections over time operating upon selections at each moment. Some selections can be selected for stabilization along a trajectory; some stabilizations can be selected for globalization and thus be incorporated. Whereas trajectories coordinate historical practices, regimes structure expectations or, in other words, the domain of possible practices. As a next-order emerges (after a bi-furcation), the meanings of the communications may have to be restructured because of unbalances in the system.

In a study entitled "The problem of transcendental intersubjectivity with Husserl," Alfred Schutz (1952, at p. 105) [10] objected that Husserl's concept of "intersubjectivity" could ultimately not be grounded. As Schutz put it:

> All communication, whether by so-called expressive movements, deictic gestures, or the use of visual or acoustic signs, already presupposes an external event in that common surrounding world which, according to Husserl, is not constituted except by communication. (Schutz, 1975, at p. 72).[11]

Such a "grounding," however, was not Husserl's intention. In his philosophy "intersubjectivity" remains *intentional*, whereas Schutz argued in favor of an *existential* grounding of intersubjectivity in a "we," for example, when he went on to say: "As long as man is born from woman, intersubjectivity and the we-relationship will be the foundation for all other categories of human existence" (*ibid*., at p. 82).[12] Schutz wished to ground the communication in the "life-world" as a common frame of reference for the communicating agents—for example, when "making music together" (Schutz, 1951; cf. Johnson & Leydesdorff, early view)—he criticized Husserl for explaining this ground as a *result* of intersubjective communication.

Husserl's intentional intersubjectivity is not a layer that objectively "exists," but it can be considered as a logic. This logic enriches the system and our reflexive understanding of it. Latour (1996) and Maturana (2000) suggested independently of each other to call this mode of pending existence "inter-objectivity.") According to Husserl (1929, at p. 159), however, "intersubjectivity *precedes* being" (italics added, L.). In the last section of the *Cartesian Meditations* (p. 181), Husserl concluded that the study

[10] Cf. Habermas, 1981, at p. 178f.; Luhmann, 1995, at p. 170.

[11] 'Alle Kommunikation, ob es sich um eine sogenannte Ausdrucksbewegung, eine Zeigegeste, oder den Gebrauch visueller oder akustischer Zeichen handelt, setzt bereits einen äußeren Vorgang in eben jener gemeinsamen Umwelt voraus, die nach Husserl erst durch die Kommunikation konstituiert werden soll' (Schutz, 1952, at p. 97).

[12] 'Solange Menschen von Müttern geboren werden, fundiert Intersubjektivität und Wir-beziehung alle anderen Kategorien des Menschseins' (Schutz, 1952, at p. 105).

of intersubjective intentionality can provide us with "*a concrete ontology and theory of science*." While Schutz's argument of grounding asks for an origin and an explanation in terms of the *genesis* of what is to be explained, the intentional perspective inverts the arrow of time and considers future possibilities and constraints explaining current states. The theory of intersubjective intentionality opens the communication towards investigating future states as causal drivers.

In later chapters, I will address this issue in terms of recursions and incursions in anticipatory systems. I shall argue that the sciences can be considered as generating *rationalized systems of expectations*. The rationalization requires specific codes which operate as feedbacks selectively structuring and regulating the claims of novelty.

1.8.2 Autopoiesis

By operating in terms of repeated selections, patterns are shaped. A network is first constructed in terms of links which build upon each other over time. The resulting structure has an architecture; one can expect main axes. Communications can be expected to differentiate along the main axes into perspectives providing possibilities for specific coordinations.

In formal terms, one can describe this differentiation in the communication as the emergence of eigenvectors or principal components of the communication matrix when this matrix is repeatedly multiplied by itself. The differentiation of coordination in terms of codes allows for more complexity, and can thus accelerate the communication. Luhmann took these concepts from cyberneticians and mathematical biologists writing mainly in German, among them Heinz von Foerster (e.g., 1960, 1993) and Ernst von Glasersfeld. Von Glasersfeld (2008, at p. 64, n. 4) translated one of Luhmann's (1992, p. 46) formulations into English as follows:

> Even if the self-description of society springs only from a recursive network of observations of observations and descriptions of descriptions, one might expect that eigenwerte ("eigenvalues," L.) arise in the course of these operations, that is, positions that will no longer change in further observations of observations but that will remain more or less stable.

Von Glasersfeld, however, qualified this "as an elegant but rather loose metaphor" (p. 64, n. 4).[13] Von Foerster's (1960) model of self-organization and the *autopoiesis* model of Varela, Maturana and Uribe (1974) build on the same intuitions. These scholars had met one another at the Biological Computer Laboratory (BCL) in Urbana, Illinois (Pickering, 2010). Maturana (1978) further elaborated the model of *autopoiesis* into "a biology of language and knowledge" (Maturana & Varela, 1980 and 1984). However, Maturana remained cautiously a biologist in his formulations: the aim was to explain linguistic *behavior*—Maturana (e.g., 2000) uses "languaging"—and not human language or the cultural content of knowledge itself.

[13] The eigenvalue of an eigenvector is the factor by which the eigenvector is scaled when multiplied by the matrix.

Can the biological model be extended for capturing interhuman communciatons? One can imagine that one understands languaging animals (whales, monkeys, etc.), but "languaging" remains a metaphor. However, the sociological analysis requires access to content since both commitment (Weber's *Verstehen*) and value-freeness are needed. Only human languages are sufficiently complex and flexible to carry the richness of such an analysis.

1.8.3 Parsons' Media Theory

Following Parsons (e.g., 1968), Luhmann proposed to analyze society as functionally differentiated. The functional subsystems (economics, science, policy, etc.) each develop their own logic by entertaining a "symbolically generalized medium of communication" with a specific code. However, the relations between the codes and the media were formulated a bit differently in Parsons' and Luhmann's sociologies. These differences were analyzed, for example, by Künzler (1987, 1989), who formulated (Künzler, 1987, at p. 323; my translation) as follows:

> In contrast to Parsons, who refers to linguistic code models, Luhmann wanted, in his programmatic explanations, the media-theoretical code term initially related to the model of the genetic code. Luhmann understands a code as a duplication rule that provides two possible expressions for occurrences and states that exist only once [...] (see Luhmann, 1981: 246; 1975: 172).

Künzler argues that unlike Parsons' linguistic codes, Luhmann's codes can be considered as (meta-)biological duplication rules which are turned "on" or "off" in a binary mode, as in the case of DNA (Habermas, 1987; Künzler, 1987: p. 331; Leydesdorff, 2000, 2006a). However, this biological perspective pays insufficient attention to the specificity of inter-human communications when the code is reduced to the dichotomy true/false.[14] Only mathematical and logical statements can be proven true or false. Empirical statements can only be more or less uncertain.

Herbert Simon's (1973) characterization of the sciences as operating in terms of truth-*finding* (heuristics) and puzzle-solving, and thus with more than a single code, seems empirically more fruitful to me. A binary scheme of "true/false" does not inform us either theoretically or empirically.[15] The specification of uncertainties—grey shades—based on *probabilities* which vary between zero and one, can be made relevant for empirical research.

Merton (1948) criticized Parsons' sociology as not fruitful for empirical research in the social sciences *because* of the a priori of a general scheme of analytically distinguished functions. What is "functional" from one perspective, however, can be

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[14]Luhmann uses "true/not-true"; for an assumed difference between "not-true" and "false," see for example Luhmann (1990a, b, at p. 416).

[15]Information-theoretically, both extremes of a binary distribution ($p = 0$ and $p = 1$) lead to a message without information (sing $1 * \log(1) = 0$ and $0 * \log(0)$ is also zero. In the case of a ratio 50/50, however, one bit of information can be expected.

dysfunctional from another perspective or in a next stage, and differentiation can also be expected to operate in opposition to integration (Mittroff, 1974). As an alternative, Merton argued in favor of "middle-range" theories. There is not one single selection mechanism or set of selection mechanisms operating, but a variety of processes of codification which are both horizontally and vertically integrated and differentiated. As Merton (1948) formulated:

> I have suggested only that an explicitly formulated theory does not invariably precede empirical inquiry, that as a matter of plain fact the theorist is not inevitably the lamp lighting the way to new observations. The sequence is often reversed. Nor is it enough to say that research and theory must be married if sociology is to bear legitimate fruit. They must not only exchange solemn vows—they must know how to carry on from there. Their reciprocal roles must be clearly defined. (p. 515)

I agree that empirical research develops *alongside* theory-development. However, the question to be raised seems to me: what precisely is differentiated and integrated, at which level and by which mechanisms? Action, for example, is integrative in the performance; differentiation, however, is structural. Whether a differentiation is functional can be investigated empirically.

In my opinion, not the functions but the codifications are differentiated. In an invited response to my (2012) paper entitled "Radical Constructivism and Radical Constructedness: Luhmann's Sociology of Semantics, Organizations, and Self-Organization," Distin (2012, p. 95) formulated as follows:

> […] while natural languages correspond to Luhmann's (linguistically-structured) communication media, and artefactual languages to his (linguistically-structured) dissemination media, the term *symbolically generalized communication media* is a misnomer. I have argued elsewhere (Distin 2011: 146–165) that money is an artefactual language; but Luhmann's other examples, such as truth, love, and power, cannot meaningfully be called either languages or media.

In her book entitled *Cultural Evolution*, Distin (2010) elaborated the definition of "meta-representations," as follows:

> A metarepresentation is a representation of another representation. Its content is that other representation, and crucially this includes information about both form and content. The ability to metarepresent is the ability to recognise the distinction between the two: to reflect on the connection between a representation and the information that it represents. The information that evolves, when we metarepresent, is information about *how we represent.* To put this another way, once we start comparing the representational features of different languages, the two systems effectively begin to compete with each other, under representational pressure.
>
> As the briefest glance at modern culture makes clear, our cognitive escape route from the restrictions of our native language has not been restricted to other natural languages. Limited as it is by the length of the critical period and by the human capacity for learning, natural language has become, over time, inadequate to the representational task that it was originally set. If language is to account for cultural evolution, then we need to look beyond natural language to the artefactual languages that have evolved in its wake. (p. 86)

When the meta-representations operate both upon one another and upon representations in one or more cycles, redundancy and therefore new options can be expected

(Krippendorff, 2009b). New options can be added to the communication because of synergies in interactions among codes (Leydesdorff et al., 2017). As noted, the generation of options is crucial, for example, for the viability of innovation systems (Petersen et al., 2016).

In summary: flows of communication are molded by selective codes, on the one hand, and variation, on the other. These contexts provide two analytically different perspectives on the same events; the data can be organized using different logics. From an historical perspective, one focuses on variation and agency, and the potential morphogenesis of systemic relations in the data. From an evolutionary perspective, the focus is on the same data indicating selection environments which can be specified on the basis of a reflexive turn. Analogously, human minds not only partake in the network dynamics as the constructive agents who generate variation, but can at the same time be involved reflexively in the processes of providing meaning to the data. The perceptive role is different from the constructive one.

Increases in the number of options provide evolutionary advantages in terms of, for example, viability of systems (Petersen et al., 2016; Stafford Beer, 1989). New options can be generated in translations among differently coded communications. Agents mediate in the translations. Following Parsons, Weinstein and Platt (1969), for example, considered the generation of new options for experiencing and action as a driver of cultural evolution. New options can also be generated in synergies and frictions between the codes of communication, on the one side, and consciousness, on the other.

When Latour (1983), for example, quoted Pasteur saying "Give me a laboratory, and I will raise the world," the resulting world was a new option attributed (by Latour) to Pasteur's imagination of a vaccine. Historically, Pasteur demonstrated his capacity to vaccinate cows against cow-pox to journalists. The journalists had to formulate "infra-reflexively" (Latour, 1988, at p. 169 ff.) the translation of scientific news to newspaper items. Their work is both reflection and action. The relations between scientific and journalistic coding are made specific in instances.

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 can be selected for globalization. The trade-offs between stabilization (de-stabilization, meta-stabilization) and globalization are empirical and therefore amenable to the measurement. I shall argue that knowledge dynamics can be considered as a third coordination mechanism at the supra-individual level interacting with wealth generation in industry and political control by governance and regulations.

1.9 The Triple Helix Model

How and why did I relate Luhmann's analysis to the Triple Helix (TH) model of University-Industry-Government Relations? Whitley (1984) may have been the first to point to the transformation of the macro-system because of the function of "organized knowledge production and control" in reputationally controlled organizations. The control function is no longer carried by individual agents (for example, a principal agent; Van der Meulen, 1998). Functions are coded at the above-individual level. Whereas political economy can be explained in terms of two coordination mechanisms (markets and governments), a knowledge-based economy is the result of three coordination mechanisms interacting and operating upon one another. Interactions among three selection environments shape a triple helix with properties very different from double helices.

The crucial book for relating Luhmann's theory to these empirical questions was, from my (autobiographical) perspective, *Die Wissenschaft der Gesellschaft* (*The Science of Society*; Luhmann, 2000). In 1989 Peter Weingart, then Professor at the Faculty of Sociology in Bielefeld, provided me with a copy of the manuscript version of this book when we met at a workshop in Amsterdam. For me, this study clarified Luhmann's more programmatic book *Soziale Systeme* (*Social Systems*, 1995 [1984]), which at the time I had found difficult to read. When the book about the sciences was published the following year (1990), however, I saw possibilities to relate this theory to my methods and techniques.

In 1992 I wrote a review for *Science, Technology, & Human Values*, the journal of the Society for the Social Studies of Science (4S; Leydesdorff, 1992). For the purpose of enriching the discourse in STS with these new perspectives, I furthermore organized a nationwide colloquium in Amsterdam, where we discussed a chapter of the book each week. Furthermore, I organized a discussion between Luhmann and Latour in a plenary session of the combined meetings in Bielefeld (Germany) of the Society for the Social Studies of Science (4S) and the European Association for the Study of Science and Technology (EASST), on 12 October 1996 (Wagner, 1996). At that occasion, Luhmann mentioned that he was ill. However, he felt relieved that his final book in the series entitled *Die Gesellschaft der Gesellschaft* (*The Society of Society*) had been sent to the publisher (Luhmann, 1997a, b). On May 11–12, 1998, I had the honor to replace Luhmann at a workshop on "*Autopoiesis* and Social Systems" held at the London School of Economics (organized by Eve Mittleton-Kelly, and with Humberto Maturana and Günter Teubner among the speakers). Luhmann passed away on November 6, 1998.

At the time of the publication of *Die Wissenschaft der Gesellschaft,* I was finishing my own (1995) book entitled *The Challenge of Scientometrics: The Development, Measurement, and Self-Organization of Scientific Communications.* My idea was first to specify a model of the self-organization of scientific communications, and then to add incrementally to the complexity by studying the interactions among codes at interfaces into technological innovations. Which models in science studies can be translated into technology studies, and how are other codes recombined into innovations in a knowledge-based economy?

Focusing on technological development and innovation, Gertrud Blauwhof took the lead in her Ph.D. project entitled *The Non-linear Dynamics of Technological Developments: An exploration of telecommunications technology* (Blauwhof, 1995; Blauwhof & Leydesdorff, 1993). Among other things, Gertrud spent some time in

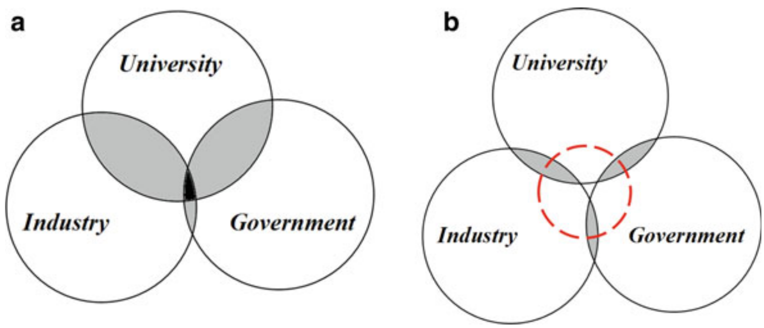

Fig. 1.2 **a** Integration in the overlaps among the three helices of a Triple Helix. **b** Differentiation and hypercyclic integration at the next level

Bielefeld during 1993 in order to attend Luhmann's lectures. I began in these years to offer my yearly course on Luhmann and self-organization.

Although Luhmann's writings remained a source of inspiration (e.g., Leydesdorff, 2005, 2013), my research interests further evolved in terms of methodologies (Leydesdorff, 2001). In collaborations with Peter van den Besselaar, we focused on the non-linear dynamics of technology and innovation using simulations (Leydesdorff & van den Besselaar, 1998a, b; van den Besselaar & Leydesdorff, 1992, 1993). In 1993 Peter and I organized a workshop entitled *Evolutionary Economics and Chaos Theory: New directions for technology studies* (Leydesdorff & van den Besselaar, 1994). In the "Epilogue" to the book I depicted the option of a hypercycle (Fig. 1.2b) as an integration mechanism among three cycles that is different from the usual overlap depicted in Fig. 1.2a.

The elaboration of this hyper-cycle model into a Triple Helix (TH) of university-industry-government relations followed in a project with Henry Etzkowitz (Etzkowitz & Leydesdorff, 1995, 1997, Etzkowitz and Leydesdorff 2000) in the years thereafter, and increasingly with other colleagues as well. Etzkowitz (1994) contributed a chapter entitled "Academic-Industry Relations: A Sociological Paradigm for Economic Development" to our 1994 book (pp. 139–151). When we met again in 1995 at a workshop in Abisko (Sweden), we agreed on "the triple helix of university-industry-government" as a common topic (Etzkowitz & Leydesdorff, 1995; see Chap. 5).

The extension of bilateral university-industry relations—Etzkowitz's main topic at the time—to trilateral university-industry-government relations was essential from my perspective, since the model of a hypercycle is only meaningful in the case of three (or more) subdynamics. The "hypercycle"—indicated with a dotted line in Fig. 1.2b—provides a metaphor for the supra-individual dynamics that give intersubjective meaning to the meanings provided by the carrying cycles. In other words, the emerging next-order-level "overlay" can contain a meta-representation of the individual representations and their interactions. This meta-representation in the hyper-cycle feeds back as a regime on the underlying dynamics which evolve historically along trajectories.

This historical development is *recursive*: the current state of a system (x_t) is a function of the previous state ($x_{t-\Delta t}$) in the historical world. However, the feed*back* of a hyper-cycle operates against the arrow of time: the expected state at a next moment of time ($t + \Delta t$) *incurs* on the carrying cycles. Expectations can incur on the present system *because* they are no longer only subjective; the intersubjectively carried code is the operator. This *incursion* of a mechanism operating on the recursive (that is, historical) dynamics against the arrow of time introduces the logic of anticipatory systems.

1.10 Anticipatory Systems

The hyper-cycle (in Fig. 1.2b) does not "exist" in the sense of being observable, but operates in terms of expectations. The next state can be anticipated by (human) agents with the reflexive capacity to make assumptions and to entertain a model. Using a model, the various options can then be explored. Thus, I will propose (in later chapters) to supplement the historical triple-helix dynamics, developing along the arrow of time and generating probabilistic entropy, with a feedback arrow of systems of expectations that operate against the arrow of time and generate redundancy instead of (Shannon-type) information.

The theory and computation of anticipatory systems were introduced to me by Daniel M. Dubois, at a conference on "Emergence" in Amiens (France) in 1996 (Leydesdorff, 1996). Dubois had read my *Epilogue* to the 1994 book and invited me as a member of the international board of his conferences about the Computation of Anticipatory Systems (CASYS) held bi-annually in Liège, Belgium, since 1997. In 2007, I had the honor to give the Vice-Presidential lecture entitled "The Communication of Meaning in Anticipatory Systems: A Simulation Study of the Dynamics of Intentionality in Social Interactions," included (albeit differently organized) in this book as Chap. 8.

The Triple-Helix model and the modeling of anticipatory systems can be related. Feedback and feedforward loops among the subdynamics can be expected to generate both uncertainty—forward and historically—and redundancy—backward and evolutionarily. However, the measurement theories for these two dynamics are very different; the difference is not only an inversion along the time dimension. The transition from a previous state (at $t = t$) to a next state (at $t = t + \Delta t$) can be very different from the reverse transition (in discrete time).

I shall use information theory to describe the historical process with a positive sign and the evolutionary one operating as a feedback with a negative sign. (One could also use other statistics—for example, analysis of variance (McGill &

Quastler, 1955)—for measuring this TH dynamics, but the relation with the evolutionary perspective is then lost.) Information theory allows us to study the *evolution* of *communication systems* and thus to address the questions formulated above as the core of Luhmann's theoretical program: "How are these theories—communication theory, systems theory, and evolution theory—related to one another? What unifies them? How must a theory that integrates them be constructed?" (Luhmann, 1975, at p. 96; Luhmann 1982b, at p. 261.)

The proposed operationalizations and methods for the measurement make it possible to distinguish between historical organization and evolutionary self-organization as a vertical dynamic which operates on the horizontal differentiation among wealth generation in industry, novelty production in academia, and normative control and governance. However, the theory and computation of anticipation were not part of Luhmann's sociology, although he noted the intuition that "(S)elf-referential autopoietic reproduction would not be possible without an anticipatory recursivity" (Luhmann, 1995, at p. 446f.). He added that such an analysis should be performed "with sufficient precision." Luhmann ([1997a] 2012) provided at some places (e.g., [pp. 206, 820] 2012, Vol. 1, p. 123; 2013, Vol. 2, p. 137) footnotes to Rosen's (1985) book entitled *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations*, but these references were not further elaborated.

The mathematical biologist Robert Rosen first defined anticipatory systems as systems that entertain models of themselves (Rosen, 1985). The model represents a future state that is available in the present and can be used for further development. Dubois (1998) provided an operationalization of Rosen's model, and Dubois (2003) added the distinction between *weak* and *strong* anticipation. As human beings we ourselves can be considered as *weakly* anticipatory systems: we are able to construct and entertain different models of ourselves, but we are also historically constrained by our current state ("the body"). We are able to construct our present state (at t) with reference to both our past ($t - 1$) and our mentally envisaged states at future moments in time ($t + 1$, $t + 2$, …, etc.)

As against weakly anticipatory systems, strongly anticipatory ones construct their next state *exclusively* from expectations representing states at $t + \Delta t$. However, one cannot expect a system other than systems of expectations to operate in this mode. (All other systems also take their past and/or present states into account as independent variables.) *The constraint of having to be historical vanishes at the level of supra-individual expectations,* since communications are not a living or even "existing" system. The evolutionary dynamics of strong anticipation in terms of interacting expectations is meta-historical; from this perspective, the history of the system is only one among other subdynamics. The historical descriptions can specify only the morpho-genesis of the system(s) under study (Archer 1995).

For example, one can expect the rule of law to operate as a highly codified system of expectations at the supra-individual level. As noted, this does not preclude that human consciousness plays a crucial role in its instantiations and translations. The rule of law, for example, presumes that judges are able to instantiate codified expectations in each verdict. Note that these expectations are not only socially constructed, but also codified at the above-individual level. One can observe the footprints of the evolutionary dynamics in history in specific forms of organization (e.g., courts) and along trajectories of discourse (e.g., jurisprudence). From an evolutionary perspective, the observable systems can also be considered as retention mechanisms.

In other words, the observable phenotypes are historical, but the "genotypes" are theoretical and meta-historical (Langton, 1989, p. 6). Unlike the biological code (DNA), the codes of communication are not materially given. The codes remain *res cogitans*: structures of expectations, which one can (re)construct using theories; that is, as hypotheses. Selections in this domain are no longer "natural," but culturally constructed. The selection mechanisms operate in terms of criteria which are coded into the communications.

The codes of communication can be expected to remain in flux. They can further be developed so that they can process more complexity. As Luhmann ([1997, p. 205] 2012, p. 123) stated: "A complex research program is hence envisaged." Luhmann's theory provides substantive theorizing, but the author sometimes shows an aversion to statistics and the testing of hypotheses (cf. Stäheli, 2000). In my opinion, one needs both a substantive and a measurement theory so that observations can eventually be flagged as statistically significant or not.

1.11 The Measurement of Triple-Helix Synergy

At a workshop about *Semiotics, Evolution, Energy, and Development* (SEED) in Toronto in 2002, the ecologist Robert Ulanowicz suggested using mutual information in three dimensions for the purpose of measuring the overlay in TH configurations (Ulanowicz, 1986, at p. 143). There is a substantial literature about this measure since McGill (1954) introduced it (e.g., Yeung, 2008). The cybernetician W. Ross Ashby, for example, explained the measure as the amount of information (e.g., in bits) due to the unique combination of a number of variables, and not reducible to any of its subsets. Krippendorff (2009a, p. 193) mentions that Ashby was so fascinated with this "synergy" indicator that he wore a necklace consisting of three interlinked chains. The necklace had the property of falling apart into separate chains if any one of them was cut.

One can consider mutual information in more than two dimensions as a quantitative indicator of synergy among the parts: the additional options are generated in the *interactions among the codes of communication* as a level different from the interactions among the observable communicators (Krippendorff, 1980).

Although it follows from the Shannon equations that the value of this indicator can be negative, this generates a puzzle in information theory. Shannon-type information can by definition only be positive—because of Shannon's (1948) choice for the H in the second law of thermodynamics ($S = k_B * H$; $H = -\Sigma_i p_i * \log_2(p_i)$). It follows that this indicator should not be considered a Shannon entropy: it measures feedback from a (hypothesized) future state in a loop both with and against the arrow of time (Krippendorff, 2009a).

A further complication is that the indicator changes sign with the dimensionality of the system(s) under study (Krippendorff, 2009b). While synergy is indicated by negative values in the case of three dimensions, it is positive in the case of four, etc. From the perspective of the TH, one would like to have an indicator which could be extended beyond the Triple helix to a Quadruple, Quintuple, or *N*-tuple helix in a single framework (Carayannis & Campbell, 2009, 2010).

In October 2013, Inga Ivanova noted in an email conversation that mutual information in three (or more) dimensions can only be negative as redundancy and not as information. In other words, one can extend the Shannon-framework with a theory (and a calculus) of redundancy (see Chap. 4 for the technical elaboration). In information theory, redundancy and uncertainty are by definition each other's complement to the maximum information content of a distribution. Adding to the redundancy reduces the relative information. I shall argue that the generation of redundancy from reflexive interactions provides the selection mechanism that Luhmann (1990a, b, at p. 27; see above) envisaged.

1.12 Concluding Remarks

The number of options available to an innovation system may be more decisive for its survival than the historically already-realized innovations. Although uncertainty features in all innovation processes (Freeman & Soete, 1997, p. 242 ff.), it poses crucial challenges to the governance of innovation. An indicator of surplus options can thus be appreciated in innovation studies from the two perspectives of (*i*) reducing uncertainty and (*ii*) increasing the number of not-yet-realized options.

First, one would expect a configuration with less prevailing uncertainty to be more rewarding with regard to risk-taking than configurations with high uncertainty. Reduction of the prevailing uncertainty provides dynamic opportunities comparable to local niches—that is, protected spaces that allow for experimentation with other co-evolutions between selection environments (e.g., Schot & Geels, 2008, p. 537).

Second, an increase in redundancy is an effect at the systems level—that is, a result of interacting selection mechanisms. Among the total number of possible options, the redundancy represents the options that have not (yet) been realized. An increase in this number does not affect the number of the realized options (Brooks & Wiley, 1986, p. 43; cf. Khalil & Boulding, 1996). Redundancy can be generated by synergy in the interactions among the codes.

In summary: whereas university-industry-government relations are historical and therefore amenable to forms of measurement, I shall use the Triple Helix model below (Chaps. 4–7) also as proxies for novelty production in academia, wealth generation in industry, and normative regulation by governments as three interacting perspectives. In Chap. 5 this TH model is generalized to a model of interactions among *demand*, *supply*, and *control* as the three dynamics structurally required in innovation processes.

A cognitive and future-oriented input to S&T policies can thus be envisaged. In Chap. 6, I demonstrate this empirically—using data of Statistics Italy—for the relations between local, regional, and national innovation systems in Italy; the measurement instrument for synergy is further developed in Chap. 7 into a computer routine. Using a matrix of aggregated references among journals, for example, one can map which combinations of journals are most synergetic. The measurement of synergy will be compared with that of interdisciplinarity.

The core of the book begins at Chap. 4. Chapters 2 and 3 are needed to position these contributions in relation to mainstream STS (Chap. 3), philosophy of science, and epistemology (Chap. 2). I elaborate my own philosophical position in Chap. 10. Chapters 4–9 explore the new perspectives both theoretically and in terms of methods.

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Part I
The Sociocybernetics of Scientific Knowledge

Chapter 2
The Communication Turn in Philosophy of Science

Whereas knowledge has often been attributed to individuals or, from a sociological perspective, to communities, a communications perspective on the sciences enables us to proceed to the measurement of the discursive knowledge contents. Knowledge claims are organized into texts which are entrained in evolving structures. The aggregated citation relations among journals, for example, can be used to visualize disciplinary structures. The structures are reproduced as "ecosystems" which differ among them in terms of using specific codes in the communications (e.g., jargons). Unlike biological DNA, these codes are not hard-wired; they can be changed in the communication. The sciences develop historically along trajectories embedded in regimes of expectations. Regimes exert selection pressure on the historical manifestations. The evolutionary dynamics at the regime level induce crises, bifurcations, etc., as historical events.

In addition to his many discoveries, Galileo changed the philosophy of science of his time by considering the Book of Nature no longer as God's Revelation, but as a text open to debate and revision. In his well-known Preface to the second edition of the *Critique of Pure Reason* (1787), Kant reflected on this crucial step in the development of the modern sciences, as follows:

> When Galileo caused balls, the weights of which he had himself previously determined, to roll down an inclined plane; when Torricelli made the air carry a weight which he had calculated beforehand to be equal to that of a definite column of water; or in more recent times, when Stahl changed metal into lime, and lime back into metal, by withdrawing something and then restoring it, a light broke upon all students of nature.[…] Reason, holding in one hand its principles, according to which alone concordant appearances can be admitted as equivalent to laws, and in the other hand the experiment which it has devised in conformity with these principles, must approach nature in order to be taught by it.[…] It is thus that the study of nature has entered on the secure path of a science, after having for so many centuries been nothing but a process of merely random groping.

The chapter is partly based on: Leydesdorff, L. (2015). The Sciences are Discursive Constructs: The Communication Perspective as an Empirical Philosophy of Science. In L. Cantoni & J. A. Danowski (Eds.), *Communication and technology* (pp. 553–562). Berlin and Boston: De Gruyter Mouton.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_2

Beyond Kant, who focused on the transcendental relation between individual reasoning and truth, Galileo was thoroughly aware of the communicative nature of the new sciences. For example, he entitled his books *Dialogo* (1632) and *Discorsi* (1638), respectively. The scholastic form of a *disputatio* had been used by him in earlier work (e.g., *Disputatio de coelo*, 1616) and was still in use by his adversaries.[1] However, this monological style was increasingly abandoned in favor of dialogue as the new mode for generating, validating, and reproducing knowledge (Biagioli, 2003). Discursive knowledge is shaped in communications among reflexive participants with reference to supra-individual horizons of meaning.

The cycling of discursive knowledge in communication networks makes the criteria stable and then potentially global. In his book *The Structure of Scientific Revolutions*, Kuhn (1962) used the "Copernican turn" of the sixteenth and early seventeenth century—Galileo's heliocentric worldview—as the prime example of a paradigm change. The Scientific Revolution changed the communication and control structures in the sciences at the above-individual level.

2.1 Discursive Knowledge

A communication-theoretical perspective on the philosophy of science can be elaborated into empirical research: the dynamics of theory development can be operationalized in terms of communication dynamics (Krohn et al., 1990; Rorty et al., 1992). The modern sciences are discursive and mediated. The mediation of knowledge production by scientific literature was historically made possible after the invention of the printing press in the second half of the fifteenth century (Eisenstein, 1979, 1983; Luhmann, 1981). Free presses for printing Protestant translations of the Bible were organized first in Geneva and Lausanne during the sixteenth century, and then in Amsterdam and Leiden in the early seventeenth century. During most of the seventeenth century, however, scholars still communicated by means of letters.

In 1665, the *Philosophical Transactions of the Royal Society* appeared as the first scholarly journal, followed in 1666 by the *Journal des Sçavants* in French. The increased circulation of knowledge triggered a bi-furcation between the knowledge production flow and the control mechanisms during the Scientific Revolution. The further organization of the sciences as written knowledge in scholarly journals followed as an achievement of mainly the eighteenth century (e.g., Bazerman, 1988). The modern citation was gradually invented in the course of the nineteenth century (Price, 1961, p. 166). A cultural evolution of communications in layers has thus been induced.

The main function of a reference was first, for example, mentioning those who had attended an experiment. The argumentative function in relating texts to other texts gradually emerged in scientific communications, leading first to the institutionalization of the sciences; for example, at German universities in terms of Chairs during

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[1] E.g., Orazio Crassi, (1619). *De tribus cometis anni MDCXVIII disputatio astronomica*, Rome.

the 19th century (Stichweh, 1984). The institutionalization can be considered as a retention mechanism of novelty (cf. Freeman & Perez, 1998), but the new forms of organization changed also the nature of the communications. The modern reference, for example, was invented as a global standard only as recently as the turn of the twentieth century (Leydesdorff & Wouters, 1999).

The referencing networks *select* upon the referenced ones, thus allowing for communications with greater specificity. In our time, hyperlinks relate documents on the internet in terms of a hypertext; references are embedded in texts as subtexts, etc. Subtexts and hypertexts can be considered as different contexts of the textually embedded knowledge. The relationships between these layers of texts, sub-texts, and super-texts have been transformed by the emergence of electronic communication and the internet. More specifically, the real-time availability of virtual hypertexts is changing the systems of referencing, indexing, and retrieval by adding degrees of freedom to the evolving communications.

From an evolutionary perspective on scientific communication, the texts provide variation (Callon et al. 1986; Law & Lodge, 1984; Hesse, 1980). By referencing, a subset of these texts is selected. References and citations can thus be used as indicators of selection processes. Words and co-words are relatively volatile indicators, while citations may function as symbols and refer preferentially to texts that have been codified. Indeed, citations can be more than ten times as precise as words (Braam et al., 1991; Leydesdorff 1989 and 1997a; cf. Garfield 1955). Baumgartner & Leydesdorff (2014) distinguished between transient and sticky knowledge claims, operationalized as relatively recent citation at a research front *versus* longer-term processes of codification.

2.2 The Modern Citation as an Example of Codification

In the pre-modern era, a manuscript had to be transcribed in a manual process that was prone to error. Nowadays, a new edition of a printed book, however, can be expected to improve on previous editions by updating the content and correcting errors. Knowledge is continuously being revised in scholarly communications (Price, 1965). Thus, one no longer proceeds from an original text (like the Bible) to an inferior copy because of mistakes in the transcriptions. One proceeds from a previous to a next version by rewriting. This process is social, and since the nineteenth century increasingly organized for the objective of technological applications (e.g., in industrial laboratories; cf. Bernal, 1939; Braverman, 1984; Noble, 1977; Van den Belt & Rip, 1987).

The modern citation was invented in the late nineteenth century, but first in the form of references without dates (Bazerman, 1988). This form was replaced with the current format around 1900. Following the invention of the new form, the older form of referencing rapidly disappeared and the number of references began to grow exponentially. For the February issue of the *Journal of the American Chemical Society*

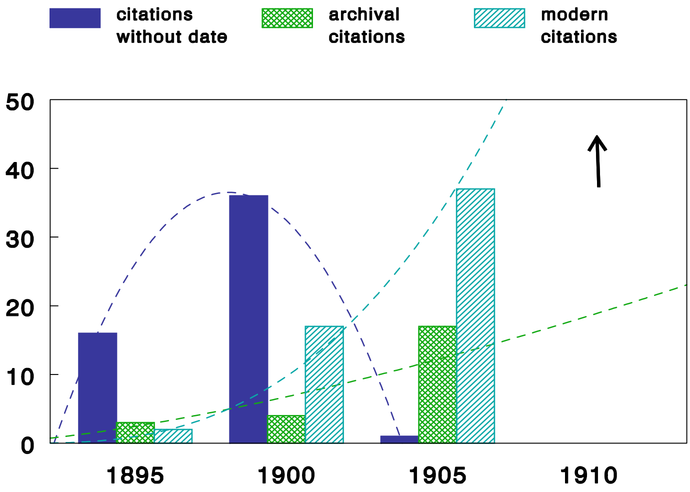

Fig. 2.1 The origins of the modern citation in the Journal of the American Chemical Society (JACS). *Source* Leydesdorff and Wouters (1999)

(JACS) in 1910, the number of modern citations had increased to sometimes more than ten on each single page (Fig. 2.1).[2]

The development of *discursive knowledge* presumes the circulation of meanings as analytically different from the communication of information as texts. The texts are historical instantiations of the development of the knowledge involved. New words are sometimes needed: for example, when "oxygen" was invented in the eighteenth century by Priestly and others to replace "phlogiston"; but at other times the same word is provided with a new meaning (such as "force" in Newtonian *versus* Aristotelian physics). Another theoretical framework can make a difference to both the meaning and the expected information content of the messages that are exchanged (Hesse, 1988; Leydesdorff, 1997; Quine, 1951).

Whereas the communication of information is studied in the information sciences and in scientometrics, the self-organization of meaning in interhuman communications has been central to Luhmann's (1995) efforts to make the theory of *autopoiesis* (Maturana & Varela, 1980) or "self-organization" relevant for sociology. As discussed above (in Chapter One), Luhmann (e.g., 1986) argued that communications carry the self-organization of meaning. However, Luhmann focused on the top layers of codification and its dynamics as domains. An empirically richer understanding of the sciences as processes of communication can be achieved when the underlying processes are also taken into account. Can one distinguish between (*a*) the communication of information and (*b*) the sharing of meanings? How should this difference be modeled and can it perhaps be measured?

[2]The assumption of exponential growth still grossly underestimates the noted observation in 1910, while this curve fits at $r > 0.99$.

2.3 The Communication Perspective

In the philosophy of science, Popper (1935) distinguished between the context of discovery and the context of justification. However, the communication perspective enables us to distinguish three contexts: (*i*) the local interactions and exchanges in *the context of discovery* operating bottom-up and submitting knowledge claims; (*ii*) the validation of knowledge in *globalized contexts of justification;* and (*iii*) the *mediation* between these two levels in terms of texts and discourse. The three contexts are historically interwoven, but they can be distinguished analytically. The context of justification can operate as a self-organizing (and largely anonymous) control mechanism. However, knowledge needs to be instantiated in texts before it can be reconstructed.

Whereas the context of discovery operates bottom-up, control mechanisms in the context of justification operate top-down. Discourses—exchanges of arguments—mediate between these two other levels (Mulkay et al., 1983). Discourses can overflow in exchanges between disciplines (Callon, 1998), as well as mediate between science and society (Gibbons et al., 1994).

The sciences self-organize into disciplines and specialties using specific codes. The codes are not manifest, but operate as selection mechanisms that coordinate the communications. Unlike communities of people, codes in the communication can be stabilized and globalized; communications travel more easily than people (Latour, 1987). Symbolic generalization of the codes at the global level span horizons of meanings. Note that this is an analytical model in which the dynamics are taken apart. Both horizontally (as different codes) and vertically (as different mechanisms), the various subdynamics of communication operate in parallel and can be expected to disturb one another.

Without mentioning—but, in my opinion, building on—Herbert Simon's (1962,1973) theory of complex systems, Luhmann (1975) proposed to distinguish three mechanisms in the dynamics of communication: interactions, organization, and self-organization. From this perspective, the interactions provide variation; for example, knowledge claims. However, this variation has to be organized (e.g., in texts) before its content can further be selected for globalization. Globalization refers to a next systems level in which codes of communication are self-organizing; for example, by disturbing one another.

The construction is bottom-up, but the cybernetic principle is that the selecting next-order level is structural and can take over control as it emerges. This model is also known as reaction–diffusion dynamics (Rashevsky, 1940; Turing, 1952). If diffusion becomes more important than the flux in the production process (for technical reasons divided by 2), the system becomes unstable and can go through a phase transition. A phase transition changes the dynamics of the system irreversibly. Which subdynamic prevails depends on the initial (and potentially random) deviations from homogeneity.

Without having concepts like phase-transitions and bifurcations available at his time, Marx (1867) went to great lengths to explain why the exchange of commodities through the mediation of money ("Ware-Geld-Ware" or WGW) is qualitatively different from the exchange of money via the mediation of commodities ("Geld-Ware-Geld" or GWG; see Marx, ([1867], 1995, pp. 66 ff.).[3] The dynamics of money are more abstract than those of material commodities. The price of a commodity can be considered as an expectation of its value, and thus this symbolic generalization of value in terms of prices enables us to handle greater complexity in the communication and at a higher speed. "Alienation" may follow when the driving forces of social developments are self-organizing and therefore increasingly beyond the control of individuals (Platt & Weinstein, 1971).

Analogously, in the sciences—albeit less frequently than in everyday transactions on the market—the submission of a knowledge claim (usually in the form of a manuscript) relates the context justification to the context of discovery in which new insights have heretofore been shaped. The epistemological status of the knowledge content under discussion is changed by entering into the differently organized layer of communications invoked for validation and justification. However, the context of discovery remains necessary as the source of the historical variation; the context of justification functions as a next-order control mechanism that operates latently alongside the context of discovery. The two dynamics—the historical one of generating specific claims *versus* selections from the perspective of hindsight—can be expected to operate with different frequencies, and also to disturb each other.

By being repeatedly selected, knowledge claims can be stabilized, meta-stabilized, and also globalized as next-order structures and dynamics in networks. However, these constructs remain fragile and in need of reconstruction. Unlike *social* networks, which find their stability in human and institutional agents as carriers of the communications on the ground, communication networks are event-based: communication is an operation that disappears as it happens (Snijders et al., 2010). Consequently, stability is constructed and needs to be explained (Latour, 1987). The reproduction of communication is anchored, on the one hand, in the layer of agents carrying the communications from below; but on the other hand, communications are selected from above at the supra-individual level with reference to next-order structures such as the codes of communication emerging within the communication networks as meta-representations which span horizons of meaning (Distin, 2010). The next-order dynamics is not resting (with a lower frequency) on the underlying ones, but tends to differentiate with a dynamic of its own. This endogenous mechanism can drive a phase transition to a more complex arrangement.

2.4 Operationalization and Measurement

The communication perspective on the sciences as evolving structures enables us to proceed to empirical operationalizations. For example, the variation of scientific communications is visible first in the form of claims in manuscripts (Myers, 1985;

[3] "Ware-Geld-Ware" can be translated as "Commodity-Money-Commodity;" see Marx, 1995, pp. 66 ff.

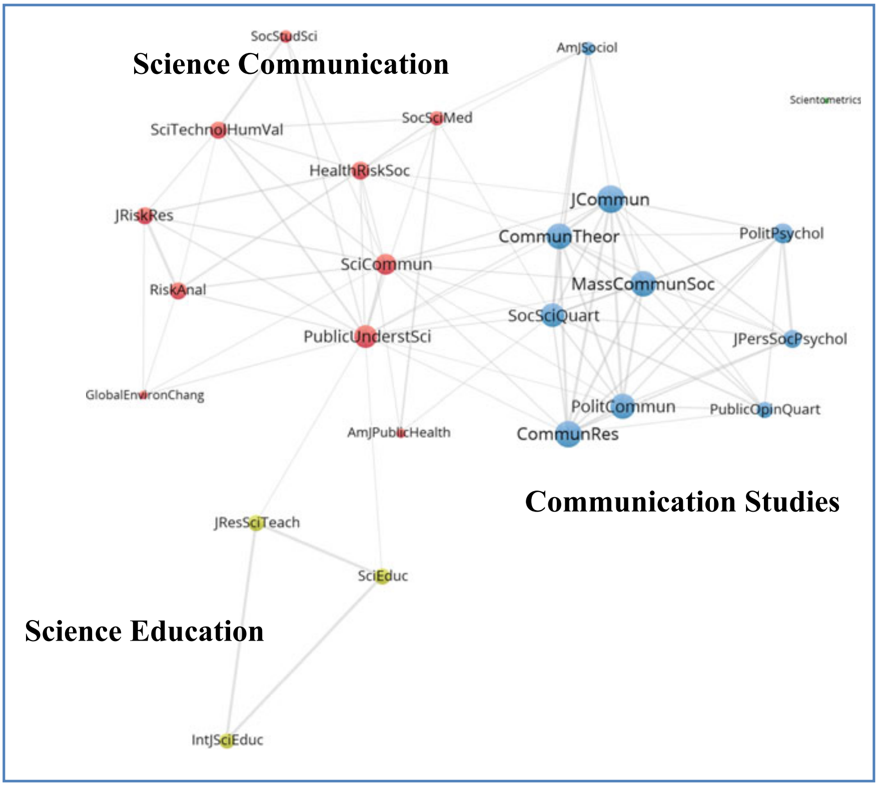

Fig. 2.2 Aggregated journal-journal citation network among 24 journals cited in *Public Understanding of Science* in 2011 to the extent of more than 1% of all references; cosine > 0.1; Blondel et al.'s (2008) modularity used for the clustering in Pajek; $Q = 0.447$.

Pinch, 1985). These knowledge claims are organized into bodies of scholarly knowledge and literature. The literature can be used to visualize the coding into specialisms and disciplines.

Figure 2.2 shows, as an example, the relevant citation environment for the 141 authors who published at least one of the 67 papers in the journal *Public Understandingof Science* (*PUS*) in 2011. After removing the incidental citations (< 1%), three main groups of journals are indicated at this aggregated level: communication studies, science communication, and science education.[4]

Figure 2.2 is based on a matrix of aggregated journal-journal relations among 24 journals cited in *PUS* in 2011. Using papers instead of journals as units of analysis, one can, for example, analyze the references to journals in the 67 papers published in 2011 (Fig. 2.3). While Fig. 2.2. shows how *PUS* as a journal is related to a larger set—providing horizons of relevance—the individual papers published in 2011 reference

[4]Three factors explain 43.06% of the variance.

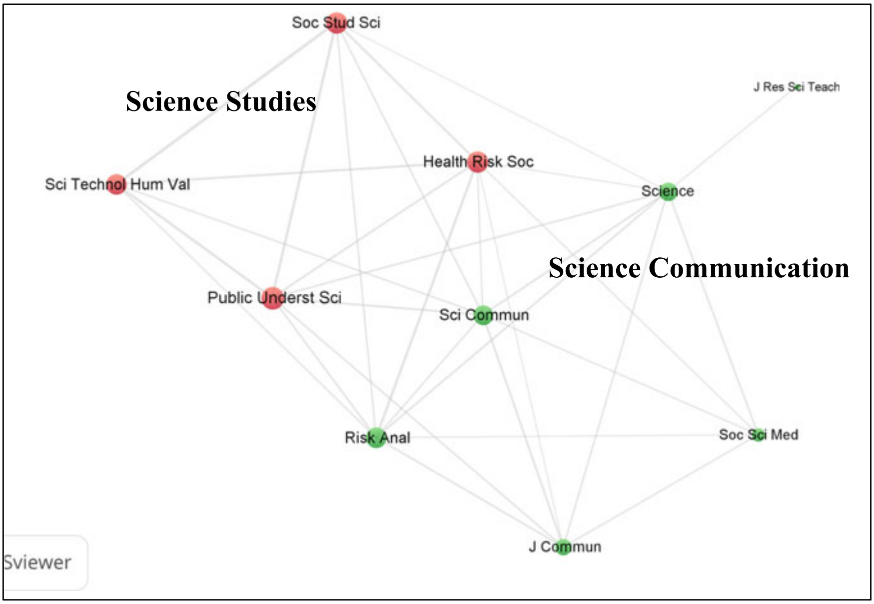

Fig. 2.3 Bibliographic coupling among ten journals cited above the 1%-level in 67 papers published in *Public Understanding of Science* in 2011; cosine > 0.1; $Q = 0.1373$

specific literatures. These bibliographic couplings of references (mapped in Fig. 2.3) are instantiations in a specific year (2011) of the latent and self-organizing structures of the relevant disciplines shown in Fig. 2.2.

Figure 2.4 shows the substantive variation in terms of the topics under study in the same 67 papers. One can further enrich the map by adding the co-author network, their institutional affiliations, national and international collaborations, etc. The tools of social and semantic network analysis enable us to study the dynamics in the various dimensions of the sciences in considerable detail (e.g., Leydesdorff et al., 2008; Scharnhorst et al., 2012).

2.5 Concluding Remarks

The shaping of the context of mediation has followed the historical development of communication technologies. For example, the printing press made the development of the sciences possible from the seventeenth to the twentieth century. The late twentieth century has witnessed the emergence of the internet as a new (global) communication technology. New media changed scientific practices both at the level of the context of discovery and the context of justification (e.g., Heimeriks & Vasileiadou, 2008). New patterns of communication can be expected to change the codes of

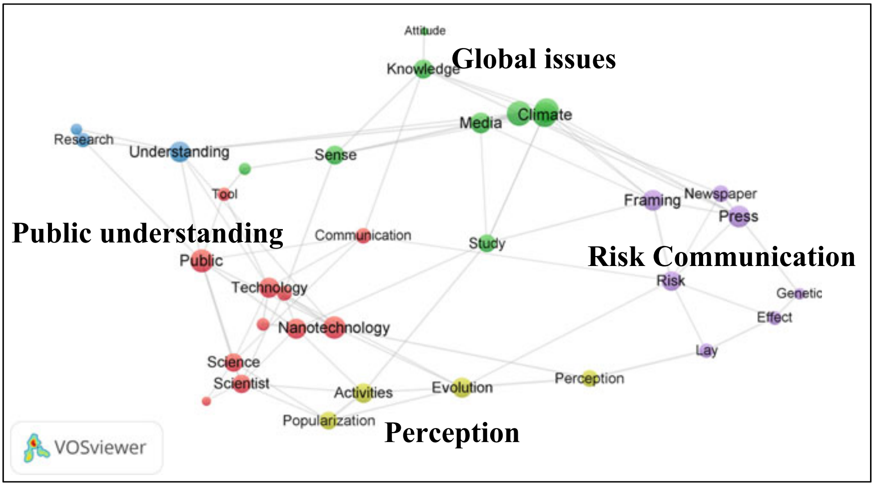

Fig. 2.4 Topical network indicated by 34 words occurring more than twice in the titles of 64 documents (Three more documents (Editorials) have no title words.) published in *Public Understanding of Science* during 2011; cosine > 0.2; 5 clusters indicated with $Q = 0.449$

communication albeit probably with a delay (Larivière et al., 2008). The various dynamics feedback on one another.

Since the 1970s, listservs and email have become communication tools changing laboratory life. The very process of science has become intensively embedded in literature and communication. The flows of communication and literature were increased by orders of magnitude (Hull et al., 2008). More recently, the development of Google Scholar (2004) has made conference proceedings, open journals, portions of books, and personal and collections of manuscripts accessible on the internet. Other major technological developments include real-time communication among collaborating scientists, shared databases of references, and webinar tools. One can expect these communication technologies to be further developed in as yet unknown directions (Chap. 9).

The mapping of the sciences using scientometric tools makes it possible to visualize the evolution of the sciences as networks (Börner, 2010). This "communication turn" adds the social-science perspective of communication and information studies to the "linguistic turn" in the philosophy of science (Rorty, 1962). The language usage under study can be coded and differentiated into specific jargons. By analyzing the sciences as communication systems in which knowledge is constructed, one obtains both a rich conceptualization and the possibility to proceed to measurement. The communicative mediation reflects the evolutionary dynamics. The study of these communication dynamics thus opens the philosophy of science to empirical operationalizations other than thick descriptions. Hypotheses about scientific developments can be formulated, and confirmed or rejected on statistical grounds (e.g., Giere, 1988; Small, 2020).

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Chapter 3
Scientific Communication and Codification

In the sociology of scientific knowledge and the sociology of translation, heterogeneous networks have been studied in terms of *practices* and so-called *actor-networks*. However, scientific practices are intellectually structured by codes. Cognitive structures interact and co-construct the organization of scholars and discourses into research programs, specialties, and disciplines. The intellectual organization of the sciences adds to and feeds back on the configurations of authors and texts. The social, textual, and cognitive sub-dynamics *select* upon each other asymmetrically. Selections can further be selected for stabilization along trajectories and then also be globalized—symbolically generalized—into regimes of expectations.

In his seminal study of the Sociology of Scientific Knowledge (SSK), David Bloor (1976, at p. 2) argued that "*knowledge for the sociologist is whatever men take to be knowledge*." Consequently, the "strong program" in the sociology of science introduced the so-called "principle of symmetry": a sociological explanation should be able to explain both true and false knowledge as human beliefs. From this perspective, scientific knowledge can no longer be considered as "true" belief, different from other knowledge or beliefs (Barnes, 1974; cf. Fuller, 2018). Bloor (1982) argued that even rules of logical inference in mathematics derive their truth from social negotiations and human beliefs.

SSK posited that in *practices* the cognitive is always social, and vice versa. The dimensions of the cognitive and the social are integrated and, from this perspective, not to be distinguished. Sociocognitive (inter-)actions shape the social *and* the cognitive at the same time (Collins, 1983). Therefore, analysis should not be pursued in terms of dimensions like "cognitive" versus "social" or "internal" versus "external." From the perspective of SSK, one could not accept an *ex ante* disciplinary division of labor among the history, philosophy, or sociology of science. The analysis is pursued instead in terms of the subject matter.

The chapter is partly based on: Leydesdorff, L. (2007). Scientific Communication and Cognitive Codification: Social Systems Theory and the Sociology of Scientific Knowledge. *European Journal of Social Theory, 10*(3), 375-388.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_3

This strong program builds on Kuhn's (1962) theory of paradigms as language games (Winch, 1958; Barnes, 1969). The focus on content led to descriptions of the world of science that were empirically richer than those provided by previous traditions in the sociology of science (Merton, 1942; 1973; cf. Barnes & Dolby, 1970). For example, it was no longer acceptable to describe a specialty only in terms of the organizational variables of a scientific community (Crane 1969 and 1972; Whitley 1984). Nor could a specialty be operationalized in purely epistemological terms, such as a set of theoretical questions linked to relations among arguments, observations, and inferences (Hesse, 1980); nor could it be adequately described as a body of literature or a communication structure (Price, 1961). As with all major concepts in science studies, it was henceforth necessary to develop the definition of "specialty" by relating the perspectives of social structure, cognitive contents, and scientific literature. The potential tensions among these different evaluations were "heterogeneously engineered" by both the participants and the analysts into *practices* which operate as "mangles" (Pickering, 1995).

From this perspective, the analyst has no choice but to "follow the actors" like an ethnographer (Latour, 1987). Scholars working in Actor-Network Theory (ANT)—originally a Parisian program developed at the École des Mines—further radicalized the symmetrical approach by including "non-humans" in their descriptions (Callon et al., 1986; Callon and Latour, 1981). For example, in his study of the introduction of scientific principles of breeding into fishery, Callon (1986) argued that the relevant "actor-network" consists of the oceanologists whose aim is to transform fishing into "aquaculture," the science of oceanology which imposes problem-formulations, the fishermen who defend their interests, *and the scallops* who breed and enter the networks of both the fisherman and the analysts studying them. When these different elements are aligned into an "actor world," the system can be "translated" at an "obligatory passage point." A translator spokesman is needed to provide the translation.

Note that in this "sociology of translation" the cognitive or natural constraints on the situation are not analyzed *as if* they acted as constraints; this program is not an heuristic. Instead, the actor-network is constructed as a next-order unit of performance on the basis of what these authors call "relational strength"; heterogeneous dimensions are homogenized in a pan-semiosis (Hagendijk, 1996). In other words, the substantive heterogeneity in the subject of study is not addressed in terms of analytically different dimensions, but in terms of an assumed coincidence, congruity, and symmetry between *explanandum* and *explanans* within the subject matter. As against the natural sciences, a sociologist in the ANT tradition cannot avoid being part of the networks under study.

From the perspective of ANT, an analyst knows a priori that the relations in the actor-network are mutual and symmetrical. Nothing can ultimately be explained, and the sole purpose of the analysis is to tell a convincing story (Latour 1987; Collins and Yearley 1992). Testing is not statistical, but in practices, and in terms of "robustness" (Rip, 2010). Consequently, the actor-network is not only an *empirical* category; this program claims also to provide an answer to the *methodological* problem of analyzing "heterogeneity" (Akrich et al., 2010). Actor-networks cannot be explained other than by describing them and thus becoming enrolled into them.

3.1 The Status of Cognitive Structures

In my book *The Challenge of Scientometrics* (1995), I argued against ANT and SSK that authors, texts, and cognitions cannot be reduced to one another. One can distinguish between the textual, cognitive, and social dimensions of the units of analysis under study. The variation in each dimension can be aggregated using grouping rules in the other two dimensions. For example, authors can be grouped in terms of substantive specialties, or in institutional terms such as departments and universities.

By considering three dimensions as orthogonal, a scheme for science studies can be unfolded (Fig. 3.1). This model allows for interactions at each moment in a static design, and for dynamic "feedbacks" and "mutual shapings" among the social, textual, and cognitive (sub)dynamics over time. Over time, a "triple helix" of cognitions, texts, and agents can thus be envisaged. Different meanings can be expected on the basis of different grouping rules. For example, one can distinguish between the meaning of a publication in cognitive terms at the field level and in social terms at the level of the research group.

Note that the implied assumption of the *analytical* independence of the cognitive dimension does not imply a return to older traditions in the philosophy and the sociology of science. Traditionally, the context of discovery and the context of justification have been conceptualized as two separate domains, to be pictured spatially as parallel planes and studied by distinctive scholarly traditions (that is, the history and philosophy of science for the context of justification *versus* sociology for the context of discovery). The three-dimensional scheme of Fig. 3.1, however, provides

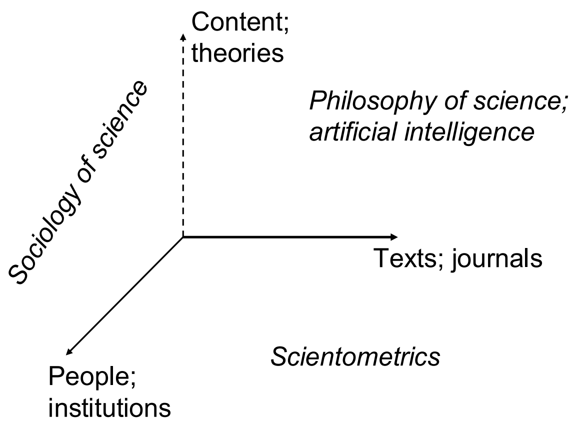

Fig. 3.1 Three main dimensions in the dynamics of the sciences; adapted from Leydesdorff (1990)

room for adding a third (textual) dynamics to the social and intellectual organization of the sciences.

I have used dashes for the vertical axis in Fig. 3.1. Unlike texts and authors, cognitions cannot be found "out there" without taking a reflexive turn. Still, the cognitive dimension provides grouping rules for organizing texts and authors in terms of research programs, specialties, and disciplines. These grouping rules are not grounded in nature, but constructed. In order to address the cognitive dimension empirically, a reflexive specification is first needed. The cognitive dimension—or, in other words, the third helix—leads us to the question of how codifications organize texts and people.

3.2 Codification in Communications

When a scientific paper is presented—for example, at a conference—the content has first the status of a knowledge claim. When the paper is subsequently reviewed and published in the literature, the knowledge claim is validated, and thus the status of both the paper and its content is changed (Myers, 1985). Peer review is, among other things, expected to evaluate the paper under study for its quality, and while doing so it ascribes an expectation of quality to the paper as a construct. In other words, this process constructs a cognitive outcome in addition to a social one.

What has been added to the article during the social process of peer reviewing? Building on Parsons's (1963a, 1963b) concept of "symbolically generalized media," on the one hand, and Husserl's (1929) notion of "horizons of meanings," on the other, Luhmann suggested that the coding of the communication implies a domain-specific selection. In other words, the paper goes through a process of recursive selections whereby it is invested with symbolic value. The status of the paper is changed from a knowledge claim into a contribution to be stored in the knowledge base for future reference.

The code of communication operating specifically in the sciences was characterized by Luhmann as a selection on whether the claim in the paper is "true" or not. I prefer Simon's (1973) characterization of the code of science in terms of heuristics (truth-finding) and puzzle-solving (see Chap. 1). The codes legitimate specific selections (cf. Zuckerman, 1999). The *expectation* of a selection environment drives the competition, and this encourages participants to focus on the content of a communication rather than its social conditions. Although the codes themselves are also constructed historically, they operate as selection mechanisms at another level and with a different frequency than the knowledge claims that were submitted.[1] Criteria operate globally and are reproduced locally by the specification under historical circumstances, that is, by the acceptance or rejection of the knowledge claims in the papers under review (Fujigaki, 1998).

[1] From an evolutionary perspective—to which I return in a later chapter—the knowledge claims can also be considered as phenotypical and the codes as genotypical (Hodgson & Knudsen, 2011).

The construction of these mechanisms as a basis for a scientific culture has taken centuries. For example, the scientific journal was an invention of the seventeenth century (Price, 1961), while—as noted in Chap. 2—the modern citation was invented only at the end of the nineteenth century. However, the codes should not be reified. They remain tendencies in the communication, constructed and therefore expected to change. In the case of a crisis in the communication, for example, the codes may also need to be redefined. Thus, the networks of communications develop an eigen-dynamics which is partly (that is, reflexively) accessible and partly latent for the communicators who carry the communications (Lazarsfeld & Henry, 1968; Von Foerster, 1982).

3.3 Beliefs *versis* Rationalized Expectations

The strong program of SSK emphasized the symmetry of true and false statements with reference to Durkheim's (1912) analysis of the forms of religious life and to Mary Douglas's (e.g., 1970) anthropology of groups and grids. From this perspective, the sciences are considered as *belief* systems attributable to agents or groups of agents. In my opinion, the sciences are socially constructed as discursive systems of rationalized expectations. Rationalized expectations are attributes of a discourse, i.e., relations among people. In other words, the units of analysis are different: beliefs are attributes of agents at the nodes of a network, whereas expectations are discursively rationalized communications. The rationalization is an attribute of the exchanges at the links.

In controversy studies, the assumption that the sciences may also function as belief systems can be empirically fruitful. In a number of other respects, however, the sciences operate differently from religions. In contrast to a system of expectations, a religion tends to be organized hierarchically with reference to a single or dominant meaning (e.g., a religious Truth) and therefore normatively integrated in terms of what is right and what is wrong. In scholarly discourse, however, the disbelief in a scientific "truth" no longer creates a schism as between religious communities in the Middle Ages; nowadays the articulation of other perspectives may raise and enrich research questions.

In other words, the mechanisms of the communications are different. Modern sciences are no longer worldly religions organized hierarchically for celebrating the "Truth," but they are discursive constructions serving heuristics—that is, truth-finding. However uncertain and variable the coding may be, the yardsticks for controlling the truth of scientific statements are different from normative integration into individual or collective beliefs.

New forms encompass (and potentially enrich) the older ones which may continue to serve as subdynamics in a more complex arrangement. Both integration into organizations and differentiation among the self-organizing codes can be expected. From this perspective, integration is a recursive network function, namely the specific one of providing a basis for action. Organization has to be carried historically by agency

(Achterbergh & Vriens, 2009). The globalizing and self-organizing functions can be expected to provide different meanings along other and potentially orthogonal dimensions in the vector space of Fig. 3.1 (cf. Simon 1969).

A hierarchy is based on integration, as in a dendrogram; differentiation adds a degree of freedom: more than a single hierarchy is then possible. In other words, each function self-organizes a different hierarchy. The different hierarchies can be expected to disturb one another, leading to a "fractional manifold" of partial hierarchies (Ivanova & Leydesdorff, 2014). Whereas a hierarchy is shaped when relations are organized into a dendogram-like structure, the resulting network contains a structure with potentially an alphabet of dimensions.

In the longer run, the sciences can allow for normative and institutional control over the conditions of the communication (e.g., resource allocations), but not over the substantive and reflexive contents of these communications; the dynamics are from this perspective self-organizing and functionally differentiated in terms of codes. Scientists have a particular need to incorporate this cognitive differentiation enabling them to change perspectives. One needs room to explore counter-intuitive interpretations or theoretically informed hypotheses ("conjectures"; Popper, 1963) that one may wish to change with hindsight.

This differentiation from normative integration has been a functional requirement for the further development of natural philosophy, that is, the new sciences. The crucial conflict between self-organization and normative control on the basis of religious or political convictions was fought in Western Europe between the appearance of Galileo's *Dialogo* in 1632 and the publication of Newton's *Principia* in 1687. From that time onwards—that is, since the so-called "Scientific Revolution" (e.g., Cohen, 1994)—the further differentiation of scientific communications has been institutionalized in the social system of science in both Europe and elsewhere (cf. Graham, 1974; Lecourt, 1976; Merton, 1938, 1942).

Why was the new "natural" philosophy able to drive this development? By reconstructing "nature" in experimental settings—that is, on the basis of a model—an observation is transformed into an instantiation with reference to an expectation. Insofar as this reconstruction proves successful, the previous ("natural") order can be replaced with a new construct (Shapin & Shaffer, 1985). In principle, the new paradigm can thus overwrite the older one and lead to new practices. This replacement may be a sudden event (an "avalanche") or a gradual development. Once the old paradigm is replaced by a new one, the former tends to lose its meaning and relevance for the further development of the communication.

The evolutionary dynamics of the sciences is both driven by and driving processes of modernization at the level of society. Marx (1848) famously characterized this process of modernization as "all that is solid, will melt into air" (cf. Berman, 1982). However, "air" is not sufficiently specific; what is in the air needs to be specified in terms of coordination and selection mechanisms. "All that is solid" can be considered for reconstruction; a phase space of other possibilities can be envisaged.

3.4 "Structuration" by Expectations

In his "structuration theory," Giddens (1979, 1984) offered another way to discuss structures in terms of the expectations of agents. According to Giddens, structures exist only as memory traces that can be instantiated in action (Giddens, 1984, p. 177). Structures can be considered as providing rules and resources which can be instantiated. However, structure, according to Giddens (e.g., 1979, at p. 64), exists outside "time and space" as "absent differences" that, in his opinion, cannot be studied empirically. He argued that sociology should retain a firm focus on observable action and empirical explanation.

How can individual memory traces be coordinated? According to Giddens, this question is not answerable. The invocation of "magical explanatory properties of social reproduction" could lead us back to abstract systems theory and (neo-)Marxism (Giddens, 1979, at pp. 73–76). As he emphasized:

> There can be no doubt about the sophistication and importance of the work of some authors currently endeavouring to develop Parsons's work in novel ways, particularly Luhmann and Habermas. But I think it as necessary to repudiate the newer versions of Parsonianism as I do the longer established varieties of non-Parsonian structural sociology. (1984, at p. xxxvii).

In Giddens' "structuration theory," the "duality of structure" is considered as a "virtual"operation. Since this virtual operation cannot be studied empirically, a *methodology* is suggested for relating institutional analysis to the analysis of strategic conduct: the one narrative can be used as a *context* for informing the other; structure is present in action and actions can be aggregated into structures. However, the two narratives remain juxtaposed by "bracketing" the one perspective as contextual when focusing on the other (Giddens, 1984).

Although Giddens (1976, at p. 162) acknowledged a possible interaction among the memory traces leading to a "double hermeneutics"—the roles of observers and participants can be combined and/or distinguished—he avoided theorizing the "second contingency" of expectations itself as a possible structure. From his perspective, this second contingency falls outside the empirical domain studied in sociology. As the author (1979, pp. 81f.) explained:

> The communication of meaning in interaction does not take place separately from the operation of relations of power, or outside the context of normative sanctions.[…] Practices are situated within intersecting sets of rules and resources that ultimately express features of the totality.

However, the focus should remain, in Giddens' opinion, on observable actions. institutions, and instantiations of structure. Although structure is implicated in the reproduction of social systems, it cannot and should not be studied as such *because it is absent*.

In my opinion, this inference does not follow: Why would one not be allowed to formulate hypotheses about a second contingency in social structures? The formulation of expectations may be helpful in the design and then lead to the specification of relevant observations. Might what is absent (the "zeros") not be equally or perhaps more interesting than what happens to be the case (Deacon, 2012)? In social network analysis, for example, one also studies missing links or structural holes (Burt, 1992; cf. Breiger, 2010).

I agree with Giddens that one should avoid "abstract systems theory" without an agenda for empirical operationalizations; but this is a different issue from denying legitimacy to the study of structures in expectations. Structures can be expected to operate as selection and coordination mechanisms, and observations can serve to test hypotheses about the dynamics of expectations.

3.5 Biological and Cybernetic Metaphors

The crucial step, in my opinion, is to join theorizing with an empirical perspective allowing for the exploration of new questions and the interpretation of empirical results (Merton, 1948). A theory without this perspective can be considered as too "grandiose" for sociological research and analysis. According to Giddens (1979, p. 237), "models of biological systems, especially those tied to the notion of homeostasis, will not suffice to illuminate some of the key issues posed by the analysis of social systems."

In addition to the specter of social Darwinism, biological models indeed tend to abstract from the individual in favor of an analysis at the level of populations. Giddens noted that Parsons & Dupree (1976) had already signaled the potential of cybernetics for developing a richer framework in which the relations between genotypes and phenotypes can be studied in a context different from biology; for example, in terms of computer simulations and linguistics. However, Parsons did not further elaborate this perspective. In an email conversation at the list of the American Cybernetics Society (dated 9 June 2010), Klaus Krippendorff suggested avoiding "systems theory" given the biological origin and epistemology of the idea of "systems." Why should the social be systemic? In Krippendorff's opinion, cybernetics offers an alternative:

> Gregory Bateson was one of the first to recognize the evolutionary epistemology that cybernetics offered him and wrote several papers about the revolutionary changes cybernetics offered. Being less tied to what exists gave cyberneticians an extraordinary creativity. Indeed, cyberneticians have been amazingly unconstrained in developing and elaborating novel concepts, starting with circularity, self-reference, information theory, all the way to several reflexive moves that have transformed cybernetics.[…] Cybernetics' contribution to information theory opened the door to theories of variety, to understanding evolutionary processes (mutation and selection of what doesn't work), and of course digitalization and computation which systems theories could not address, largely because their discourse directed systems theorists to shared wholes, away from perturbations, diversity, and *building computational realities.*

From the perspective of cybernetics, theoretical reification into a presumably global system is outdated. The analysis can instead be pursued in terms of dynamics and subdynamics, which one is able to hypothesize. The status of theorizing is then more modest; theories serve us as heuristics for solving problems (Simon, 1969; Newell & Simon, 1972).

3.6 Sociocybernetics

How do these considerations lead to a sociology of science that is different from the sociology of scientific knowledge or Luhmann's social-systems theory? The shift from historical observations to the specification of expectations seems crucial to me. Theories can be tested, and historicism can be avoided; cases that actually occurred can be used as examples of what could have occurred. However, the historical narrative cannot by itself inform us about the distribution of instances that one would have expected.

Despite Luhmann's programmatic intention to "de-ontologize" sociology (e.g., Luhmann, 1990, p. 67), one can find in his texts remainders of a tendency to reification. Differentiation, for example, is labeled "functional," whereas differentiation can also be dysfunctional (Mitroff, 1974). As noted, Künzler (1987, p. 323) argued that Luhmann understood code as a binary duplication rule much like DNA.[2] Statements do not have to be wholly true or false, but can be true to variable extents.

In his book entitled *Social Systems*, Luhmann ([1984, at p. 30] 1995, at p. 12) went one step further in the direction of a biological model by explicitly assuming that "systems are given." As he put it:

> The following considerations assume that there are systems. Thus, they do not begin with epistemological doubt. They also do not advocate a "purely analytical relevance" for systems theory. The most narrow interpretation of systems theory as a mere method of analyzing reality is deliberately avoided.[…] In systems theory, scientific statements are not only statements, but they also refer to the real world.

Although one can place the emphasis in the first sentence of this quotation on "assume," the given-ness of systems in "the real world" raises ontological questions. At other places, however, Luhmann (e.g., 1990, p. 76) emphasized that "reality itself remains unknown": each self-referential system generates its own "transcendental"environment ("bubble"); a self-organizing system can "observe" in terms of the distinctions that it has learned to make. He formulated for example:

> The effect of the intervention of systems theory can be described as a *de-ontologization of reality.* This does not mean that reality is denied, for then there would be nothing that operated—nothing that observed, and nothing on which one would gain a purchase by means of distinctions. It is only the epistemological relevance of an ontological representation of reality that is being called into question.

It seems to me that Luhmann alternated between two repertoires: one of general systems theory and another of socio-cybernetics as a specifically sociological branch of systems theory. The sociological perspective is elaborated using historical studies. The case materials are "observed" by reading and analyzing texts (e.g., Luhmann, 1982). However, the specifically human component of using language—as reflected

[2]Why should the codes be binary and not allow for grey shades? When discussing this issue, Luhmann (1986, p. 2; 2004, p. 116) argued (in a discussion with Maturana) that a woman can be either pregnant or not pregnant, but not half-pregnant. However, this is again a biological argument. Culturally, one can also be pregnant with ideas.

in *discourse analysis and hermeneutics*—is backgrounded. The purpose remained eventually to develop a *general* systems theory. As Künzler (1987, p. 331) put it:

> Language haunts as a foreign body in systems theory as a supertheory, and in its sub-theories, emerging as a surprise in nebulous passages in order to vanish as surprisingly, and is obviously perceived as a disturbing element and one which also cannot be eliminated.

Habermas (1986) identified this model in a sharp critique, as follows:

> The flow of official documents among administrative authorities and the monadically encapsulated consciousness of a Robinson Crusoe provide the guiding images for the conceptual uncoupling of the social and psychic systems, according to which the one is supposedly based solely on communications and the other solely on consciousness.[…].
>
> What a burden is assumed by a theory that divides up linguistic structures that cover both the psychic and the social dimensions into two different systems. (p. 378f.)

In summary: Luhmann's theory can also be read as a meta-biology. Because of the common roots in systems theory, Luhmann tends to model language after "languaging," that is, a form of behavior (Maturana, 1978). The languaging agents—human beings—can be considered as interacting "observers" (von Foerster, 1982).[3] However, one cannot infer from this formal definition of an *observer* to the content of an *observation* (see Chap. 1).[4] The content itself is the cultural object.

In summary, my approach is fundamentally dualistic as opposed to the holistic approaches nowadays prevailing in artificial intelligence and biology (e.g., Damasio, 1994; Sherman, 2017). In my opinion, the specification of expectations is not "epigenetic" (e.g., Ramstead et al. 2017, p. 12; see Chapter Ten), but constitutive for inter-human communications in general, and scientific communications in particular. The logic of an emerging system can increasingly be different (that is, "bi-furcate") from its genesis.[5] The story about the historical genesis may serve didactic purposes, but should not be confused with the specification of theoretical content. Genesis is not validity; historicism were to be avoided.

---

[3]Luhmann (e.g., [1993] 1999) turned to George Spencer Brown's (1969) book *Laws of Form* to legitimate this "grounding" of his theory in "observations." However, *Laws of Form* cannot be used for this purpose: the "observer" mentioned by Spencer Brown is only one possible consequence of the operations of distinguishing and designation.

[4]Spencer Brown (1969, at p. 76) concludes (on the final page of this study) that "an observer, since he distinguishes the space he occupies, is also a mark," and he adds: "a distinction drawn in any space is a mark distinguishing the space. Equally and conversely, any mark in a space draws a distinction.[…] We see now that the first distinction, the mark, and the observer are not only interchangeable, but, in the form, identical." Note that "in the form" means (à la Aristotle) that this observer can be a cause of content—i.e., observations.

[5]See Leydesdorff (2006, pp. 169 ff.) for an explanation and derivation of bifurcation and morphogenesis in terms of reaction–diffusion dynamics.

3.7 Concluding Remarks

I have argued in this chapter that—unlike DNA—non-biological codes in communications structure expectations in relation to horizons of meaning without being hard-wired. The codes are theoretically constructed and reconstructed in history; for example, in action. A cultural evolution is thus shaped on top of biological evolution. The exchange and sharing of expectations in the second contingency can be considered as the *differentia specifica* of inter-human communication.

The second contingency evolves as interacting expectations. A reflexive dynamic of meaning and intentionality is thus added to the first contingency of observable actions. As against biological systems in which operational closure can be structural, translations among codes remain possible across boundaries in social systems. The differences among the codes do not "exist" physically and the codes do not need to be organized into a hierarchy. The codes can be expected to span a space of possibilities of which only some are realized in each instance As Latour (1988, at p. 164) argued, there is no need to assume an *ex ante* hierarchy; order is established *ex post*.

Furthermore, I have argued in this chapter that cognition is manifested at the social level as discursive knowledge. The development of discursive knowledge is guided by latent codes in the communications. The codes remain socially constructed, but tend to develop into a control and coordination mechanism that can organize authors and texts selectively. While the instantiations can be observed, the codes selecting upon the observables can only be hypothesized.

In my opinion, Luhmann's theory read as socio-cybernetics provides us with a heuristic for exploring the dynamics of expectations. In order to proceed to empirical research and testing, however, one needs additionally a theory of measurement. Can this model of interacting communications and the self-organization of meaning be made compatible with Shannon's information theory as a measurement theory? Is it possible to specify how the processing of information and meaning are related?

In the next chapter, I first extend the Shannon model of communication into a complex systems model in which communications are differentiated. My long-term objective is to bridge the gap between Luhmann's sociological focus on meaning processing and Shannon's focus on information processing by decomposing the problem using Simon's (1973a) model of complex systems that are differentiated both vertically and horizontally. A complex dynamic of (horizontal) differentiations among the codes versus (vertical) integration in instantiations can be expected, which will be further specified in Chapters Eight and Nine in terms of weakly and strongly anticipatory systems (Dubois, 2003).

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Chapter 4
Towards a Calculus of Redundancy

In this chapter, I extend Shannon's linear model of communication into a model in which communication is differentiated both vertically and horizontally (Simon, 1973). Following Weaver (1949), three layers are distinguished operating in relation to one another: (*i*) at level A, the events are sequenced historically along the arrow of time, generating Shannon-type information (that is, uncertainty); (*ii*) the incursion of meanings at level B is referential to (*iii*) horizons of meaning spanned by codes in the communication at level C. In other words, *relations* at level A are first distinguished from *correlations* among patterns of relations and non-relations at level B. The correlations span a vector space on top of the network of relations. *Relations are positioned* in this vector space and can then be provided with meaning. Different positions provide other perspectives and horizons of meaning. Perspectives can overlap, for example, in Triple-Helix relations. Overlapping perspectives can generate redundancies—that is, new options—as a result of synergies.

In the opening statements of *A Mathematical Theory of Communications*, Shannon (1948, at p. 3) emphasized that the semantic aspects of communication are irrelevant to the engineering problem." Information can be defined as "uncertainty" and is not "informative" in the sense of reducing uncertainty. Although Shannon's coauthor Weaver called this definition "bizarre," he considered the change of perspective as "potentially so penetratingly clearing the air that one is now, perhaps for the first time, ready for a real theory of meaning" (at p. 27). Weaver (1949, p. 8) emphasized that "*information* must not be confused with meaning." Varela (1979, at p. 266), however, argued for defining "information" in accordance with the semantic root of the word "in-formare." Bateson's (1973) aphorism of information as "a difference which makes a difference" defines information as "meaningful information" and has been widely accepted among cyberneticians (e.g., Scott, 2004).

In my opinion, meanings can be attributed to information from the perspective of hindsight and with reference to other possible meanings. Meaning is thus not added

The chapter is partly based on: Leydesdorff, L., Johnson, M., & Ivanova, I. (2018). Toward a Calculus of Redundancy: Signification, Codification, and Anticipation in Cultural Evolution. *Journal of the Association for Information Science and Technology, 69*(10), 1181–1192. https://doi.org/10.1002/asi.24052

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*, Qualitative and Quantitative Analysis of Scientific and Scholarly Communication, https://doi.org/10.1007/978-3-030-59951-5_4

to the information, but events can be considered from different perspectives. Whereas Shannon-type information is generated in *relations* (between a sender and a receiver), meaning is provided from a *position* in a network of relations. Positions are based on *correlations* among patterns of *relations and non-relations*. The correlations span a vector space with dimensions ("eigenvectors") on top of the network of relations. The vector space and the network graph can be considered as different evaluations of the events. First, information is generated operationally by links between senders and receivers. Second, providing meaning to information assumes a position in the network as an aggregate of nodes and links; and third, positions provide perspectives.

4.1 The Network Graph and the Vector Space

As a first step in the specification of a theory of meaning within the framework provided by information theory, Weaver (1949, at p. 26) proposed two "minor additions" to Shannon's linear diagram of a communication channel (Fig. 4.1).

Weaver explained these extensions—the box labeled "semantic noise" and the one labeled "semantic receiver"—as follows:

> One can imagine, as an addition to the diagram, another box labeled "Semantic Receiver" interposed between the engineering receiver (which changes signals into messages) and the destination. This semantic receiver subjects the message to a second decoding, the demand on this one being that it must match the statistical semantic characteristics of the message with the statistical semantic capacities of the totality of receivers, or of that subset of receivers which constitute the audience one wishes to affect.
>
> Similarly, one can imagine another box in the diagram which, inserted between the information source and the transmitter, would be labeled "semantic noise," the box previously labeled as simply "noise" now being labeled "engineering noise." From this source is imposed into

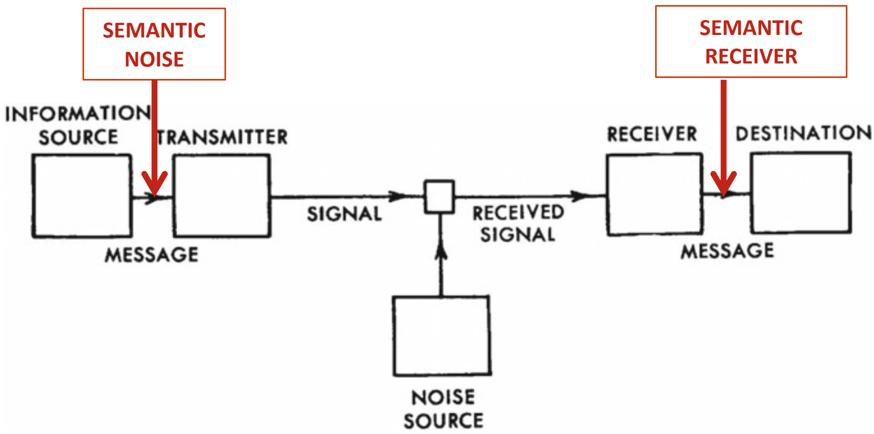


Fig. 4.1 Weaver's (1949) "minor" additions penciled into Shannon's (1948) diagram of a communication channel. Source: Leydesdorff (2016), p. 282

> the signal the perturbations or distortions of meaning which are not intended by the source but which inescapably affect the destination. And the problem of semantic decoding must take this semantic noise into account.

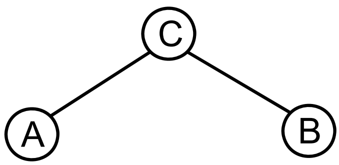
A "semantic receiver" recodes the information in the messages received from the engineering "receiver," while the latter can only change signals into messages. The semantic receiver is able to distinguish the signals from the noise. However, "the semantic aspects" were defined by Shannon as external to the model. Therefore, the relation between the two newly added boxes cannot be considered as communication of Shannon-type information.

Can this semantic dimension of the communication be considered another (non-Shannon) transfer mechanism? Meanings cannot be communicated, but they can be shared and organized depending on positions and perspectives, even without requiring a direct communication relation. Semantics are based not on relations, but on patterns of relations or, in other words, *correlations*. For example, two firms (at the nodes of a network) may have similar patterns of relations with their clients without necessarily relating directly to one another (Burt, 1982). Two synonyms, analogously, can occupy a similar position in a vector space of word co-occurrences without any empirical co-occurrences in the domain under study.

In the case of a single relation, the relational distance is not different from the correlational one; but in the case of three (or more) interacting nodes (Fig. 4.2), distances in the vector space can be very different from distances in the network (e.g., geodesics).

The graph in the left-hand panel of Fig. 4.2, for example, represents a configuration of empirically observable nodes and links. The edges correspond to the ones in the right-hand panel. However, the zeros in the right-hand panel are equally included when defining the vector space. The shortest distance between A and B in the left-hand panel is two. The positional distance between *A* and *B* is zero, since the Pearson correlation $r_{AB} = 1.0$: A and B are at precisely the same position in this network.

As against Shannon-type information which flows linearly from the sender to the receiver, one can expect meanings to loop, and thereby to develop next-order dimensionalities (Krippendorff, 2009a, 2009b). Horizons of meaning are spanned by



Distance$_{AB}$ = 2

	A	B	C
A	0	0	1
B	0	0	1
C	1	1	0

Pearson's r_{AB} = 1.0

Fig. 4.2 Relational distance between and structurally equivalent positions of A and B. Source: Leydesdorff et al. (2018, p. 1185) codes evolving in the communication. Overlapping codes may generate *redundancies* by describing the same events from different perspectives.

Redundancy can be measured if the maximum entropy can be defined or, in other words, the system of reference be specified. Whereas information (Shannon's H) measures the number of options that have already been realized, redundancy measures the number of options that could alternatively have been realized. In other words, the zeros—such as the ones in the right-hand pane of Fig. 4.2—do not add to the information, but they add to the redundancy.

4.2 Dimensions and Dynamics of Information

A communication matrix is shaped when a vertical distinction—such as the levels distinguished by Weaver—is added to the horizontal channel (vector) of communications in the Shannon model (Fig. 4.1). A matrix can be considered as a two-dimensional aggregate of one-dimensional vectors. Whereas each vector models relations, a matrix can represent both relations and positions (see Fig. 4.2). The vectors are positioned in the matrix, for example, by a sequence number. However, a matrix contains also a structure different from and orthogonal to the sum of the vectors of relations. Structures can operate as selection environments; for example, providing meanings to the variation.

In Fig. 4.3a, each slice represents a communication matrix at a specific time; the repetition over time adds the third dimension. The development of information in a three-dimensional array can be visualized as a historical *trajectory*; the uncertainty is then organized over time (depicted as a cylinder in the cube of Fig. 4.3a). A four-dimensional array or hyper-cube of information is more difficult to imagine or represent graphically. However, a four-dimensional array can, among other things, contain

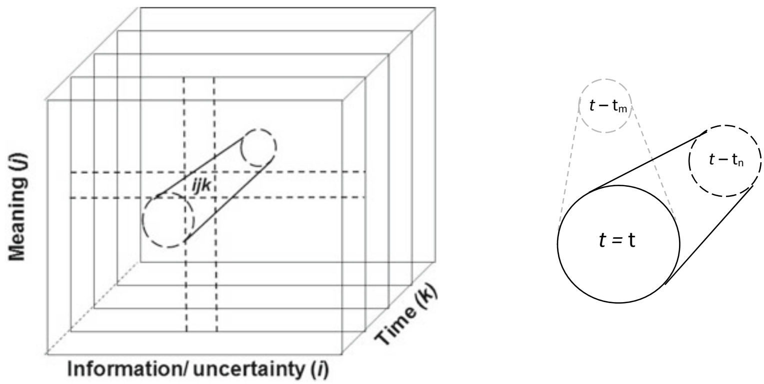


Fig. 4.3 **a** left and **b** right: A three-dimensional array of information can contain a trajectory; a four-dimensional hypercube contains one more degree of freedom and thus a variety of possible trajectories. Adapted from Leydesdorff (1997, p. 29)

a *regime* as a next-order feedback on historical developments along trajectories (Fig. 4.3b; cf. Dosi, 1982).

In other words: a regime has one degree of freedom more than a trajectory and can thus "select" among the possible trajectories as representations in three dimensions of the system's history (Fig. 4.3b). The additional degree of freedom provides room for another selection *within* an emerging system: a selection of one sub-dynamic or another. When mutual selections are repeated, a trajectory can be shaped in a co-evolution or "mutual shaping." Whereas a trajectory is organized in history, a next-order regime provides meta-historical selection pressure in terms of expectations. In this fourth (or higher) dimension, one trajectory can be "weighted" differently from another. Each selection can refine the self-organization of a system of selections. Refinements can be expected to add to the performativity of a system.

For the intuitive understanding, it may be helpful to consider ourselves as psychologies with the reflexive capacity to reconstruct possible representations of our personal histories from the perspective of hindsight. For example, one might tell a story at work differently from what one could say at home. I suggest reading Luhmann's model as a proposal to consider the social system of communications as a system without psychological consciousness, but *with a similar complexity*. Communications can be expected to entertain different representations of the history and organization of communications. Communications and consciousness are substantively different.

Whereas a psychological system operates in terms of individual consciousness and tends towards integration (Haken & Portugali, 2014), a communication system can be expected to remain distributed as a "*dividuum*" (Luhmann, 1984: 625; cf. Nietzsche, [1878] 1967: 76); this additional degree of freedom allows for the processing of more complexity at the supra-individual level than would be possible as the sum of individual processes. As a next-order system, the communications can thus provide a regime to the communicating individuals developing along historical trajectories at a one-lower level. Since communication systems are not biologically alive, they do *not need to be integrated and constrained in terms of life-cycles.*

In summary: whereas variation can be modeled as a one-dimensional vector, a two-dimensional matrix can represent selection and coordination mechanisms leading potentially to trajectories as stabilizations of the uncertainty over time. Codes in the communication add one more selection mechanism and make globalization at the regime level possible. Selections can be meta-selected for stabilization along trajectories, and some stabilizations can be selected for globalization at a regime level. Stabilizations are historical and can be at variance. They can thus be considered as providing a second-order variation; globalization functions analogously as a next-order selection. Because the second-order selections (regimes) select on the second-order variation (stabilizations along trajectories) *in parallel to* first-order variations and selection, the operations loop into themselves and one another with the resulting complexity and the possibility of self-organization, leading to unintended consequences. (What can be considered first- and second-order may change over time.) The loops are not hierarchically organized, but can interact and thus disturb one another.

Since the communication of information and the sharing of meanings operate in terms of recursive and incursive selections, the historical origin of the variation may no longer be visible in the present after a series of selective rewrites. Both the historical trajectories and the evolutionary regimes can be expected to change, but at different speeds or, in other words, without a priori synchronization. The two momenta of historical development (at the trajectory level) and evolutionary change (at the regime level) relate in dynamic trade-offs. The regime is instantiated as a meta-historical selection environment pending on the historical trajectories.

For example, airplane series such as the DC3 to the DC9 are developed along trajectories, but the introduction of the jet-engine as a replacement of the propeller motor was a systems innovation (Frenken & Leydesdorff, 2000). While helicopters are developed in another regime, the discontinuity between propeller airplanes and jet aircraft can be a change at the trajectory and/or regime level. One would need empirical research for answering this question. Dosi (1982, p. 152), for example, provided operational definitions for regimes (or paradigms) and historical trajectories, as follows:

> In broad analogy with the Kuhnian definition of a "scientific paradigm," we shall define a "technological paradigm" as "model" and a "pattern" of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies.[…].
>
> As "normal science" is the "actualization of a promise" contained in a scientific paradigm, so is "technical progress" defined by a certain "technological paradigm". We will define a *technological trajectory* as the pattern of "normal" problem solving activity (i.e. of "progress") on the ground of a technological paradigm.

Note that Dosi (1982) articulated a model with three selection environments operating upon one another. This predates the neo-evolutionary version of the Triple-Helix model by two decades. However, Dosi did not elaborate specifically the evolutionary model (Andersen, 1994).

The metaphor of hill-climbing is also used in this context: hills are climbed along trajectories. However, climbing is different at night or during the day, and the difference between day and night is meta-historical for the hill-climbing agents. In terms of Dosi's above definitions, the technological problems may be differently selected in daylight than during the night. In his article about "objectivity" in the social and cultural sciences, Max Weber used this same metaphor when he expressed change in the dynamics at the supra-individual level of a regime, as follows:

> […] at one moment or another, the color will change: the meaning of the perspective which was used without reflection, will become insecure; the road seems now to lead into zones of twilight. The light of the important problems of the culture has advanced. At such moments, the sciences have to provide themselves with the means of changing position and of changing their methodological apparatus, in order reflexively to grasp the higher grounds of reasoning from which to look down on the stream of history. Science follows the constellations which make it a meaningful enterprise. (Weber [1904] [3]1968, p. 214.)

Changes at the regime level happen beyond control; changes at the trajectory level can be organized by agency (e.g., entrepreneurs).

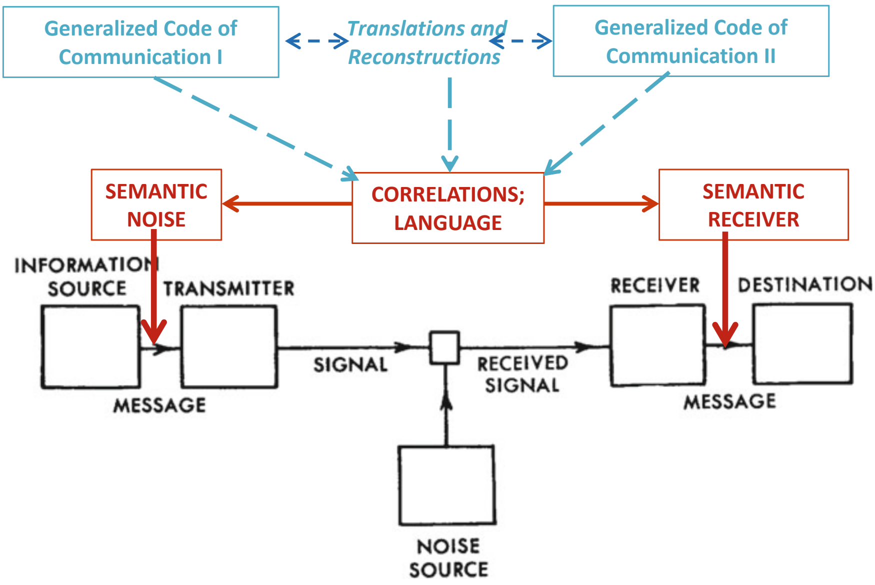


Fig. 4.4 Levels B and C added to the Shannon diagram (in red-brown and dark-blue, respectively). Source: Leydesdorff (2016), p. 283

4.3 Levels B and C in the Shannon Diagram

In addition to proposing the two new boxes in Shannon's diagram (Fig. 4.1), Weaver (1949, p. 24) suggested adding to this diagram the levels B and C: meaning is conveyed at level B, and the received meaning can affect behavior at level C (because codes are genotypical and binding). Elaborating Figs. 4.1 and 4.4 shows a scheme for distinguishing among these three levels.

As noted above, the relations among a *semantic* receiver and *semantic* noise at level B are based on correlations among sets of relations at level A. In the vector space thus constructed at level B, meanings can be shared, while information continues to be communicated in the links at level A. The use of language facilitates and potentially reinforces the options for sharing (and distinguishing!) meanings at level B. Natural languages provide opportunities to develop semantics; symbolic meanings, however, require codes to operate in the communications.

Codes of communication are invoked from level C for regulating the use of language. The codes enable us, among other things,[1] to short-cut the communication; for example, by paying the price for something instead of negotiating using language. The codes enable us to make the communications far more efficient than is possible in natural languages. The communication can both vertically and horizontally be differentiated: horizontally in terms of different codes operating in parallel

[1] Spelling rules, syntax, and pragmatics can also be considered as codes in the use of language, but we focus on the semantics.

and vertically between historical organization and evolutionary self-organization. In the following sections, these two differentiations are related.

4.4 Scholarly Discourse and Codification

The tension between historical organization and evolutionary self-organization is articulated in the sociology of science as the difference between "group" and "field"-level dynamics. Following up on his (1976) historical analysis of "Le champ scientifique," for example, Bourdieu (2004, at p. 83) added a further reflection on the study of the sciences in his book, entitled *Science of Science and Reflexivity.* He formulated as follows:

> Each field (discipline) is the site of a specific legality (a nomos), a product of history, which is embodied in the objective regularities of the functioning of the field and, more precisely, in the mechanisms governing the circulation of information, in the logic of the allocation of rewards, etc., and in the scientific habitus produced by the field, which are the condition of the functioning of the field […].
>
> What are called epistemic criteria are the formalization of the "rules of the game" that have to be observed in the field, that is, of the sociological rules of interactions within the field, in particular, rules of argumentation or norms of communication. Argumentation is a collective process performed before an audience and subject to rules.

From a very different perspective, Popper (1972) denoted the domain of supra-individual codifications as World 3. Bourdieu (2004; at p. 78) called this transition from "objectivity" to "intersubjectivity" a "Kantian" or transcendental turn. However, the philosopher to be associated with this transition, is Husserl, who criticized the empiristic self-understanding of the modern (European) sciences (Husserl, [1935/36] 1962). According to Husserl ([1929] 1960, at p. 155), the possibility to communicate expectations intersubjectively grounds the empirical sciences "in a concrete *theory of science*." In Chap. 2, I called this the communicative turn in the philosophy of science.

Neither Popper nor Husserl specified the evolutionary dynamics of expectations in terms of or in relation to communications. I shall argue that the dynamics of *res cogitans* can be further specified information-theoretically. The symbolically generalized codes in the communication enable us to multiply meanings at the intersubjective level—that is, within the communication—as new options. The proliferation of expectations can take place in a techno-cultural evolution at a speed much faster than in biological evolution.

The intersubjective layer of expectations codes and structures the communications. The different codes can be recombined and reconstructed in translations. At level B, meanings are instantiated in specific combinations of codes, while at level C the codes themselves evolve in response to the integrations in the instantiations as historical events. The superstructure of codes continues to be driven into differentiations by the need to cope with the increasing complexity of the communication at the bottom. At this level A, the probabilistic entropy (H) increases because of the coupling of information to entropy and the second law of thermodynamics.

4.5 Redundancy and Evolution

Shannon (1948) defined information (H) as probabilistic entropy $\left[H = -\Sigma_{\mathrm{i}} p_{\mathrm{i}} * \log(p_{\mathrm{i}})\right]$ in accordance with Gibbs's formula for thermodynamic entropy: $S = k_B * H$. In this equation, k_B is the Boltzmann constant that provides the dimensionality Joule/Kelvin to the thermodynamic entropy S; H provides a dimensionless statistic. H can be measured as uncertainty in a probability distribution: $H = -\Sigma_{\mathrm{i}} p_{\mathrm{i}} * \log(p_{\mathrm{i}})$. (When two is taken as the basis for the logarithm, the measurement is in bits of information.)

The second law of thermodynamics states that entropy increases with each operation. Because of the linear relation between S and H, historical developments unfold with the arrow of time; that is, from an origin to the future. However, models enable us to anticipate future states from our position in the present, that is, to use future states ($x_{\mathrm{t+n}}$) represented in the present (x_{t}) against the arrow of time for the reconstruction. In other words, the dynamics of expectations are very different from the historical dynamics "following the actors." In the remainder of this chapter, the focus will be on the interactions among differently coded expectations and how they can generate redundancy (against the second law).

Redundancy R is defined in information theory as the fraction of the capacity of a communication channel ($H_{\max}$) that is *not* used. In formulic format:

$$R = \frac{H_{\max} - H_{observed}}{H_{\max}} \tag{4.1}$$

H is equal to the uncertainty in a relative frequency distribution ($\Sigma_{\mathrm{i}}\, p_{\mathrm{i}} = \Sigma_{\mathrm{i}}\, [f_{\mathrm{i}}/N]$) as follows:

$$H = -\Sigma_{\mathrm{i}} p_{\mathrm{i}} * \log_2(p_{\mathrm{i}}) \tag{4.2}$$

When all N probabilities are equally probable and thus equal to $1/N$, one can formulate the maximum information content H_{max} as follows:

$$\begin{aligned} H_{\max} &= -\sum_{i=1}^{N}\left(\frac{1}{N}\right)\log(\frac{1}{N}) \\ &= -\frac{N}{N}\log\left(\frac{1}{N}\right) \end{aligned} \tag{4.3}$$

$$= \log(N) \tag{4.4}$$

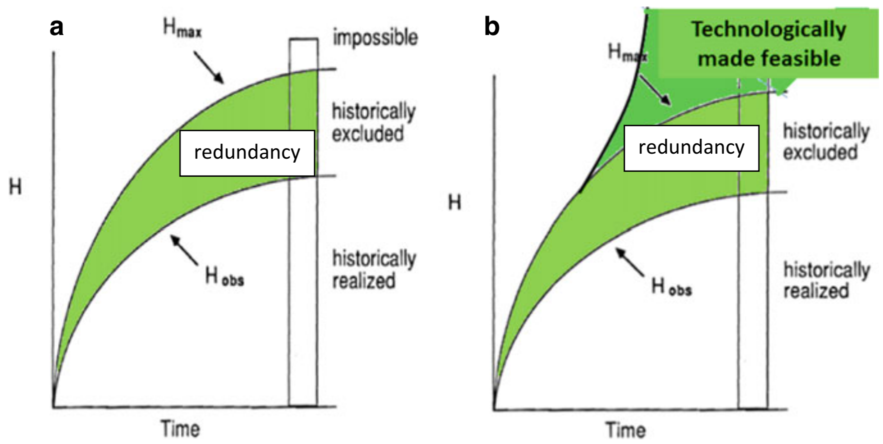


Fig. 4.5 **a** The development of entropy (H_{obs}), maximum entropy (H_{max}), and redundancy ($H_{\text{max}} - H_{\text{obs}}$). **b** Hitherto impossible options are made possible because of cultural and technological evolution. Adapted from: Brooks & Wiley (1986, at p. 43)

In the case of an evolving system—e.g., an eco-system in which new species can be generated—not only the observed information (H_{observed}) of the system increases with time, but also H_{max}, representing the number of *possible* states (N). The difference between H_{max} and the observed information H_{observed} is (by definition) equal to the redundancy R; that is, the options that are available but have not yet been realized. From the engineering perspective of information theory, these options are redundant. Redundancy can be used, among other things, for error-correction (Shannon, 1945).

Figure 4.5a shows Brooks & Wiley's (1986, at p. 43) illustration of the dynamics of a biological system. I have added green to the redundancy as part of the evolving capacity of this system. As noted, redundancy provides a measure of the options that were not realized, but could have been realized. The exclusion of these options is "historical." Kauffman (2000), for example, called these in principle possible realizations "adjacent." Above this (green) area, however, Brooks & Wiley (1986) added the label of categorically "impossible" as a legend of Fig. 4.5a.

In Fig. 4.5b, I have replaced the label "impossible" with "technologically made feasible" in order to introduce a model which includes the levels B and C. Unlike a biological system, the techno-cultural evolution of expectations can be expected to generate redundancy. An intentional system is able to add new options without necessarily realizing them; one can keep options in mind. The cycling of information on top of the linear flow generates redundancy (Maturana, 2000). Redundancy is generated when two (or more) perspectives on the same information are operating at an interface.

For example, in the case of introducing a new technology into a market, the markets operate with a (supra-individual) logic different from technological criteria. When both the economic and the technological logic can operate, innovations can be enhanced because of the options made visible by the cross-tabling. (In Fig. 4.2b, for

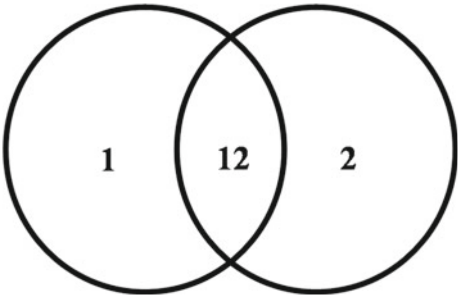


Fig. 4.6 Set-theoretical representation of two sets of overlapping options

example, five zeros were added to the representation in Fig. 4.2a.) The redundancy added to the green surfaces of Fig. 4.5b is generated by the recombination of different expectations organized in terms of the variety of perspectives that can be entertained in the communication. Let me first specify this process in information-theoretical terms and then return to the interpretation. The reader who is less interested in the following derivations may wish to skip to Sect. 4.8.

4.6 The Generation of Mutual Redundancy

The total number of options available in a system is (by definition) equal to the sum of the realized options and the not-yet-realized but possible ones. This sum of realized and possible options determines the capacity of a system.

In information theory, one counts by using relative frequencies multiplied by their respective logarithms.[2] This transformation is monotonous. For example, the two sets in Fig. 4.6 can be summed as follows:

$$H_{12} = H_1 + H_2 - T_{12} \tag{4.5}$$

[2]The counting rules in information theory (Shannon, 1948; cf. Leydesdorff, 1991; Theil, 1972; Yeung, 2008) are based on relative frequencies. Observed frequencies are divided by the grand total in order to obtain relative frequencies or, in other words, probabilities:

$$p_{ijk\ldots} = f_{ijk\ldots} / \sum_{ijk\ldots} f_{ijk\ldots} = f_{ijk\ldots}/N$$

The probabilistic entropy of the distribution of relative frequencies is:

$$\begin{aligned} H_{\text{observed}} &= -\sum_{ijk\ldots} p_{ijk\ldots} \log_2 p_{ijk\ldots} \\ &= -\frac{\sum_{ijk_w} f_{ijk_w}}{N} * \log_2 \frac{f_{ijk_m}}{N} \\ &= \log_2 N - \sum_{ijk\ldots} f_{ijk\ldots} \log_2 f_{ijk\ldots} \end{aligned}$$

It follows that the maximum entropy $H_{\max} = \log_2 N$. The relative uncertainty or information is $H_{observed}/H_{\max}$. The redundancy is defined by Shannon (1948) as the relative value of the not-realized options:

$$Redundancy = [H_{\max} - H_{observed}]/H_{\max}$$

H_1 and H_2 can be used as labels for the information contents of the two sets with an overlap in T_{12}. T_{12} is called "mutual information" or "transmission" between H_1 and H_2. If T_{12} were not subtracted from $(H_1 + H_2)$, the overlap would be counted twice. However, the second time would be redundant. This redundancy R_{12} is equal to $-T_{12}$ or, in other words, negative since the mutual information (T_{12}) itself is Shanon-type information and therefore necessarily positive (Theil, 1972, p. 59f.).

Weaver (1949) already noted that redundancy might be a prime candidate for the development of a theory of meaning. Using a different definition of information (as "a difference which makes a difference"; see Mackay, 1969), Bateson (1972, p. 420) argued that "the concept 'redundancy' is at least a partial synonym of 'meaning': [...] if the receiver can guess at missing parts of the message, then those parts must, in fact, carry a *meaning* which refers to the missing part and is information about these parts." Unlike information, redundancy is not observable; the maximum information has to be specified on theoretical grounds. This specification has the status of a hypothesis (which one may wish to update after the research process).

The same information can be appreciated differently by other agents or at different moments and other levels. Whenever information is *appreciated*, a system-specific meaning is generated. Whereas information can be communicated, meanings can be shared. Sharing can generate an *intersubjective* layer with a dynamic different from that of information processing. The redundancy in the overlaps can be measured as reduction of uncertainty at the systems level; that is, as *negative* bits of information. The relative uncertainty is reduced when the redundancy is increased. Whereas the events are historical and generate entropy along trajectories following the arrow of time, appreciations are analytical and can add redundancy or negative entropy from the perspective of hindsight—that is, against the arrow of time. One can also consider this redundancy as feedback or error correction against the arrow of time (Kline & Rosenberg, 1986; Krippendorff, 2009b).

In Fig. 4.7, Fig. 4.6 is extended to three sets. The two possible configurations in Fig. 4.7 indicate that T_{123} (the set in the centre) can be positive, negative, or zero.

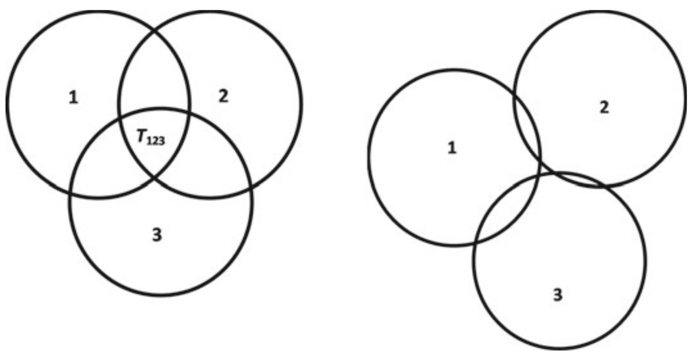


Fig. 4.7 Overlapping uncertainties in three variables x_1, x_2, and x_3: two configurations with opposite signs of T_{123}

Redundancy is a measure of these absent options which can be defined (Bateson, 1972; Deacon, 2012). Unlike the empty space outside the three circles, the gap among the three circles in the centre can be quantified.

The formula for the entropy of the combined set H_{123} follows the corrected numbers of elements using summations and subtractions as in overlaps among sets, as follows:

$$H_{123} = H_1 + H_2 + H_3 - T_{12} - T_{13} - T_{23} + T_{123} \tag{4.6}$$

In Eq. 4.6, the central overlap T_{123} is included three times in $(H_1 + H_2 + H_3)$ and then three times subtracted by $(- T_{12} - T_{13} - T_{23})$. It follows that T_{123} has to be added once more after the subtractions. Since T_{123} is *added*, while T_{12} was *subtracted* (in Eq. 4.4), the sign of the last term, representing the mutual redundancy in three dimensions, is opposite to that representing a model with an even number of dimensions: $R_{12} = -T_{12}$ and $R_{123} = + T_{123}$, etc.

By replacing T_{12} in Eq. 4.6 with $(H_1 + H_2 - H_{12})$ as in Eq. 4.5, one can formulate as follows:

$$\begin{aligned} H_{123} = H_1 + H_2 + H_3 - (H_1 + H_2 - H_{12}) - (H_1 + H_3 - H_{13}) \\ - (H_2 + H_3 - H_{23}) + T_{123} \end{aligned} \tag{4.7}$$

Or after reorganization of the order of the terms:

$$\begin{aligned} T_{123} &= H_{123} - [H_1 + H_2 + H_3] + (H_1 + H_2 - H_{12}) + (H_1 + H_3 - H_{13}) \\ &\quad + (H_2 + H_3 - H_{23})T_{123} \\ &= [H_1 + H_2 + H_3] - [H_{12} + H_{13} + H_{23}] + H_{123} \end{aligned} \tag{4.8}$$

Using sets of relative frequency distributions—variables—the measurement of T_{123} is straightforward: all H values can be aggregated from writing the data as relative frequencies. The values of T_{123} follow from adding and subtracting H-values using Eq. 4.8.

4.7 Generalization

The sign change of the mutual information with the number dimensions was until recently an unsolved problem in information theory.[3] However, Alexander Petersen

[3]Krippendorff (2009b, at p. 670; cf. Leydesdorff, 2010, at p. 68) provided a general *notation* for this alteration with changing dimensionality—but with the opposite sign as follows:

$$Q(\Gamma) = \sum_{X \subseteq \Gamma} (-1)^{1+|\Gamma|-|X|} H(X) \tag{4.9}$$

has proven that this sign, indeed, changes with the addition of each next dimension.[4] In other words, it can be shown that mutual redundancy is a consistent measure of negative entropy (Leydesdorff, Petersen, & Ivanova, 2017, p. 17).

Equation 4.8 can be rewritten as follows:

$$\begin{aligned}
T_{123} &= H_1 + H_2 + H_3 - H_{12} - H_{13} - H_{23} + H_{123} \\
T_{123} &= [(H_1 + H_2 - H_{12}) + (H_1 + H_3 - H_{13}) + (H_2 + H_3 - H_{23})] \\
&\quad + [H_{123} - H_1 - H_2 - H_3] \\
T_{123} &= [T_{12} + T_{13} + T_{23}] + [H_{123} - H_1 - H_2 - H_3]
\end{aligned} \tag{4.10}$$

The terms in the first set of brackets in Eq. 4.10— $[T_{12} + T_{13} + T_{23}]$—are Shannon-type information values and therefore strictly positive. The second bracketed term—$[H_{123} - H_1 - H_2 - H_3]$—makes a negative contribution, because of the subadditivity of the entropy: $H(x_1, \ldots, x_n) \leq \sum_1^n H(x_i)$, which holds for any dimension $n \geq 2$. For example, $H_{123} \leq (H_1 + H_2 + H_3)$. The sign of the resulting value of T_{123} depends on the empirical configurations of nodes (H-values) and links (T-values). Figure 4.7 shows the two opposites with positive and negative overlaps. This empirical trade-off can change over time and can also be considered as "the triple-helix dynamics" (Etzkowitz & Leydesdorff, 2000; see Chap. 5).

It follows inductively that for any given dimension n, one can formulate combinations of mutual information corresponding to $\sum_1^n H(x_i) - H(x_1, \ldots, x_n)$ that are by definition positive (or zero in the null case of complete independence). For example (up to four dimensions) as follows:

$$\begin{aligned}
&0 \leq \sum_{i=1}^{n=2} H(x_i) - H(x_1, x_2) = T_{12} \\
&0 \leq \sum_{i=1}^{n=3} H(x_i) - H(x_1, x_2, x_3) = \sum_{ij}^{3} T_{ij} - T_{123} \\
&0 \leq \sum_{i=1}^{n=4} H(x_i) - H(x_1, x_2, x_3, x_4) = \sum_{ij}^{6} T_{ij} - \sum_{ijk}^{4} T_{ijk} + T_{1234}
\end{aligned} \tag{4.11}$$

where the sums on the right-hand side are over the $\binom{n}{k}$ permutations of the indices.

Equation 4.11 can be extended for general n as follows:

$$0 \leq \sum_{i=1}^{n} H(x_i) - H(x_1, \ldots, x_n)$$

In this equation, Γ is the set of variables of which X is a subset, and $H(X)$ is the uncertainty of the distribution; $|\Gamma|$ is the cardinality of Γ, and $|X|$ the cardinality of X.

[4]The sign change finds its origin in the non-additivity of the entropy: $H_{12} \leq H_1 + H_2$.

$$= \sum_{ij}^{\binom{n}{2}} T_{ij} - \sum_{ijk}^{\binom{n}{3}} T_{ijk} + \sum_{ijkl}^{\binom{n}{4}} T_{ijkl} - \cdots + (-1)^{1+n} \sum_{ijkl\ldots(n-1)}^{\binom{n}{n-1}} T_{ijkl\ldots(n-1)}$$
$$+ (-1)^n \sum_{ijkl\ldots(n)}^{\binom{n}{n}} T_{ijkl\ldots(n)} \tag{4.12}$$

where the last term on the right-hand side is equal to $(-1)^n T_{1234\ldots n}$.

Returning to the relation between R_{12} and T_{12}, it follows (using first two dimensions instructively) that:

$$\begin{aligned} R_{12} &= -T_{12} \\ &= H(x_1, x_2) - \sum_1^2 H(x_i) \leq 0 \\ \text{and} \quad T_{12} &\geq 0 \end{aligned} \tag{4.13}$$

In other words, mutual information between two information sources is either positive or zero (Theil, 1972, p. 59f.). The relations for R_{123} and R_{1234} follow analogously from Eq. (4.12). In the general case of more than two dimensions ($n > 2$):

$$R_n = (-1)^{1+n} T_{1234\ldots n}$$

$$R_n = \left[H(x_1, \ldots, x_n) - \sum_1^n H(x_i) \right]$$
$$+ \left[\sum_{ij}^{\binom{n}{2}} T_{ij} - \sum_{ijk}^{\binom{n}{3}} T_{ijk} + \sum_{ijkl}^{\binom{n}{4}} T_{ijkl} - \cdots + (-1)^{1+n} \sum_{ijkl\ldots(n-1)}^{\binom{n}{n-1}} T_{ijkl\ldots(n-1)} \right] \tag{4.14}$$

The left-bracketed term of Eq. 4.14—$\left[H(x_1, \ldots, x_n) - \sum_1^n H(x_i)\right]$—is necessarily negative (because of the subadditivity of the entropy; see above), while the configuration of mutual information relations contributes a second term on the right which can be positive. This latter term represents the entropy generated by the realization of the network in terms of links. The links are historical and thus add information.

In summary, Eq. 4.14 models the generation of redundancy (with a negative sign) on the one side versus the historical process of uncertainty generation in the relations (with a positive sign) on the other. A system with more than two codes (e.g., three alphabets; cf. Abramson, 1963, p. 127 ff.) can operate as an empirical (im)balance. When the resulting R_n is negative, self-organization prevails over organization in the configuration under study, whereas a positive R_n indicates conversely a predominance of historical organization over evolutionary self-organization.

4.8 Clockwise and Anti-clockwise Rotations

When the relation between two subdynamics is extended with a third, the third may feed back or feed forward on the communication relation between the other two, and thus a system is shaped (Sun & Negishi, 2010). This principle is known in social network analysis as "triadic closure." Triadic closure can be considered as the basic mechanism of systems formation (Bianconi et al., 2014; de Nooy & Leydesdorff, 2015). The cycling may take control as in a self-organizing vortex (Fig. 4.8). A cycle with the reverse order of the operations (counter-clockwise) is equally possible stabilizing the dynamic in organizational formats.

The two cycles can be modeled as two vectors P_{ABC} and Q_{ABC} with three (or more) dimensions (A, B, and C), and this system can then be simulated in terms of the rotations of the two vectors (Ivanova & Leydesdorff, 2014b). One rotation can be understood as corresponding to the tendency of historical realization, and the evolving self-organization of horizons of meaning. Using simulations, Ivanova & Leydesdorff (2014a) showed that the operation of these two (three-dimensional) vectors upon each other can be expected to generate an R. The value of R is determined by the network configuration as were the values of $T_{123\ldots\mathrm{n}}$ in (Eq. 4.14). A negative sign of R can be associated with clockwise and the positive sign with counter-clockwise rotations of the vectors in the *simulation*, while the values of the two terms in Eq. 4.14 *measure* the relative weights of the two rotations in empirical data. The theorizing, simulation, and measurement can thus be brought into the single and comprehensive framework of a calculus of redundancy as a complement to Shannon's calculus of information (Bar-Hillel, 1955). The resulting value of R can be positive or negative reflecting the possibility of an inversion along the time axis.

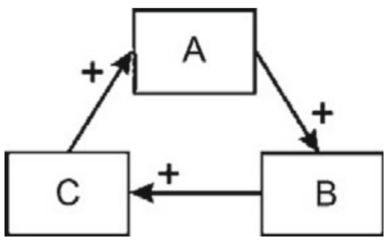


Fig. 4.8 Schematic of a hypothetical three-component autocatalytic cycle. *Source* Ulanowicz (2009, at p. 1888, Fig. 3)

4.9 Summary and Conclusions

I first extended Shannon's model of communication (at level A) with Weaver's levels B and C. This changes Shannon's linear model into a non-linear and potentially evolutionary one, since feedback and feed-forward loops among the levels become possible. The three levels distinguished in Fig. 4.3 correspond with Luhmann's distinction among (*i*) interactions, (*ii*) organization on the basis of decisions, and (*iii*) self-organization among the fluxes of communications. At level A, *information is communicated* in interactions among senders and receivers; at level B, *meanings can be shared* to variable extents and thus meaningful information is organized into a vector-space. However, this vector space is constructed and therefore remains subject to reflexive reconstructions. The reconstructions, in terms of different weights of the codes of communication, open self-organizing horizons of meaning at level C.

The question central to the next chapters can now be formulated as follows: under what conditions can the different codes be expected to interact and co-evolve, and thus lead to new options? In this chapter, I have first focused on the coherence and tensions among the communication-, evolution-, and systems-theoretical perspectives with reference to Luhmann's formulation of the program of theory construction (cited in Chap. 1). I have argued that redundancies can be generated at interfaces among *sets of relations* which are structured by codes.

In Luhmann's theory, however, interactions among codes were a priori held to be *impossible;* the (sub)systems are *defined* as "operationally closed" (Luhmann, 1986a and b; cf. Maturana, 1978). In my opinion, this assumption leads to a meta-biology, since the analyst remains external to the closed systems under study which can only be "observed." Whereas biological systems can gain in complexity by closing themselves operationally—for example, by shaping a membrane—expectations can disturb and penetrate one another "infra-reflexively" (Latour, 1988, at p. 169 ff.) and across domains in the second contingency. Neither the communication "systems" nor the codes "exist" as hardware (*res extensa*).

The reflexive layers (*res cogitans*)—at the individual and the above-individual levels—can be expected to operate with specific selection criteria upon one another and over time. Because of these reflexive couplings in terms of expectations, cultural evolution can be much faster than biological evolution, which operates in terms of realizations (over generations). Writing and rewriting in the hardware requires more energy and time than the exploration and codification of new combinations of expectations.

In other words, I draw a sharper line than Luhmann did between biology and sociology. Different from Luhmann, I do *not* make the assumption that systems "exist." On the contrary, I assume that "systems" are analytical constructs. These constructs can eventually be tested as sets of expectations. Cognitive constructs are thus different from living systems. The philosophy in the background is fundamentally opposed to the holistic and biologically oriented ones nowadays prevailing in artificial intelligence (e.g., Damasio, 1994; Sherman, 2017). Theories of information and redundancy span different domains (Deacon, 2012). *In the reflexive domain of* *the social sciences, we study our methods of studying, since these methods are the constraints of our respective perspectives.*

Furthermore, Luhmann (e.g., 2013, p. 98) stated "avoidance of redundancy" as an objective. But it remained unclear why. From my perspective, this a priori makes it impossible to contribute to his original objective to specify "a form of selection that prevents the world from shrinking down to just one particular content of consciousness with each act of determining experience" ([1971] 1990, p. 27). The new options are redundant. The generation of redundancy proceeds in a domain of expectations about options that do not (yet) exist, but that one can imagine reflexively, refine, and (re)construct.

By turning away from an objectivistic self-understanding of the sciences as "observers" and "observations" room thus can be found for a theory of meaning and knowledge-generation as an extension of Shannon's information theory (Fig. 4.3). Whereas Shannon felt the need to distance himself explicitly from this potential extension, his co-author Weaver understood this possible consequence as the proper intension of information theory (Bar-Hillel, 1955).

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Part II
Synergy in Triple-Helix Relations

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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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_5

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.

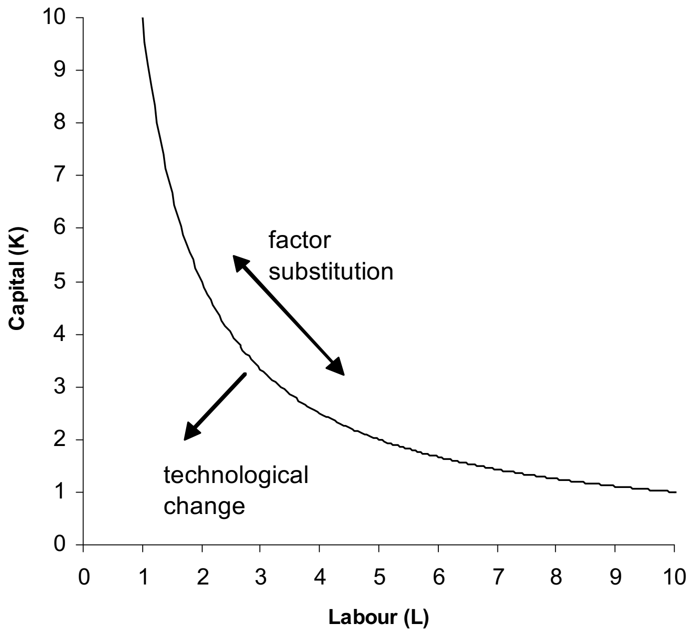


Fig. 5.1 Schumpeter's model of technological change as a shift of the (Cobb-Douglas) production function towards the origin *versus* factor substitution as a shift along the production function

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).

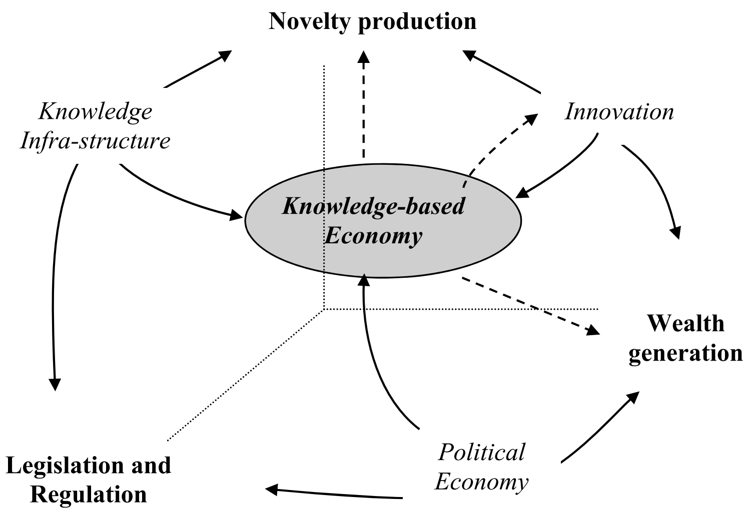


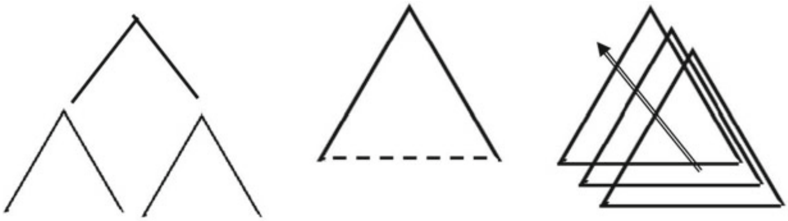
Fig. 5.2 The first-order interactions generate a knowledge-based economy as a next-order system. *Source* Leydesdorff (2010, at p. 379)

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)

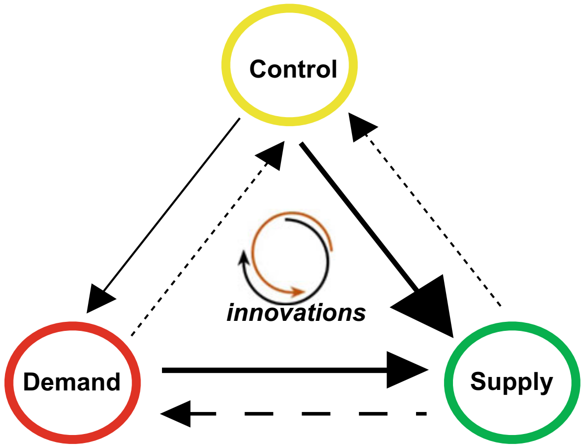


Fig. 5.4 The generalized Triple-Helix model of innovations. *Source* Further development from Petersen et al. (2016, Fig. 1, at p. 667)

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.

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[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).

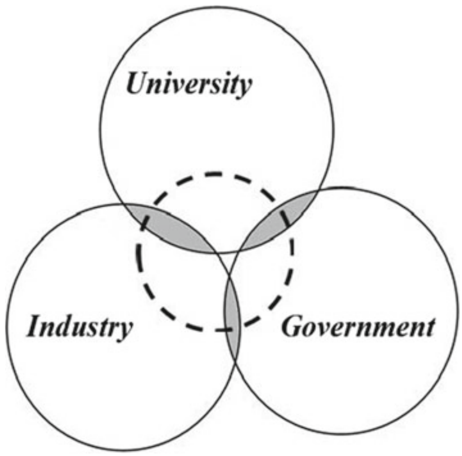
A triangle can be tipped clockwise or counter-clockwise. The two rotations (depicted as cyclic arrows in the center of Fig. 5.4) precondition each other as local organization and global self-organization; networks instantiated at the organizational level provide stepping-stones and retention mechanisms 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"



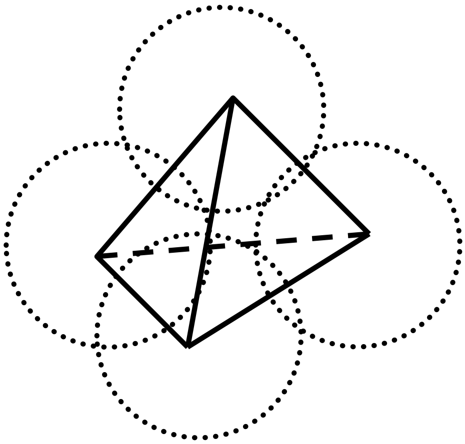


Fig. 5.6 Tetrahedron of three communication systems with an overlay

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

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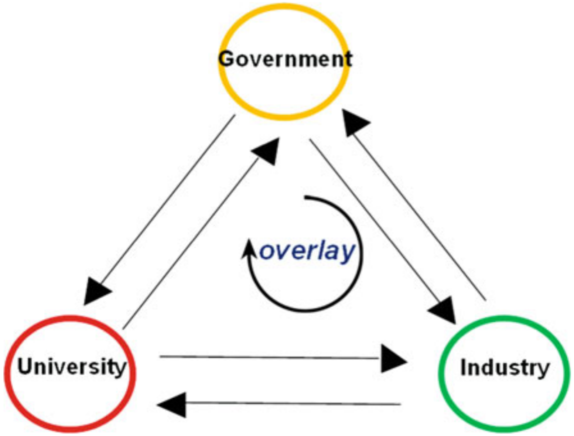
<td>
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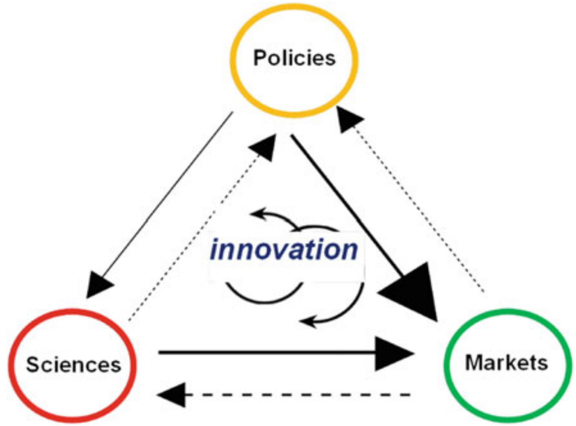
<td>
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<tr>
<td>• University-Industry-Government Relations
• (Inter-)institutional
• Entrepreneurship (agents)
• Network analysis; graphs;
• Historical cases (“phenotypes”);
• Inductive:
– “Best practices”; comparative case studies (Saad & Zawdie, 2011);
– Bottom-up (e.g., Li, Arora, Youtie, & Shapira, 2016);
– Policy analysis (Etzkowitz, 2008; Zhou & Peng, 2008)
(Etzkowitz & Leydesdorff, 1995, 2000)</td>
<td>• 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)</td>
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</table>

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

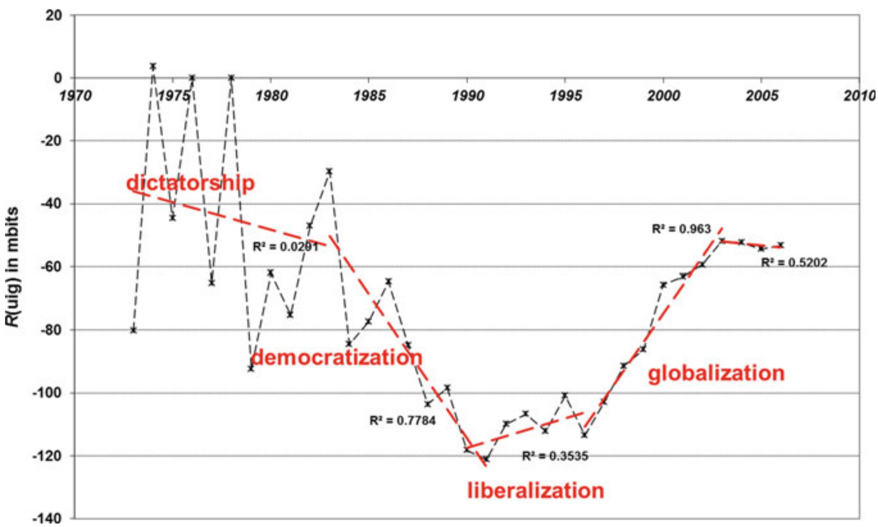

Fig. 5.7 The development of mutual redundancy in South Korean university-industry-government relations during the dictatorship and the periods of democratization, liberalization, and globalization, respectively. *Source* Elaborated from Park and Leydesdorff (2010, at p. 645)

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.

[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).

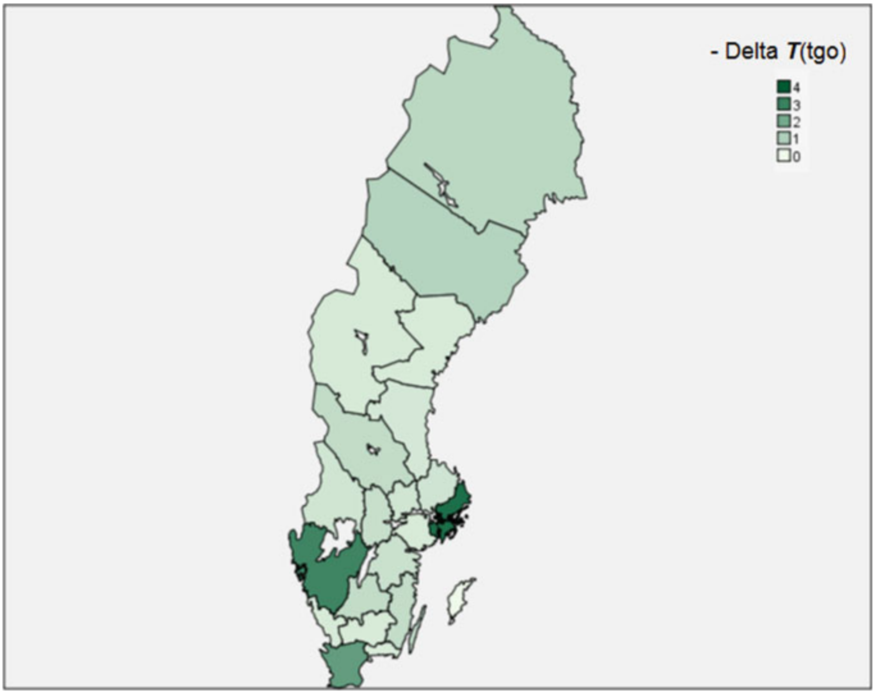

Fig. 5.8 Percentages of contributions to redundancy at the level of 21 Swedish counties (NUTS-3)

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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Chapter 6
Regions, Innovations, and the North–South Divide in Italy

Using firm-level data collected by Statistics Italy for 2008, 2011, and 2015, the Triple-Helix synergy among geographical and size distributions of firms and technology classes is analyzed both regionally and nationally. The Italian system is both knowledge-based and knowledge-intensive, and therefore an interesting case. The contributions to national synergy of the twenty regions in Italy have increased between 2008 and 2015, but synergy generation at levels above the regions has remained relatively stable at approximately 45%. As against the statistical classification into twenty regions, or into Northern, Central, and Southern Italy, the greatest synergy is retrieved by defining the country in terms of Northern and Southern Italy as two sub-systems, with Tuscany included as part of Northern Italy. Different innovation strategies could be developed for these two parts of the country. However, the current focus on twenty regions for innovation policies may to some extent be an artefact of the statistics and EU policies. In terms of sectors, both medium- and high-tech manufacturing (MHTM) and knowledge-intensive services (KIS) are integrated proportionally in the various regions.

Italy was shaped as a nation state in the period 1848–1870. During the Second War of Independence (1859–1861), the northern part of Italy was unified under the leadership of the Kingdom of Piemonte (Turin), and the southern part—the Kingdom of the Two Sicilies (with Naples as capital)—was conquered by Garibaldi in 1860. Central Italy, which until then had been the Papal State, was invaded by Italy in 1870 and thereafter Rome became the capital of the nation. The division into three parts—Northern, Central, and Southern Italy—has remained important; it is commonly used for policy purposes. However, the North/South divide is also a common terminology in political discourse. In short, the North and the South have different cultural traditions and marked differences in GDP per capita, the composition of economic activities, and employment indicators.

At a lower level of aggregation, the country is administrated in terms of twenty regions, of which five have a special status. Among these, Valle d'Aosta is an

This is a shortened and rewritten version of Leydesdorff, L., & Cucco, I. (2019). Regions, Innovation Systems, and the North-South Divide in Italy. *El profesional de la información, 28*(2), e280214. https://doi.org/10.3145/epi.2019.mar.14.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*, Qualitative and Quantitative Analysis of Scientific and Scholarly Communication, https://doi.org/10.1007/978-3-030-59951-5_6

autonomous region in which French functions as a second language. Alto Adige (also known as Süd-Tirol) is an autonomous province of Trentino-Alto Adige, bordering on Austria, with German as a second language. Below the level of regions, 107 provinces are defined in the statistics.[1] Furthermore, Italy is known for its "industrial districts" which often cover a small territory within one or more provinces, with specialized manufacturing or services (Becattini et al., 2003; Bertamino et al., 2017). These districts are highly innovative and mainly located in the northern part of the country (Biggiero, 1998). Using 2011 census data, Statistics Italy (IStat) distinguished 141 industrial districts and furthermore 611 so-called local labour systems based on commuting patterns ("sistemi locali del lavoro," SLL). Insofar as SLLs overlap with industrial districts, the data allows for economic analyses at the district level(e.g., Paci & Usai, 2000; Mameli, Faggian, & McCann, 2008). Industrial districts, however, are not a separate level of administration and hence not included in the national statistics.

National statistics for Italy are aligned with the hierarchical classification of the European Union in the "Nomenclature des Unités Territoriales Statistiques" (Nomenclature of Territorial Units for Statistics, or NUTS). In this classification, NUTS1 is defined as lands (e.g., the German *Länder*), NUTS2 as regions (e.g., Lombardia), and NUTS3 as provinces or metropolitan areas (e.g., the metropolitan region of Milano or the province of Lecce).

Grilliches (1994) noted that the use of administrative units in statistics can be a data constraint for innovation studies and also for innovation policies. For example, innovation is not constrained geographically (Carlsson & Stankiewicz, 1991). Innovation systems may depend on interactions and infrastructures that do not match regional and national boundaries. Sectorial innovation systems (e.g., oil refinement, biotechnology) are in important respects organized internationally (Carlsson, 2006 and 2013). Furthermore, firms can interact with non-regional universities if the knowledge and skills required are not available within the region (Asheim & Coenen, 2006; Fritsch & Schwirten, 1999), or when they are seeking higher-quality collaboration partners at the international level (d'Este & Iammarino, 2010; Laursen, Reichstein, & Salter, 2011). For the purpose of implementing innovation policies at the appropriate level, however, it is important to understand the boundaries of innovation systems. This is a complex undertaking which could be addressed at different levels (e.g., municipal, provincial, regional, national, supra-national; by sector or comprehensively) and using different instruments, such as various combinations of qualitative analyses and quantitative indicators.

Italy is a challenging and exemplary case: to what extent and at which levels is innovation-systemness indicated? Can the regions carry the function of regional innovation organizers (Etzkowitz & Klofsten, 2005)? If we test regional innovation systems using the generation of redundancy as an indicator of synergy, the results show that the understanding of Italy in terms of regional innovation systems is not optimal when synergy is measured in terms of the interactions among (i) the geographical distributions of firms, (ii) the economic structure in terms of firm sizes, and (iii) the technological knowledge bases of these firms as indicated by the

[1] These numbers change over time. The current count of provinces is 110.

NACE-codes. (NACE is the acronym for the "Nomenclature générale des Activités économiques dans les Communautés Européennes" used by the OECD and Euro-Stat.) Most synergy is found by considering Italy in terms of a northern and southern part, with Tuscany as part of Northern Italy.

6.1 Innovation Policies and Innovation Systems in Italy

Both the OECD and the EU provide incentives for organizing regional innovation policies. Among other things, the OECD reviews regional innovation policies with the objective of providing policy recommendations (e.g., OECD, 2009). In innovation studies (economic geography and evolutionary economics), it is increasingly assumed that regions (including metropolitan regions) are the appropriate units of analysis for studying the transition to a knowledge-based economy (e.g., Braczyk, Cooke, & Heidenreich, 1998; Cooke, 2002; Feldman & Storper, 2016; Florida, 2002; Storper, Kemeny, Makarem, Makarem, & Osman, 2015).

In Italy, regions have gained importance as innovation-policy units since 2001, when the Italian constitution was changed (*Riforma del Titolo Quinto*). A range of devolution measures gave regional governments greater control over policy areas such as health, education, and economic and industrial development, including innovation policy (Rolfo & Calabrese, 2006). This devolution led to a sharp reduction of the national budget for the support of industrial and R&D activities, particularly in the South. Brancati (2015) estimates that between 2002 and 2013, state aid decreased by 72%; the remaining state interventions privileged Central and Northern Italy, while industrial policies in favor of the Southern regions were virtually abandoned after 2000 (Prota & Viesti, 2013).

Furthermore, the 2007–2009 economic and financial crisis has severely impacted the Italian industrial system. Compared with the trends calculated for the 1992–2008 period, about 300 bn Euro of gross investment were lost in Italy between 2008 and 2013 (Cappellin et al., 2014). Southern regions were disproportionally affected: between 2007 and 2012, industrial investment in the South decreased by 47% (Prota & Viesti, 2013). This retreat of national policy has only partly been compensated by regional policies, supported to varying degrees by EU Cohesion and Structural funds. In the EU programs during the period 2007–2013, about 21.6 bn Euro of EU funds (FESR/ERDF and FSE/EFS) were allocated to regions in Southern Italy for Convergence objectives (Calabria, Campania, Puglia, and Sicilia) and 6.3 bn to regions in Central and Northern Italy for so-called Competitiveness objectives.

Despite the increasing role played by regional governments in innovation policy, it has remained a subject of debate whether the regional level is most appropriate for the design and implementation of such policies. On the basis of an analysis of the performance of the Italian national innovation system during the 1980s and 1990s, Malerba (1993, at p. 230), for example, argued that "not one, but two innovation systems are present in Italy." The first is a "core R&D system" that operates at the national level through systematic cooperation between large firms with industrial laboratories, small high-tech firms, universities, public research institutes, and the national government. The second innovation system would be a "small-firms network" composed of a plurality of small- and medium-sized firms that cooperate intensively at the local level, often within industrial districts, and generate incremental innovation through learning-by-doing.

Malerba mentions the lack of overall coordination in public policy and R&D support services and a weak tradition of successful university-industry cooperation in research as major problems in the Italian innovation system. Nuvolari & Vasta (2015) added that Italy can be characterized as a structurally weak national innovation system in comparison to its main competitors. The diverging performance between scientific and technological activities can lead to major difficulties in the technology transfer of scientific results from universities to firms due to a lack of bridging institutions (e.g., Balconi et al., 2004).

A number of studies in various sectors of the economy (e.g., Antonioli et al., 2014; Belusssi et al., 2010; De Marchi & Grandinetti, 2017; Lew et al., 2018) have argued that the international orientation of research collaborations means that Italian regions cannot be considered as innovation systems. These innovative regions are better characterized as "glocal" systems. They pair a relatively low connectedness at the local level with strong knowledge-intensive relationships at the international level. On the industrial side, this international orientation carries a threat of de-industrialization of innovative districts and regions because new options can easily be bought by multinational corporations and relocated elsewhere (Cooke & Leydesdorff, 2006; Dei Ottati, 2003).

In sum, the gradual emergence of knowledge production as an additional coordination mechanism in an industrial system that is otherwise coordinated in terms of institutions and markets introduces the risk of "footloose-ness" (Vernon, 1979). Knowledge-intensive services and high-tech manufacturing tend to uncouple an innovation system from a specific geographical address and can thus be counter-productive from the perspective of regional innovation policies (Leydesdorff & Fritsch, 2006).

6.2 Methods

Elaborating on the reasoning in Chaps. 4 and 5, I note that mutual information among three (or more) dimensions does not measure action (e.g., academic entrepreneurship) as *relations* between input and output, but the investment climate as a structural consequence of *correlations* among distributions of relations. However, the distinction between these structural dynamics in terms of changing selection environments and the historical dynamics of relations is analytical; the historical and the evolutionary dynamics are coupled in the events. Mutual information indicates a trade-off between variation and selection as positive and negative contributions to the prevailing uncertainty. The question of systemness can thus be made empirical and amenable to measurement: when the generation of redundancy prevails over the generation of uncertainty, "innovation systemness" is indicated.

Furthermore, in the case of groups (e.g., subsamples at a lower geographical scale), one can decompose the information as follows: $H = H_0 + \sum_G \frac{n_G}{N} H_G$ (Theil, 1972, pp. 20f.). Since T values are decomposable in terms of H values, one can analogously derive (see Chap. 5; Leydesdorff & Strand, 2013, at p. 1895):

$$T = T_0 + \sum_G \frac{n_G}{N} T_G \quad (1)$$

In this formula, T_G provides a measure of synergy at the geographical scale G; n_G is the number of firms at this scale, and N is the total number of firms under study. One can also decompose across regions, in terms of firm sizes, or in terms of combinations of these dimensions.

The three relevant dimensions are the (g)eographical, (t)echnological, and (o)rganizational; synergy will be denoted as T_{GTO} and measured in millibits with a minus sign. Because the scales are sample-dependent, values are normalized for comparisons across samples as percentages. After normalization, the contributions of regions or groups of regions can be compared. The between-group term T_0 (Eq. 6.1) provides us with a measure of what the next-order system (e.g., the nation) adds in terms of synergy to the sum of the regional systems.[2]

6.3 Data and Descriptive Statistics

Statistics Italy (IStat) collects firm census data every ten years. Complete data sets for the years 2008, 2011, and 2015 were harvested from the so-called ASIA ("Archivo Statistico delle Imprese Attive") database of Statistics Italy. This database includes all enterprises that performed productive activities for at least six months during the reference year. However, this data does not cover the sectors agriculture, fisheries, and forestry. Public administration and non-profit private organizations are also excluded. The data contain 4,514,022 firms in 2008, 4,450,937 firms in 2011, and 4,338,085 in 2015.

For a Triple-Helix analysis of synergy, we need three key variables: (1) the administrative location of the firm in the form of its postal address indicating the geographical dimension (government); (2) the NACE code indicating the main technology in the knowledge base of the firm; and (3) the character of the firm in terms of its size indicated as the numbers of employees. These three dimensions have been used in a number of previous studies about the TH in various nations (see Chap. 5).

[2] A routine with further instructions is available at https://www.leydesdorff.net/software/th4 which generates the synergy values from data which for this purpose have to be organized as comma-separated variables with for each case (that is, firm) a unique identifier, a postal code, a size class, and a NACE code. The results are organized into a file which can be read into programs like SPSS or Excel for further processing.

6.3.1 *The Geographical Distribution of Firms in Italy*

The administrative division of Italy into Northern, Central, and Southern Italy and, alternatively, into twenty regions is visualized in Fig. 6.1 and further specified in

Fig. 6.1 Organization of Italy into Northern, Southern, and Central Italy, and regions; Northern Italy is indicated in dark green, Central Italy is in very light green, and Southern Italy is in light green. *Source* Figure produced by the authors using SPSS v.22

Table 6.1 Regional Division of Italy at the NUTS 1 and NUTS 2 levels

Codes of *ISTAT*	NUTS1	NUTS2	Name of the region	Macro-regions	North–South
	(a)	(b)	(c)	(d)	(e)
1	North-west Italy (ITC)	ITC1	Piemonte	*Northern Italy*	*Northern Italy*
2		ITC2	Valle d'Aosta		
7		ITC3	Liguria		
3		ITC4	Lombardia		
4	North-east Italy (ITH)	ITH1/TH2	Trentino-Alto Adige		
5		ITH3	Veneto		
6		ITH4	Friuli Venezia Giulia		
8		ITH5	Emilia Romagna		
9	Central Italy (ITI)	ITI1	Toscana	*Central Italy*	
10		ITI2	Umbria		*Southern Italy*
11		ITI3	Marche		
12		ITI4	Lazio		
13	Southern Italy (ITF)	ITF1	Abruzzo	*Southern Italy (Mezzogiorno)*	
14		ITF2	Molise		
15		ITF3	Campania		
16		ITF4	Puglia		
17		ITF5	Basilicata		
18		ITF6	Calabria		
19	Insular Italy (ITG)	ITG1	Sicilia		
20		ITG2	Sardegna		

Table 6.1. Among other things, I shall test the three conventional partitions of Italy provided in columns *c*, *d*, and *e* of Table 6.1.

Table 6.2 provides the numbers of firms in the years under study. With the exceptions of Trentino-Alto Adige and Lazio, the numbers of firms have been declining during this past decade. This confirms the impression of stagnation since the crisis of 2007–2009. Italy has only partly recovered from this crisis.

6.3.2 Small, Medium-Sized, and Large Enterprises

In addition to the assignment of geographical addresses and NACE codes, firms can be scaled in terms of the number of their employees. SMEs, for example, are commonly defined in terms of this proxy. Financial turn-over is also available in the

Table 6.2 *N* of firms in 20 Italian regions

Region	2008	2011	2015	% change 2008–2015
Piemonte	344,334	339,261	323,184	−6.1
Valle d'Aosta	11,959	11,933	11,257	−5.9
Lombardia	822,579	818,998	805,755	−2.0
Trentino-Alto Adige	83,121	83,656	84,398	1.5
Veneto	406,800	402,976	391,474	−3.8
Friuli-Venezia Giulia	88,683	86,797	82,720	−6.7
Liguria	132,288	129,708	122,874	−7.1
Emilia-Romagna	389,123	370,778	366,475	−5.8
Toscana	338,943	332,563	320,167	−5.5
Umbria	70,892	69,411	66,455	−6.3
Marche	133,261	131,567	126,213	−5.3
Lazio	423,059	428,715	426,322	0.8
Abruzzo	100,120	101,115	97,184	−2.9
Molise	21,705	21,445	20,631	−4.9
Campania	351,688	340,601	336,819	−4.2
Apulia	254,431	254,277	249,196	−2.1
Basilicata	36,169	35,234	34,586	−4.4
Calabria	114,858	110,391	105,878	−7.8
Sicily	278,451	273,155	264,480	−5.0
Sardegna	111,558	108,356	102,017	−8.6
Sum	4,514,022	4,450,937	4,338,085	−3.9

data as an alternative indicator of economic structure. However, we chose to use the number of employees since one can expect this number to exhibit less volatility than turn-over, which may vary with stock value and economic conjecture more readily than numbers of employees. However, the numbers of employees are sensitive to other activities, such as outsourcing.

The definitions of small and medium-sized businesses, large enterprises, etc., vary among world regions. Most classifications use six or so categories for summary statistics. I use the nine classes provided in Table 6.3 because this finer-grained scheme produces richer results (Blau & Schoenherr, 1971; Pugh, Hickson, & Hinings, 1969a, b; Rocha, 1999).

6.3.3 The Technological Dimension (NACE Codes)

The third dimension of the data to be used is the attribution of NACE codes. The classification of firms in terms of the *Nomenclature générale des Activités*

Table 6.3 Classification of firms (2015) in terms of the number of employees. *Source* Statistics Italy

CLASS	Number of employees	Frequency	Percent	Valid percent	Cumulative percent
1	0–1	3,473,928	80.1	80.1	80.1
2	2–4	493,365	11.4	11.4	91.5
3	5–9	201,497	4.6	4.6	96.1
4	10–19	99,554	2.3	2.3	98.4
5	20–49	45,476	1.0	1.0	99.4
6	50–99	13,275	0.3	0.3	99.7
7	100–199	6223	0.1	0.1	99.9
8	200–499	3225	0.1	0.1	100.0
9	500 or more	1542	0.0	0.0	100.0
		4,338,085	100.0	100.0	

Note that micro-enterprises (with fewer than five employees) constitute 91.5% of the firms under study

économiques dans les Communautés Européennes (NACE, Rev. 2) is used for indicating the technological dimension.[3] The NACE code can be translated into the International Standard Industrial Classification (ISIC) that is used in the USA (e.g., Leydesdorff, Wagner, Porto-Gomez, Comins, & Phillips, 2019). The disaggregation in terms of medium- and high-tech manufacturing, and knowledge-intensive services, is provided in Table 6.4.[4]

We will additionally analyze the subsets of high- and medium-tech companies, and (high-tech) knowledge-intensive services, because one can expect very different dynamics for these sectors in contributing to synergy in the knowledge base of regions.

6.4 Results

6.4.1 Regions

Figure 6.2 provides a visualization of the percentage contribution of the twenty regions to the national synergy of Italy in 2015. The visualizations for 2008 and 2011 are not essentially different.[5]

[3]Firms are classified in the ASIA database using ATECO 2007 codes, the Italian version of NACE Rev. 2.

[4]A complete index of NACE codes can be found, for example, at https://www.cso.ie/px/u/NACECoder/Index.asp.

[5]The rank-order correlations among the regions in these three years are significantly the same (Spearman's $\rho > .99$; $p < 0.001$).

Table 6.4 NACE classifications (Rev. 2) of high- and medium-tech manufacturing, and knowledge-intensive services. Sources: Eurostat/OECD (2011); cf. Laafia (2002, p. 7) and Leydesdorff et al. (2006, p. 186)

High-tech Manufacturing 21 Manufacture of basic pharmaceutical products and pharmaceutical preparations 26 Manufacture of computer, electronic and optical products 30.3 Manufacture of air and spacecraft and related machinery ***Medium–high-tech Manufacturing*** 20 Manufacture of chemicals and chemical products 25.4 Manufacture of weapons and ammunition 27 Manufacture of electrical equipment 28 Manufacture of machinery and equipment n.e.c 29 Manufacture of motor vehicles, trailers and semi-trailers, 30 Manufacture of other transport equipment • Excluding 30.1 Building of ships and boats, and • Excluding 30.3 Manufacture of air and spacecraft and related machinery 32.5 Manufacture of medical and dental instruments and supplies	***Medium–high-tech Manufacturing*** 50 Water transport 51 Air transport 58 Publishing activities 59 Motion picture, video and television programme production, sound recording and music publishing activities 60 Programming and broadcasting activities 61 Telecommunications 62 Computer programming, consultancy and related activities 63 Information service activities 64–66 Financial and insurance activities 69 Legal and accounting activities 70 Activities of head offices; management consultancy activities 71 Architectural and engineering activities; technical testing and analysis 72 Scientific research and development 73 Advertising and market research 74 Other professional, scientific and technical activities 75 Veterinary activities 78 Employment activities 80 Security and investigation activities 84 Public administration and defence, compulsory social security 85 Education 86 to 88 Human health and social work activities 90 to 93 Arts, entertainment and recreation Of these sectors, 59 to 63, and 72 are considered ***high-tech services***

Figure 6.2 shows that Tuscany belongs to the northern part of Italy as a knowledge-based economy; the distinction of Central Italy including Tuscany is not supported by this data.

Mountainous regions both along the Alps and in the Apennines are weakest in generating synergy. However, one should keep in mind that Italy has a system of excellent highways and trains that cross these regions. Their relative marginality is thus not likely to be due to the mountainous character of these regions, but perhaps more a consequence of their structural positions such as their distance from metropolitan centers, harbors, and airports.

Figure 6.3 shows that triple-helix synergy has increased over time in virtually all regions (but not in Sardegna). The strongest regions became even stronger in terms of their contributions to the national synergy. For example, Lombardia increased its

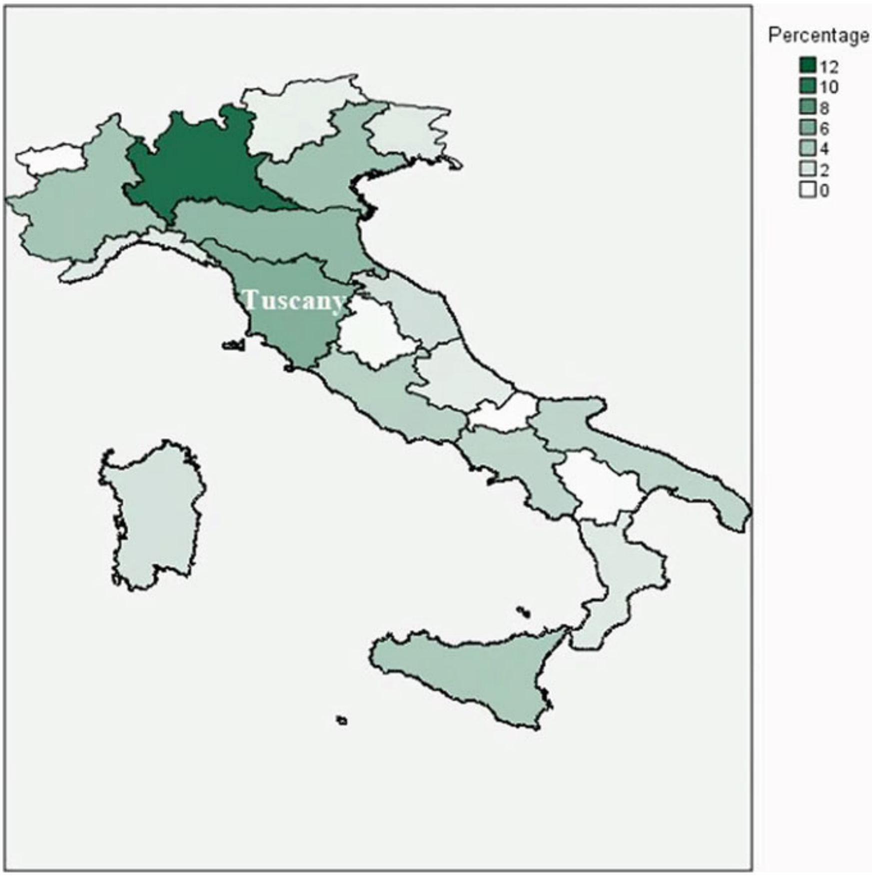

Fig. 6.2 Percentages of contributions of the regions to the national synergy of Italy in 2015

leading contribution to the national synergy by a further 1.8%. The percentage of synergy generated above the regional level—that is, the complement to 100% of the sum of the regional contributions—declined from 48.9% in 2008 to 44.4% in 2015 (–4.5%). This reduction of above-regional synergy contribution over time as a percentage is consistent with the progressive withdrawal of innovation policy-making at the national level, and the growing importance of the regions (Table 6.5).

In summary: regions have become more important, but only 55% of the synergy is realized at the regional level. The other 45% is realized at the above-regional level (such as across the North/South divide or in Italy as a national system).

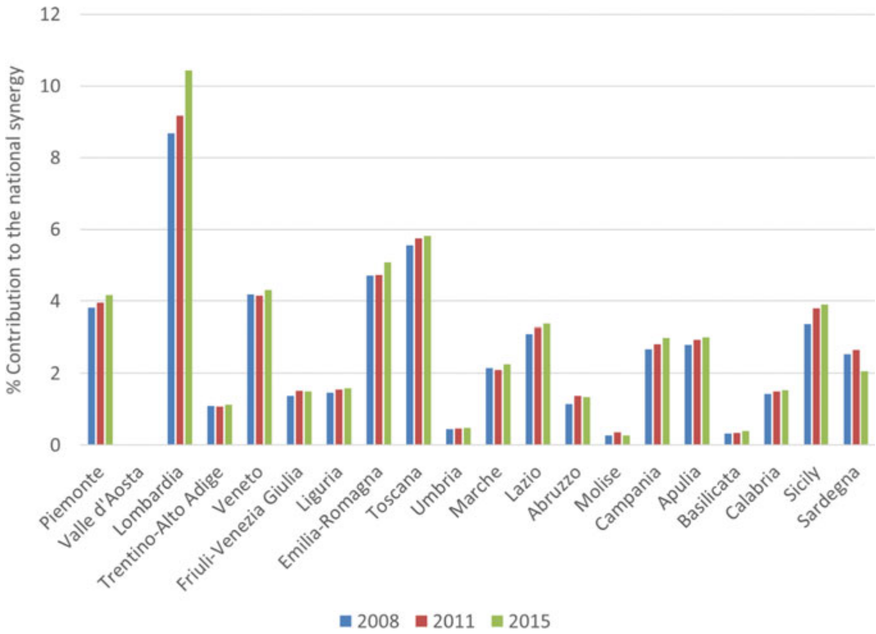

Fig. 6.3 Percentages of contributions of the regions to the national synergy of Italy in 2008, 2011, and 2015

6.4.2 Northern, Central, and Southern Italy

Using the classification of regions into Northern, Southern, and Central Italy as provided in Table 6.1 , Fig. 6.4 shows the above-regional synergy development using three (northern, southern, central) or two (northern and southern) groups of regions, respectively, on the right side, and the values of T_0 on the basis of twenty regions on the left side. As noted, the latter declined from 48.9 in 2008 to 44.4% in 2015.

The above-regional synergy development among the *three* groups of regions (north–south-center) is of the order of 22.5%, but is not increasing consistently as the supplement of the synergy among the twenty regions. Among *two* groups of regions (north–south), however, T_0 was further reduced to 18.2% in 2015.

Both the northern and southern parts are more synergetic when compared with the division into three parts. If Tuscany is analyzed as part of northern Italy, however, the northern part of Italy accounts for 47.0% of the synergy and the southern part for 34.9%; with an additional 18.2% synergy at the national level. Values around 20% for the national surplus synergy were also found for other countries in previous studies. Adding Tuscany, which itself contributes only 5.8% to the synergy at the national level, to the northern part (instead of the central one) increases the contribution of the north by more than 9% (=46.95 − 37.90; in Table 6.6). Thus, an additional synergy is indicated by using this model of Italy.

Table 6.5 Percentages of contributions of the regions to the national synergy of Italy in 2015

Region	2008	2011	2015	% change 2008–2015
Piemonte	3.82	3.95	4.17	9.2
Valle d'Aosta	0.00	0.00	0.00	0.0
Lombardia	8.67	9.18	10.43	20.3
Trentino-Alto Adige	1.09	1.08	1.13	3.6
Veneto	4.19	4.15	4.31	3.0
Friuli-Venezia Giulia	1.37	1.51	1.49	8.4
Liguria	1.47	1.56	1.58	7.5
Emilia-Romagna	4.71	4.73	5.08	7.7
Toscana	5.55	5.75	5.81	4.7
Umbria	0.45	0.46	0.48	6.0
Marche	2.14	2.10	2.26	5.6
Lazio	3.09	3.27	3.38	9.5
Abruzzo	1.15	1.37	1.33	15.5
Molise	0.27	0.35	0.26	−4.6
Campania	2.67	2.82	2.99	12.2
Apulia	2.79	2.94	3.01	8.1
Basilicata	0.32	0.33	0.38	21.4
Calabria	1.43	1.50	1.54	7.5
Sicily	3.36	3.79	3.89	16.0
Sardegna	2.54	2.66	2.07	−18.7
T_0	48.91	46.48 lePara>	44.40	−9.2

Sources Eurostat/OECD (2011); cf. Laafia (2002, p. 7) and Leydesdorff et al. (2006, p. 186)

The conclusion is that considering Italy as twenty regions leaves 45% of the synergy in the Italian innovation system unexplained. This is extremely high when compared with other nations. In the USA, we found that the additional synergy at the national (above-state) level is only 2.8%. This is much less than we found in previous studies of national innovation systems: Norway (11.7%), China (18.0%), the Netherlands (27.1%), Sweden (20.4%), and Russia (37.9%). Italy would score above the Russian Federation when considered in these terms, but for very different reasons (Leydesdorff, Perevodchikov, & Uvarov, 2015). The high surplus in Russia is caused by the centralized nature of this system, while in Italy, the high surplus is unexplained when the wrong data model is used. When Italy is conceptualized as a country with two or three innovation systems, the results accord with those for other EU nations.

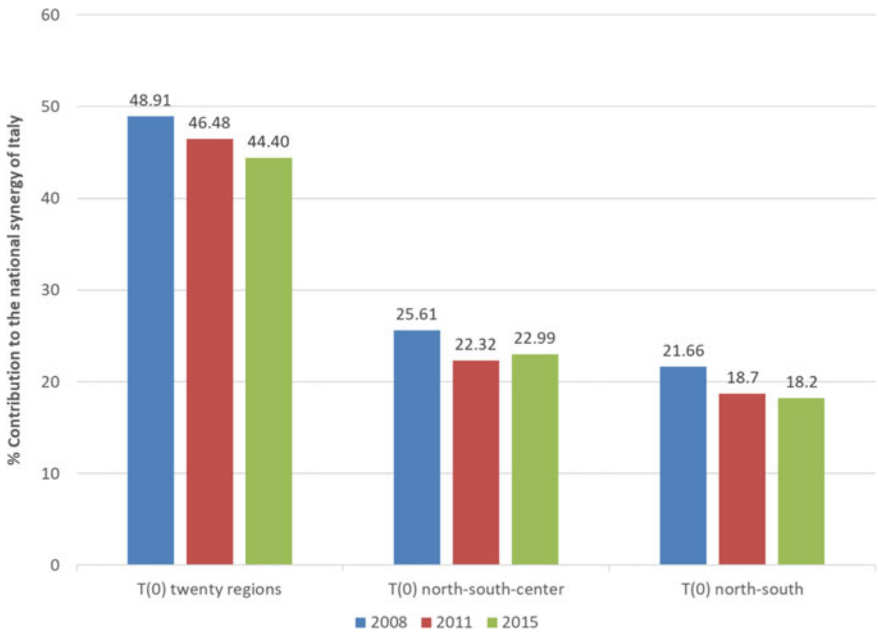

Fig. 6.4 Above-regional synergy for Italy on the basis of 20 NUTS2-regions (left) and three macro-regions (north—south—center)

Table 6.6 Percentage contributions of Northern, Southern, and Central Italy to the national synergy in 2015

	North-central-south	North–south
North	37.90	46.95
Center	17.50	
South	21.62	34.85
Sum	77.02	81.80
T_0	22.98	18.20
	100	100

6.4.3 Sectorial Decomposition

Using the NACE codes (provided in Table 6.4), we can repeat the analysis for subsets of firms which are classified as high- or medium–high-tech, and for knowledge-intensive services. Of the approximately 4.3 million firms, 1,294,874 (29.8%) provide knowledge-intensive services, while only 40,083 (0.9%) are classified as MHTM in 2015. However, the differences between the distribution of the set and the subsets are marginal. Table 6.7 shows the rank-order correlations which are all above 0.95 ($p < 0.001$). In other words: both medium-high-tech and knowledge-intensive services are distributed proportionally over the country in terms of numbers of firms. Table 6.8 provides a summary of the results, including the values for these subsets as

Table 6.7 Rank-order correlations between the samples of firms classified as high- and medium–high-tech manufacturing (MHTM) and knowledge-intensive services (KIS) over the twenty regions of Italy

		Full set	MHTM
MHTM	Correlation Coefficient	0.955**	
	Sig. (2-tailed)	0.000	
	N	20	
KIS	Correlation Coefficient	0.982**	0.950**
	Sig. (2-tailed)	0.000	0.000
	N	20	20

** Spearman's rho; correlation is significant at the 0.01 level (2-tailed)

Table 6.8 Summary table of percentages of contributions to the synergy in the Italian innovation system (2015)

Region	2015	north_south_center	north_south	MHTM	KIS
Piemonte	4.17	37.90	46.95	**7.14**	3.58
Valle d'Aosta	0.00			0.00	0.00
Lombardia	10.43			11.68	**9.19**
Trentino-Alto Adige	1.13			0.94	0.80
Veneto	4.31			**7.66**	3.54
Friuli-Venezia Giulia	1.49			2.72	1.38
Liguria	1.58			1.93	1.59
Emilia-Romagna	5.08			**7.40**	5.20
Toscana	5.81	17.50		**8.15**	4.81
Umbria	0.48		34.85	0.67	0.50
Marche	2.26			4.06	2.12
Lazio	3.38			3.07	**2.07**
Abruzzo	1.33	21.62		2.32	1.30
Molise	0.26			0.30	0.21
Campania	2.99			3.70	2.45
Apulia	3.01			3.76	2.36
Basilicata	0.38			0.70	0.42
Calabria	1.54			1.96	1.47
Sicily	3.89			4.44	4.09
Sardegna	2.07			1.34	1.85
Sum	55.60	77.01	81.80	73.94	48.93
T_0	44.40	22.99	18.20	26.06	51.07

percentages of synergy in the two right-most columns.

In Table 6.8, values with outliers for MHTM and/or KIS are boldfaced in the right-most columns: when we focus on MHTM, Piemonte, Veneto, Emilia-Romagna, and Toscana provide contributions to the synergy more than two percent higher than without this focus. Lombardia, Marche, and Friuli-Venezia Giulia follow with more than one percent higher values.

Unlike manufacturing, services can be offered nation-wide or even beyond the nation, and thus tend to uncouple from a specific location, leading to a negative effect on the local synergy. In Italy, this is the case mainly for services in Lombardia and Lazio, since these two regions contain the two metropoles of Milano and Rome with airports, etc. Toscana (Florence) and Veneto (Venice) follow with smaller effects.

In Southern Italy, there are no effects from either MHTM or KIS. A negative effect of MHTM is indicated for Lazio, probably meaning that some manufacturing may have administrative offices located in Rome without contributing to the knowledge-based synergy in this region (Lazio). Sardegna also has a negative effect when focusing on MHTM because the medium- and high-tech sectors are marginal in this local economy.

6.5 Conclusions and Discussion

In analogy to "national innovation systems" (Freeman, 1987; Lundvall, 1988, 1992; Nelson, 1993), many studies have argued for studying "regional innovation systems" such as Wales or Catalonia (Braczyk, Cooke, & Heidenreich, 1998; Cooke, 1998, 2002). However, innovation systems are not bound by administrative and political borders. In my opinion, one should not make the choice between studying regions or nations on a priori grounds and across the board. The function of regions in an otherwise relatively homogeneous country (e.g., Denmark) is different from that in a country with a federal structure, such as Belgium.

From this perspective, Italy is an interesting case because there is a traditional divide between the North and the South, but there are also common denominators such as a single language (with small exceptions), and national institutions such as a network of state universities, a national research council (CNR) with a similar structure in all regions, and a national government without a federal structure. During the last two decades, the regions have become more important because of the devolution policies of the central government and the emphasis on regions in EU policies.

One would expect the coherence of an innovation system to be a mixture of both national and regional aspects. The research question then becomes: how much innovation-systemness is generated at the various levels? Is this innovation-systemness distributed across regions or specialized in specific regions? The synergy measure enables us to address these questions empirically and in considerable detail.

In summary, Italy as a nation is integrated, albeit not at the level of the twenty regions. Eight regions in Northern Italy (including Tuscany) are well developed as innovation systems. These eight regions contribute 34.0% to the national synergy.

However, as a separate subsystem Northern Italy contributes 47.0% of the synergy (Table 6.6). This is 13% more than the sum of the individual regions. The regions on the Northern borders with different cultural orientations (Alto Adige and Valle d'Aosta) contribute marginally to the synergy in the Northern-Italian system.

If we apply the same reasoning to Southern Italy (the Italian *Mezzogiorno*), twelve regions contribute 21.6% to the national synergy. Considered as a subsystem (Table 6), the South contributes 34.9%; that is, another 13.3% more synergy. On top of these two sub-systems, Italy as a nation contributes 18.2% to the national synergy. This can be interpreted as a synergy generated as a result of interactions among sub-systems. Most synergy is found by considering Italy in terms of a northern and southern part, with Tuscany as part of Northern Italy.

As one would expect, synergy is enhanced by focusing on high- and medium-tech manufacturing. Rome and Milano function as metropolitan centers of innovation systems, followed by Florence and the region of Venice (including the harbour). Unlike Spain, where Barcelona and Madrid function as metropolitan innovation systems without much further integration into the remainder of the country (Leydesdorff & Porto-Gómez, 2018), the Italian system is nationally integrated in terms of MHTM and KIS.

6.6 Policy Implications

Innovation policies focusing on the regional level in Italy may miss important opportunities in inter-regional interactions. In other words, the coordination of innovation policies among regions, particularly within each of the two major innovation (sub)systems of Northern and Southern Italy, could be considered as potentially more effective. More generally, our results provide support for the argument that administrative borders which originated for historical and administrative reasons should be examined critically in terms of their functionality for innovation, particularly in a knowledge-based economy that is far more networked than a political economy.

The knowledge dynamics added to the economic and political dynamics generates a complex system with a volatile dynamics that *tends to self-organize its boundaries* (Bathelt, 2003). A complex system is resilient and thus adapts to signals that do not accord with its internal dynamics. A political administration that is not reflexively aware of and informed about how the relevant innovation systems are shaped may lack the flexibility required to steer these systems and feel in the longer term constrained by the unintended consequences of its own actions (Ashby, 1958; Luhmann, 1997).

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Chapter 7
The Measurement of Synergy

When policy-makers call for "interdisciplinarity," they often mean "synergy." Problem-solving requires crossing boundaries, such as those between disciplines. However, synergy can also be generated in inter-sectorial or geographical collaborations. Synergy is indicated when the whole offers more possibilities than the sum of its parts; "interdisciplinarity" can be an instrument for creating "synergy." Synergy can be measured as an increase of redundancy; that is, the number of options which are available, but not-yet used. Instead of asking for the synergy among pre-defined categories, such as regions, sectors, size-classes, or nations, etc., I propose to let the most synergetic combinations among (potentially heterogenous) variables emerge from the data matrix. A synergy map can be drawn showing (cluster of) available but not-yet-realized options. A computer routine is made available at https://www.leydesdorff.net/software/synergy.triads which compares all possible triads in a data matrix in terms of their contributions to the synergy in a configuration.

In this chapter, I generalize the Triple-Helix indicator for measuring synergy in interactions among three or more helices to an indicator for any data set (e.g., an Excel sheet). As noted, a routine is made available for automating the analysis. I first discuss a toy model that one can follow using pen and paper and then upscale to empirical cases.

In the TH model, synergy is assumed to be generated in interactions among the three TH partners—universities, industries, and governments. Carayannis and Campbell (2009 and 2010), however, proposed to extend the analysis to four and five helices. However, the helices remained defined *ex ante*. In this chapter, I turn the question around and ask for the measurement of synergy among any three variables in a data set. The variables can be permutated so that one can compare among all possible triads. Which combinations of variables (nodes) and relations (links) are most synergetic? Are triplets that generate redundancy sparse and isolated? Or are they connected to a large component?

This chapter is partly based on: Leydesdorff, L., & Ivanova, I. A. The Measurement of "Interdisciplinarity" and "Synergy" in Scientific and Extra-Scientific Collaborations. Journal of the Association for Information Science & Technology (2020, Early view); https://doi.org/10.1002/asi.24416.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_7

"Synergy" is an objective different from "interdisciplinarity." The third mission of the university does not necessarily challenge the internal—disciplinary or interdisciplinary—organization of research. In my opinion, the crucial question is whether and how social and scientific relevance can be synergetic so that surplus value for the various stakeholders can be generated (Bunders & Leydesdorff, 1987).

7.1 "Synergy"

The term *synergy* originates from the word $\sigma\upsilon\nu\varepsilon\rho\gamma\acute{\iota}\alpha$ in classical Greek which means "working together." By working together, a whole can be created that is greater than the sum of its parts. In science, for example, synergy may mean that new options have become available because of collaborations across disciplinary, sectorial, or geographic boundaries.

Newly emerging options are vital to innovative systems, more than past performance. A system may run out of steam and be deadlocked if new options are not sufficiently generated. A larger number of *options* adds to the maximum capacity of a system. Unlike biological systems, this maximum capacity of a cultural system—the $H_{\max}$ in information theory—is not a given, but a construct that can further be informed and thus enlarged (see Fig. 4.2). For example, new means of transport can be invented. This adds capacity to (in this case) the transportation system.

The generation of redundancy is based on interactions among selection environments. Whereas interactions among variations generate uncertainty, selections can be expected to reduce uncertainty. The same information can be selected differently by various stakeholders using different criteria. The appreciations from different perspectives ("the meanings of the information") can be shared and thus generate redundancy. Thus, the same or overlapping informations can be involved more than once. Whereas information can be communicated in relations (and measured using Shannon's formulas), meanings are provided and can be shared from different perspectives with reference to horizons of meaning. Sharing can generate an "overlay" among perspectives with a dynamic of redundancy different from that of information processing (Etzkowitz & Leydesdorff, 2000).

For example, when a child asks permission from one of its parents, the other parent is latently present in the response albeit with a potentially different interpretation of the uncertainty in the configuration. Uncertainty can be reduced or increased when a third perspective operates in the background, like in this case of the relation between the parents (Abramson, 1963, pp. 130f.). In a triad, the correlation between each two variables can spuriously be co-determined by a third with a plus or a minus sign.

As discussed in Chapter Five, triads are the building blocks of systems (Bianconi et al., 2014; cf. Krackhart, 1999). All higher-order configurations in networks can be decomposed into triads (Freeman, 1996). The values for uncertainty and redundancy in triads can be aggregated and disaggregated since the Shannon-formulas are based on sigma's (Leydesdorff & Strand, 2013, p. 1895, n. 5). I exploit these possibilities for the development of the indicator of synergy here below.

Table 7.1 Four column vectors and their margin totals in a toy model

v1	v2	v3	v4	Sum
0	0	3	0	3
0	6	0	4	10
9	0	0	3	12
4	4	0	5	13
0	3	4	0	7
13	13	7	12	45

The number of possible triads among n sets or variables is $n * (n - 1) * (n - 2)/(2 * 3)$. This number grows rapidly with an increasing number of n. For $n = 10$, for example, this number of triads is $(10 * 9 * 8)/6) = 120$. (The denominator [2 * 3] corrects for double counting.) Each *node* can partake in $n - 1$ links of which some are parts of triads which generate redundancy and others are not.

Triads contain three nodes and three edges: both links and nodes can be part of more than a single triad.[1] In each of these triads, the nodes and links partake in both the redundancy and uncertainty generated in a triad. How much redundancy is generated at the level of nodes, links, and triads? Let me specify this step-by-step using a toy model; thereafter, I shall upscale to empirical examples.

7.2 A Toy Model

In the "toy" model in Table 7.1, for example, four variables are attributed to five cases like column vectors of a matrix.

One can compute the joint entropy (H_{12}) and mutual information or transmission between the horizontal and vertical dimensions of this matrix (T_{12}) by following the steps explicated in Table 7.2.

Column e in Table 7.2 contains the margin totals of the five rows of the data matrix (columns a to d). Using the grand total of the matrix ($N = 45$) as denominator, relative frequencies are provided in columns f to i. In column k to n, the values in this two-dimensional probability distribution (p_{ij}) are transformed into the contributions to the Shannon-type information (by using $H_{ij} = -\Sigma\, p_{ij} * \log_2 p_{ij}$) in bits. It follows from the summation of the cell values that $H_{ij} = 3.23$ bits (at the bottom of column o). This is the two-dimensional information content of this matrix.

[1] For example, if the number of nodes $n = 4$, each of the four nodes can participate in $n - 1 = 3$ direct relations [e.g., in the case of node 1 (n1): (1) n1 – n2; (2) n1 – n3; (3) n1 – n4]. The number of unique relations possible in this network is 4 * 3 / 2 = 6, namely: (1) n1 – n2; (2) n1 – n3; (3) n1 – n4; (4) n2 – n3; (5) n2 – n4; (6) n3 – n4. The number of possible triads in this case is (4 * 3 * 2)/(3 * 2) = 4; in this case: (i) n1 – n2 – n3; (ii) n1 – n2 – n4; (iii) n1 – n3 – n 4; and (iv) n2 – n3 – n4.

Table 7.2 Computation of the one- and two-dimensional information in the toy model

Toy model					Probabilities; relative frequencies (n/N)					Two-dimensional $H(12)$ in bits = $-\Sigma\, p_{ij} \log_2(p_{ij})$				
$v1$	$v2$	$v3$	$v4$		$p1$	$p2$	$p3$	$p4$		$i1$	$i2$	$i3$	$i4$	
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*
0	0	3	0	3	0.00	0.00	0.07	0.00	0.07	0.00	0.00	0.26	0.00	0.26
0	6	0	4	10	0.00	0.13	0.00	0.09	0.22	0.00	0.39	0.00	0.31	0.70
9	0	0	3	12	0.20	0.00	0.00	0.07	0.27	0.46	0.00	0.00	0.26	0.72
4	4	0	5	13	0.09	0.09	0.00	0.11	0.29	0.31	0.31	0.00	0.35	0.97
0	3	4	0	7	0.00	0.07	0.09	0.00	0.16	0.00	0.26	0.31	0.00	0.57
13	13	7	12	45	0.29	0.29	0.16	0.27	1.00	0.77	0.96	0.57	0.92	3.23

The margin totals in the vertical and horizontal direction provide us with the one-dimensional probabilities: the information values in column *e* add up to $H_1 = 2.19$ bits. Analogously on the basis of the values in the bottom row of columns *a* to *d*, $H_2 = 1.96$ bits. Using Eq. 4.5 (above):

$$T_{12} = H_1 + H_2 - H_{12} = 2.19 + 1.96 - 3.23 = 0.92\text{bits} \tag{7.1}$$

A matrix contains by definition a two-dimensional distribution $\left(\sum_{ij} p_{ij} = 1\right)$; mutual information in two dimensions is necessarily positive (Theil, 1972). For the representation of a three-dimensional distribution, however, one would need three independent dimensions.

7.3 Vector Coordinates

One can also consider the values in each three columns as vector representations in the *x, y,* and *z* dimensions of a three-dimensional array [*x, y, z*]. The four vectors in Table 7.1 contain four such triplets: {$v1$,$v2$,$v3$}, {$v1$, $v2$,$v4$}, {$v1$,$v3$,$v4$}, {$v2$,$v3$,$v4$}. One can compute for each triplet a three-dimensional H_{123}, the three bidimensional information contents H_{12}, H_{13}, H_{23}, and three one-dimensional information contents H_1, H_3, H_3. I elaborated the computation in the case of the first triplet {$v1$,$v2$,$v3$} in Table 7.3.

Using the bottom line of Table 7.3 and Eq. 4.8, it follows that

$$\begin{aligned} T_{123} &= [H_1 + H_2 + H_3] - [H_{12} + H_{13} + H_{23}] + H_{123} \\ &= (0.89 + 1.53 + 0.99) - (2.21 + 1.86 + 2.27) + 2.69 \\ &= 3.40 - 6.34 + 2.69 = -0.24 \text{ bits} \end{aligned} \tag{7.2}$$

Table 7.3 Exemplary elaboration of the computation of redundancy in the first triplet $\{v1, v2, v3\}$

The first triplet {v1, v2, v3}

v1	*v2*	*v3*	*Sum*
0	0	3	3
0	6	0	6
9	0	0	9
4	4	0	8
0	3	4	7
13	13	7	33

Probabilites	One dimension			Two dimensions						Three dimensions		
	p1	*p2*	*p3*	*p12*		*p13*		*p23*		*p123*		
	0.00	0.00	0.43	0.00	0.00	0.00	0.15	0.00	0.15	0.00	0.00	0.09
	0.00	0.46	0.00	0.00	0.23	0.00	0.00	0.30	0.00	0.00	0.18	0.00
	0.69	0.00	0.00	0.35	0.00	0.45	0.00	0.00	0.00	0.27	0.00	0.00
	0.31	0.31	0.00	0.15	0.15	0.20	0.00	0.20	0.00	0.12	0.12	0.00
	0.00	0.23	0.57	0.00	0.12	0.00	0.20	0.15	0.20	0.00	0.09	0.12
Sum:	1.00	1.00	1.00	0.50	0.50	0.65	0.35	0.65	0.35	0.39	0.39	0.21

Information in bits	H1	H2	H3	H12		H13		H23		H123		
	0.00	0.00	0.52	0.00	0.00	0.00	0.41	0.00	0.41	0.00	0.00	0.31
	0.00	0.51	0.00	0.00	0.49	0.00	0.00	0.52	0.00	0.00	0.45	0.00
	0.37	0.00	0.00	0.53	0.00	0.52	0.00	0.00	0.00	0.51	0.00	0.00
	0.52	0.52	0.00	0.42	0.42	0.46	0.00	0.46	0.00	0.37	0.37	0.00
	0.00	0.49	0.46	0.00	0.36	0.00	0.46	0.41	0.46	0.00	0.31	0.37
Sum:	0.89	1.53	0.99		2.21		1.86		2.27			2.69

Analogously, the other three possible triplets provide: T_{124} = –0.08; T_{134} = –0.23, and T_{234} = –0.08 bits. The values for the four triplets can be aggregated for the set (because of the sigma's in the Shannon formulas). The sum of the redundancies in the relevant triads can be attributed as a synergy value to the nodes and links participating in the respective triads (Leydesdorff & Strand, 2013, p. 1895, n. 5). As noted, the routine (available at https://www.leydesdorff.net/software/synergy.triads) permutes all column vectors of a data matrix so that all possible combinations of variables are evaluated in terms of their contributions to the synergy.

For example, $v2$ participates in the triads $\{v1, v2, v3\}$, $\{v1, v2, v4\}$, and $\{v2, v3, v4\}$, but not in $\{v1, v3, v4\}$. Among the triads in which a vector participates some will generate information ($T_{123} > 0$) and others redundancy ($T_{123} < 0$). One can define the synergy value of $v2$ in this matrix as the sum of the negative values of the triplets in which $v2$ participates. For $v2$, this is [–0.24 – 0.08 – 0.08] = –0.40 bit of information.

Both $v1$ and $v2$ participate in the triads $\{v1, v2, v3\}$ and $\{v1, v2, v4\}$ which generate –0.24 and –0.08 bits of redundancy, respectively. The link between $v1$ and $v2$ can analogously be attributed with this redundancy shared between $v1$ and $v2$. This is – 0.24 for $\{v1, v2, v3\}$ plus – 0.08 for $\{v1, v2, v4\}$, and thus –0.32 bits. One can visualize the resulting retentions of synergy in this toy network as in Fig. 7.1. It happens that all links and nodes participate in the generation of redundancy in this specific "toy" model.

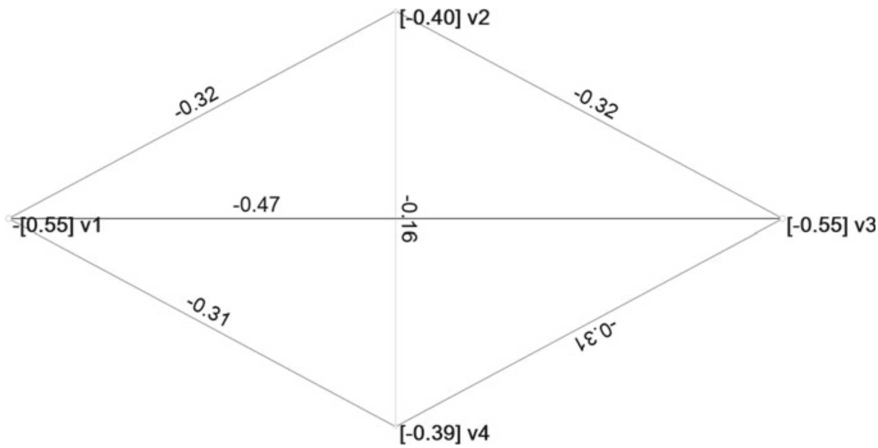

Fig. 7.1 Synergy retention network of the toy model (in bits of information)

7.4 Empirical Applications

7.4.1 Synergy in International Co-Authorship Relations

In addition to interactions among the disciplines, synergy can also be generated in extra-scientific contexts, such as university-industry relations or in geographical co-locations. Using data collected from the Web-of-Science on 28 June 2020 (Leydesdorff et al., 2013),[2] Table 7.4 shows the numbers of internationally co-authored papers among six western-Mediterranean countries in 2009: France, Italy, Spain, Morocco, Tunisia, and Algeria.

Figure 7.2a shows the affiliations network of internationally co-authored papers among these six nations. France has relations with Italy and Spain (within the EU),

Table 7.4 International co-authorship relations among six western-Mediterranean countries in 2009

	France	Italy	Spain	Morocco	Algeria	Tunisia
France	0	3970	3065	383	681	765
Italy	3970	0	2834	68	35	85
Spain	3065	2834	0	118	45	70
Morocco	383	68	118	0	33	53
Algeria	681	35	45	33	0	29
Tunisia	765	85	70	53	29	0

[2] I repeated the data analysis on June 26, 2008.

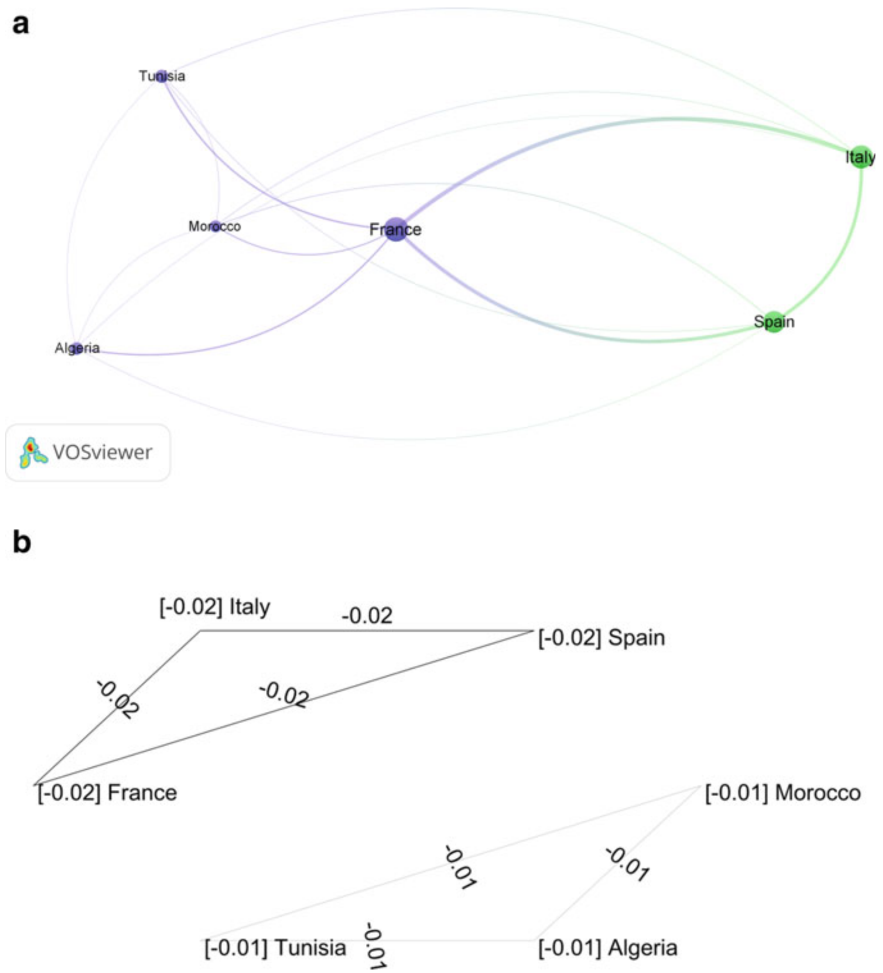

Fig. 7.2 **a** Affiliations network among six western-Mediterranean countries, **b** synergy network among six western-Mediterranean countries

but one can expect co-authorship relations with scholars in the former colonies of France in northern Africa. Scholars in these countries are often francophone.

Figure 7.2b shows the synergy network among these six nations: the three European nations generate synergy from their collaborations as do the three northern-African nations among them. However, the values for the European countries are twice those for the African ones. However, there is no synergy indicated between France and the northern-African countries in 2009, although there was synergy in previous years. One thus can conclude that scholars in France have more options in relations to EU partners than with the northern-African nations.

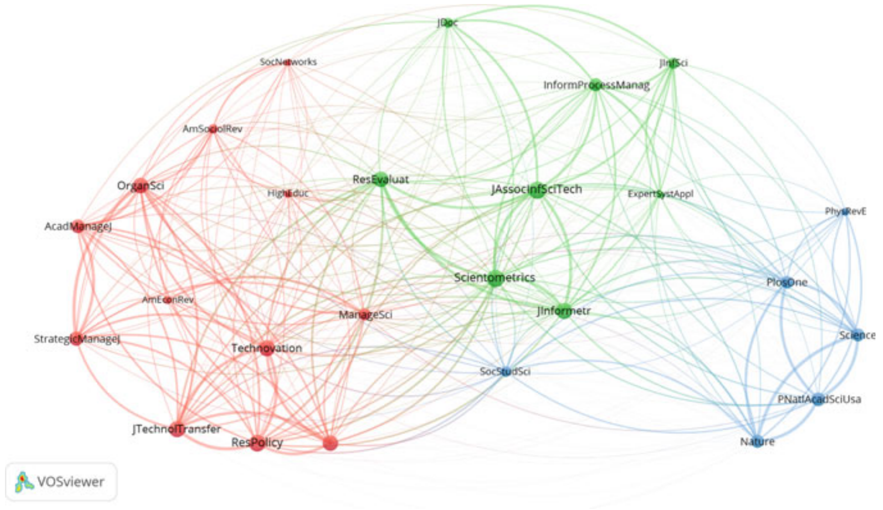

Fig. 7.3 Map based on cosine-normalized citing patterns among 26 journals cited in *Scientometrics* during 2017. Clustering based on the Louvain algorithm (Blondel et al., 2008); VOSviewer was used for the layout and visualization

7.4.2 *Synergy in Aggregated Citation Relations Among Journals*

As a second example, I use the aggregated journal-journal citation matrix of 26 journals cited in reference lists of publications in *Scientometrics* during 2017 more than a threshold value of 43 times.[3] I chose this example because the disciplinary and interdisciplinary classification of journals is often intuitive.

Figure 7.3 provides a map of this network of journal-journal relations on the basis of the cosine-normalized ("citing") vectors in the citation matrix. The structure induced by Blondel et al.'s (2008) algorithm for decomposition shows three groups of journals: information-science journals in the direct environment of *Scientometrics*, multidisciplinary ones (e.g., *PNAS, PLOS One*, and *Nature*) on the right side, and policy and management journals on the left side of the map (e.g., *Research Policy* and *Technovation*).

For $n = 26$ (as in this case), the number of possible triads among the vectors is (26 * 25 * 24)/(2 * 3) = 2,600. Of these triads, 38 (1.4%) contribute to the redundancy. Consequently, the vast majority of triplets (98.6%) does not generate redundancy. However, 18 of the 26 (69.2%) journals participate in triplets which generate redundancy.

[3]This threshold is based on using 1% of the total number of references summed over the papers in this journal (6464) after subtraction of the 2161 within-journal self-citations; one percent of (6464 – 2161 =) 4303 references. One-percent of this is 43, the threshold value in this study.

Table 7.5 Rank-ordering of synergy contributions of 26 journals and journal-journal relations

Journal (Nodes)	Synergy in bits	Journal-journal relation (Links)		Synergy in bits
Am Econ Rev	-4.27	*Expert Syst Appl*	*Am Econ Rev*	-3.08
Expert Syst Appl	-3.08	*Manage Sci*	*Am Econ Rev*	-0.79
Manage Sci	-0.79	*Strategic Manage J*	*Am Econ Rev*	-0.75
Strategic Manage J	-0.75	*Acad Manage J*	*Am Econ Rev*	-0.65
Acad Manage J	-0.65	*Science*	*Am Econ Rev*	-0.56
Science	-0.56	*Soc Networks*	*Am Econ Rev*	-0.50
Soc Networks	-0.50	*Nature*	*Am Econ Rev*	-0.48
Nature	-0.48	*Expert Syst Appl*	*Strategic Manage J*	-0.33
Technol Forecast Soc	-0.32	*Technol Forecast Soc*	*Am Econ Rev*	-0.32
Phys Rev E	-0.26	*Expert Syst Appl*	*Science*	-0.31
Res Policy	-0.23	*Nature*	*Expert Syst Appl*	-0.29
P Natl Acad Sci USA	-0.22	*Manage Sci*	*Expert Syst Appl*	-0.28
Scientometrics	-0.22	*Expert Syst Appl*	*Acad Manage J*	-0.28
Plos One	-0.21	*Phys Rev E*	*Am Econ Rev*	-0.26
Organ Sci	-0.15	*Expert Syst Appl*	*Technol Forecast Soc*	-0.25
High Educ	-0.08	*Expert Syst Appl*	*Phys Rev E*	-0.25
J Technol Transfer	-0.03	*Res Policy*	*Am Econ Rev*	-0.23
Am Sociol Rev	0.00	*P Natl Acad Sci USA*	*Expert Syst Appl*	-0.22
J Inf Sci	0.00	*P Natl Acad Sci USA*	*Am Econ Rev*	-0.22
Inform Process Manag	0.00	*Scientometrics*	*Am Econ Rev*	-0.22
Technovation	0.00	*Scientometrics*	*Expert Syst Appl*	-0.22
J Informetr	0.00	*Expert Syst Appl*	*Plos One*	-0.21
J Assoc Inf Sci Tech	0.00	*Plos One*	*Am Econ Rev*	-0.21
Soc Stud Sci	0.00	*Expert Syst Appl*	*Res Policy*	-0.19
J Doc	0.00	*Organ Sci*	*Am Econ Rev*	-0.15
Res Evaluat	0.00	*Expert Syst Appl*	*Soc Networks*	-0.13
		… (55 – 25 =) 30 other link		…

Furthermore, each *link* can be part of $n * (n - 1)/2$ triads. For $n = 26$, this amounts to 325 possible values; 55 of them (16.9%) have a negative value. In Table 7.5 the links are listed in terms of most synergy. Combining the redundancy values for nodes and links, one can generate a network; VOSviewer was used to visualize this network in Fig. 7.3.[4] Table 7.5 lists the 26 journals in terms of synergy values in the left-most column, and in terms of decreasing redundancy in links between these journals in the next two columns.

Science ranks on the synergy indicator on the 6th position, and *Nature* follows on the 8th rank. However, large journals with a pronouncedly disciplinary identity such as the *Am Econ Rev* and a number of journals in the management sciences generate more synergy than *Science* and *Nature.* Among the library and information-science journals, the journal *Scientometrics* scores highest on synergy (with rank number 13 and −0.22 bits of redundancy). However, the journal *Social Networks* occupies the

[4]The noted computer routine provides among other things the files "minus.net" and "minus.vec" in the Pajek format so that one can proceed to the visualization and further analysis of the synergy network.

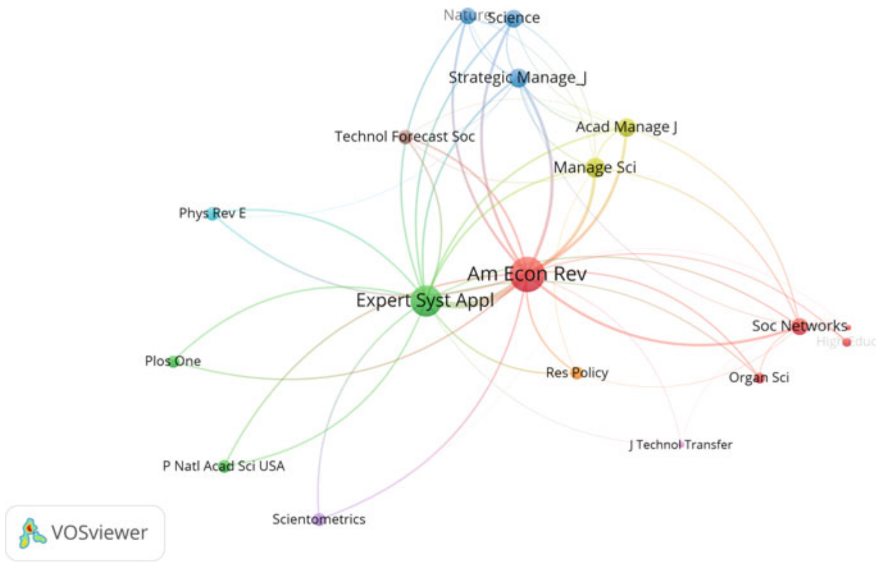

Fig. 7.4 Synergy network among the citing patterns of 26 journals in the citation environment of *Scientometrics* in 2017

7th position on the ranking of synergy values with −0.50 bits of redundancy. This is more than twice as high as the value of −0.22 for *Scientometrics*.

The synergy map in Fig. 7.4 is very different from the affiliations map in Fig. 7.3. The interpretation of this figure raises all kinds of questions. For example, *Scientometrics* is not central to its synergy map. However, one should keep in mind that this is a single case; the purpose of this exercise was a proof of concept. More cases and further refinement of parameter choices are needed before one can draw empirical conclusions; for example, about the significance of differences. Note that the synergy indicator allows to combine, for example, authorship and disciplinary-specific variables (e.g., title-words). The indicator can be used for the evaluation of any set of three or more variables, including disciplinary affiliations, geographical address, or demographic characteristics.

7.5 Discussion and Concluding Remarks

Unlike most performance indicators, the synergy indictor was not generated in a research evaluation practice, but is theory-based (McGill, 1954; Ulanowicz, 1997; Yeung, 2008; cf. Krippendorff, 2009a and b). Bridging the gap from theory to practice will require more empirical work and examples. For example, in a next project, it may be interesting to study synergy in translation research because the generation of synergy is a stated objective of this research program. In translation research, the objective is to accelerate the application of new knowledge from basic (e.g., molecular) biology in the clinic ("from bench to bed") or vice versa to articulate demand at the bedside in terms which can be made relevant for research agendas in pre-clinical specialisms.

In my opinion, "synergy" is more important for the evaluation of the social functions of science than performance indicators which usually are intended to serve the management of research. However, university-industry relations can be conceptualized as non-linear processes of transfer, application, and incubation. The mediation between supply and demand may require managerial or governmental interventions. In university-industry-government ("Triple Helix") relations, feedbacks can be more important than linear transfer.

Wu et al. (2019) developed an indicator of disruptiveness using the differences between citing and cited patterns over generations of papers as an indicator of change. The comparison of disruptiveness with synergy can be a subject for further research. Using Medical Subject Headings (MeSH) of MEDLINE/PubMed, Petersen et al. (2016) showed a relation between synergy-development and innovativeness during technology-specific periods of time.

In sum: by appreciating redundancies, one shifts the focus from the measurement of past performance to the question of the number of options. The measurement of synergy can also be relevant for the coupling to other areas of policy making (cf. Rotolo et al., 2017). Synergy refers to options which are possible, but not yet fulfilled, whereas most bibliometric indicators hitherto evaluate past performance; that is, options that have already been realized. More generally, the measurement of redundancy may provide methodologies opening a range of future-oriented indicators.

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Part III
The Dynamics of Expectations and Knowledge

Chapter 8
Anticipation and the Dynamics of Expectations

The operationalization of socio-cognitive structures in terms of observables such as texts (e.g., in discourse analysis and scientometrics) or the behavior of agents (e.g., in the sociology of scientific knowledge) may inadvertedly lead to reification. The dynamics of knowledge are not directly observable, but knowledge contents can be reconstructed. The reconstructions have the status of hypotheses; hypotheses can be tested against observations. Whereas agent-based modelling (ABM) focuses on observable behavior, simulations based on algorithms developed in the theory and computation of anticipatory systems (CASYS) enable us to visualize the incursive and recursive dynamics of knowledge at the individual level as different from the potentially hyper-incursive dynamics at the intersubjective level. The sciences can be considered as "strongly anticipatory" at this supra-individual level: expectations are discursively reconstructed in terms of next generations of expectations. This reflexive restructuring is embedded in historical dynamics on which it feeds back as a selection environment. The agents and texts entertain discursive models and thus be considered "weakly anticipatory" participants in the communication.

In a lecture entitled "Epistemology Without a Knowing Subject," the philosopher Karl Popper (1967, 1972) elaborated his argument about "objective knowledge" in "World 3" as follows:

> […] it is important to distinguish between different senses of the word *knowledge*:
>
> (1) Subjective knowledge which consists of certain inborn dispositions to act, and of their acquired modifications.
> (2) Objective knowledge, for example, scientific knowledge which consists of conjectural theories, open problems, problem situations, and arguments.
>
> All work in science is work directed towards the growth of objective knowledge. We are workers who are adding to the growth of objective knowledge as masons work on a cathedral. (pp. 131f.)

As is probably well-known, Popper distinguished three worlds: World 1 consisting of physical objects and events, including biological phenomena; World 2 as the world

This chapter is based on: Leydesdorff (2015).

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_8

of mental processes; and World 3 as containing "objective knowledge." The three worlds are substantively different and operate in parallel.

Objective knowledge in World 3 is possible because human language has also a descriptive function. A description can be objectified; for example, by writing it on paper. As Popper formulated:

> Without the development of an exosomatic descriptive language—a language which, like a tool, develops outside the body—there can be *no object* for our critical discussion. But with the development of a descriptive language (and further, of a written language), a linguistic third world can emerge. (p. 120)

In my opinion, language not only provides the option of exosomatic descriptions, but enables us to shape *discursive knowledge* as a result of interactions among the descriptions. In this context, "discursive" is different from Popper's use of the word "linguistic."

From an evolutionary perspective, discursive knowledge can be considered as "speciation" of another medium in the communication. In Chap. 2, I argued for "a communicative turn in the philosophy of science"—beyond Rorty's 1992 [1967] "linguistic turn." Synergies based on interactions among *codes in the communication* can induce a knowledge base which operates in terms of expectations. This neo-evolutionary model was elaborated in Chaps. 4 and 5 for the case of the Triple Helix of university-industry-government relations.

With the coding of the communications, the medium has changed into discursive knowledge. A symbolic layer is added to the language. One needs a specific competence to participate in the discourse beyond linguistic competence. Concepts can be symbolically generalized and function in the next-order communication dynamic of interacting codes. The functionally different codes span horizons of meaning that operate as selection environments at arm's length from the intentions of the language users. The relations between language users and cognitive structures are mediated by language.

Adding a second dimension to language changes the medium into a performative medium. For example, one can use this second dimension first for rank-ordering the communications on a speakers list in a debate; for example, in parliament. However, the second dimension can also be used as a grouping variable. Specific languages usages (e.g., jargons) invoke other symbols. The communication can become richer and more performative because of an additional selection in the second dimension (Broszewski, 2018; Distin, 2010). A restricted discourse can always be elaborated into natural language (Bernstein, 1971; Coser, 1975).

The newly added dynamics (of discourse) feeds back as a modifier on the carrying one of common language. Luhmann (1997a, b, pp. 393f; 2012, pp. 238f.) formulated the dual-layered communication dynamics, as follows:

> [...] the medium therefore has to be both condensed and confirmed in a paradoxical because contrary operation of generalization through specification. Media symbols thus generate, we could say, the eigenvalues of their own recursivity. When they are reused, such medium-specific eigenvalues develop—for example, as the value of otherwise valueless money symbols. [...]

In Chap. 1, I discussed Marx' (1867) argument that the mediation of money ("Ware-Geld-Ware" or WGW) is qualitatively different from the exchange of money via the mediation of commodities ("Geld-Ware-Geld" or GWG).[1] The dynamics of money are more abstract than those of commodities; more transactions can be processed. Further codification of money into credit enables us to shop worldwide. Luhmann (1997a, b, pp. 393f.; 2012, pp. 238f.) added that "the issue of generalized acceptance has been discussed particularly with regard to the medium of money. But it concerns all other media as well." The more fine-tuned the medium is, the richer the communication can be. The capacity of the medium to select from the variation is limited by the quality of the reflection in the medium (cf. Ashby, 1958).

When the processing grows more complex than the content of the communications, a change in the relative weights of couplings among subdynamics may restructure the system. In abstract terms, one can consider this as reaction-diffusion dynamics and its bifurcations. Avoiding this abstract vocabulary, Luhmann formulated as follows:

> All communication is an operation that takes place concretely under the direction of specific meaning intentions. It is concerned with the truth of certain statements, compliance with certain instructions, the purchase of certain objects, certain signs of love—or indifference. Individual com-munications of this type are, however, never self-motivating, they draw on a recursive network of reusability of the same medium. In each and every case, the medium therefore has to be both condensed and confirmed in a paradoxical because contrary operation of generalization through specifi-cation. Media symbols thus generate, we could say, the eigenvalues (grouping variables, l.) of their own recursivity.

The selective cycling may lead to stabilization of patterns of communication over time and globalization as a pending selection mechanism in the representation of the future. When stability is lost, the communication still has the option of this external hold of globalization:

> […] a medium can use the *future* of its own operations as a *focus for externalizations.* Future is and remains external in that it can never be-come reality but is always only held in abeyance. In so far as real-ity is actual, every system always finds itself at the end of its history. However, one can test at every moment, in every present, whether the future still holds what was promised. Whether others are still willing to accept money can, however, be tried out only in the present, but in every present. Lovers swear to be eternally faithful—at a moment for the mo-ment. But here, too, one situation follows another, and we can (however self-destructive this might be) check over and again whether the oath is still valid. Truths can already be revised tomorrow; but if new truths are to be convincing, they must be able to offer an explanation for what, as one now knows, the old truths had wrongly explained, for otherwise there would be not competition for substitutes.
>
> We can accordingly very well assume that media validate themselves with reference to previous states and even derive certain form requirements from this self-validation. We need only a sufficiently subtle theory of time that determines the present as the boundary between past and future.

I shall argue in this and the next chapter that the theory and computation of anticipatory systems as developed by Rosen (1985) and Dubois (e.g., 1998, 2003;

[1] "Ware-Geld-Ware" can be translated as "Commodity-Money-Commodity" (Marx, 1995, pp. 66 ff.).

Dubois & Resconi, 1992) can serve us as this "sufficiently subtle theory of time." In addition to the *recursive* shaping of the codes along the arrow of time (morphogenesis in texts and practices), one can define incursions at the border between past and future, and hyper-incursion in restructuring the order of expectations. Different from recursion on a previous state, incursion operates with reference to the current state and hyper-incursion inverts the arrow of time so that anticipated states can drive the operation. However, the various dynamics cannot sufficiently be distinguished using common ("natural") languages, since one would have to add time-subscripts to all language usage as in the case of algorithms. Language operates with geometrical metaphors and on the assumption that meanings are relatively stable within a single text or context. Algorithmically, the descriptions, the described, and the meanings can change in strange loops with irregular transitions.[2]

As we shall see below, the incursive, recursive, and hyper-incursive equations can have very different solutions despite their common background. The equations provide access to different realities because of the involvement of other selection mechanisms (Casti, 1989). What is "true" from one perspective, may be "false" from another. When a routine is evaluated as "false," the prevailing regime of a "do while true" loop is interrupted and another routine is invoked.

8.1 Popper's Perspective on the Growth of Knowledge

Can the dynamics of Popper's "objective knowledge" in World 3 be specified as a selection mechanism? Are incursive and hyper-incursive selection mechanisms different from recursive ones so that we can envisage to answer Luhmann's (1971, p. 34; 1990a, b, at p. 27) quest for a selection mechanism that does not shrink, but enriches the data? "[W]hat is special about the meaningful or meaning-based processing of experience is that it makes possible *both* the reduction and the preservation of complexity; i.e., it provides a form of selection that prevents the world from shrinking down to just one particular content of consciousness with each act of determining experience."

In the noted lecture, Popper (1967; 1972, at p. 121) explicated the evolutionary mechanism operating within World 3 as follows:

> The autonomous world of the higher functions of language becomes the world of science. And the schema, originally valid for the animal world as well as for primitive man,
>
> $$P_1 \to TT \to EE \to P_2$$
>
> becomes the schema of the growth of knowledge through error-elimination by way of systematic *rational criticism.* It becomes the schema of the search for truth and content by means of rational discussion. It describes the way in which we lift ourselves by our bootstraps. (p. 121)

[2] The loops can be strange because a stochastic element can be involved.

The scheme $P_1 \rightarrow TT \rightarrow EE \rightarrow P_2$ begins with a problem P_1 which is "tentatively theorized" (TT) and then via "error elimination" (EE) leads to a next problem P_2 which can enter a next cycle in a loop. The cycles can build upon each other, co-evolving into a trajectory.[3] According to Popper, this scheme is "originally valid for the animal world as well as for primitive man." However, the *mechanism* of how this scheme "becomes the world of science" was not further specified. The text suggests that this evolutionary step can be achieved by cumulative and gradual changes.

On the basis of Maturana and Varela's (1984) model of *autopoiesis* ("self-organization") and Luhmann's elaboration of this model for the sciences as systems of expectations, I argued above that as a consequence of cycling, codes can be developed that function as shortcuts in the communication. The codes can be expected to develop further along the eigenvectors of the communication matrix when this matrix is repeatedly multiplied by itself (von Foerster, 1960). Each code adds a dimension and therefore increases the redundancy. Most cells will initially be empty: the information content is then not affected, but the redundancy is.[4] Interactions among differently coded communications (e.g., economic, technological, and political) can bootstrap a knowledge-based order into virtual existence. Using the word "virtual" is here intended to signal that the codes and this order (in a vector space) are not "given" but remain a reconstruction, for example, in language (cf. Giddens, 1981, p. 64).

Whereas the cycles continue to loop along trajectories at $\{t_1, t_2, \ldots t_n\}$ with the arrow of time—stepwise as in Popper's above scheme [$P_1 \rightarrow TT \rightarrow EE \rightarrow P_2$]—each solution to a problem *incurs* as a feedback on historical developments and can then trigger discontinuity. When this feedback term prevails, historical trajectories can bifurcate into branches (cf. Sahal, 1985; Waddington, 1957). This mechanism of bifurcation is known as reaction-diffusion dynamics (Turing, 1952; cf. Leydesdorff 2006, pp. 169 ff. for an extensive explanation): the reaction process generates a diffusion dynamic with a different logic. After a bifurcation the diffusion dynamic becomes a selection environment for the reaction process which continues to provide variation. Selection is deterministic and thus this feedback can take control.

In a related lecture entitled "Evolution and the Tree of Knowledge," Popper ([1961] 1972, pp. 262f.) elaborated the analogy with and the difference from biological growth. Like a tree, knowledge "grows," but "almost in the opposite direction." The time axis is inverted by the dynamics of knowledge when compared with biological growth:

> When we spoke of the tree of evolution we assumed, of course, that the direction of time points upwards—the way the tree grows. Assuming the same upward direction of time, we should have to represent the tree of knowledge as springing from countless roots which grow up into the air rather than down, and which ultimately, high up, tend to unite into one common stem. In other words, the evolutionary structure of the growth of pure knowledge is almost the opposite of that of the evolutionary tree of living organisms, or of human implements, or of applied knowledge.

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[3] One can also consider such a longitudinal series of cycles as a helix.

[4] The maximum entropy $H_{\max}$ is extended from $H_{\max} = log(n * m)$ to $H_{\max} = \log(n * (m + 1))$. If n is large, this change can have large consequences.

In summary, three elements relevant to my argument were articulated in Popper's philosophy of science: (i) scholarly discourse is constitutive for the development of knowledge at the supra-individual level; (ii) the growth of knowledge operates with another time direction than biological evolution; and (iii) the emerging World 3 exhibits a (quasi-)autonomous dynamic.[5]

I added the possibility of an incursive dynamics at 90° to the plus and minus directions of "with" or "against" the arrow of time. Incursions operate orthogonally (as interventions) on trajectories; regimes operate with one more turn of 90 degrees as feedbacks in the opposite direction; that is, as selections from the perspective of hindsight—against the arrow of time. The codes anchor meanings in the domain of expectations, but some meanings are anchored more than others; the strength of incursive couplings between variation and selection can be expected to vary. The less anchored meanings may be discarded as noise or be forgotten. Whereas the feedback is first shaped against the arrow of time (at 180°), a bifurcation can lead to a second eigenvector at ninety degrees which codifies the dynamics of incursion. However, the relative priorities of the eigenvectors can be expected to change over time, so that the main perspective for the reflection becomes one among two (or more) orthogonal dimensions.

8.2 The Hyper-incursive Order of Expectations

In addition to sequences of events (along trajectories), an event at time t can be provided with meaning at a later moment $t + \Delta t$. In other words, meaning can be provided from the perspective of hindsight to events that have already happened or are happening. Whereas meanings incur on the events, codification operates hyper-incursively on meanings, that is, by grounding the subjective—historically contingent—perspectives on intersubjective layers of control.

In their "sociology of expectations," Brown and Michael (2003) noted a tension between the forward movement along the arrow of time and backward interpretation and control as a balance between "retrospecting prospects and prospecting retrospects." In a similar vein, Latour (1987, at p. 97) argued that "the two versions […] are not uttered by the same face of Janus."[6] However, a reflection in the time domain stands orthogonally—i.e., is independent of—substantive reflections at each moment of time. The word "reflexive" can have different meanings in these various contexts.

In a static design, one focuses on latent structures, whereas the development over time can be reconstructed as shaping a trajectory. When the spatial and the temporal reconstructions can operate upon each other, an inter-objective reality of expectations—horizon of meanings—can be generated in a newly emerging dimension.

[5]Maturana and Varela (1984) used the same metaphor of "a tree of knowledge," but two decades later and without a reference to Popper's World 3.

[6]One is reminded of Walter Benjamin's ([1940] 1974) "Angel of History".

However, this construct "exists" only as a structure of expectations; it remains a *cogitatum* or, in other words, a matter about which we remain uncertain. (Popper (1963) preferred to use the word "conjectures.") Discursive knowledge develops in interactive processes which are "self-organizing" as an evolutionary dynamic including, for example, refutations (at the trajectory level) and crises or paradigm changes (at the regime level). As Popper formulated in *The Logic of Scientific Discovery* ([1935] 1959, at p. 111):

> The empirical basis of objective science has thus nothing 'absolute' about it. Science does not rest upon solid bedrock. The bold structure of its theories rises, as it were, above a swamp. It is like a building erected on piles. The piles are driven down from above into the swamp, but not down to any natural or 'given' base; and if we stop driving the piles deeper, it is not because we have reached firm ground. We simply stop when we are satisfied that the piles are firm enough to carry the structure, at least for the time being.

Although an evolutionary mechanism was envisaged, the evolutionary model was not yet specified by Popper. When he formulated in this quotation that "we simply stop when we are satisfied," one can raise the question "who are the 'we'?" Was not "objective knowledge" knowledge without a subject? Are the "we" an aggregate of the "I"s or an interaction term among us? By focusing on "meanings," the unit of analysis shifts from the constructing agency to the dynamics of "reconstructions and revolutions" in the constructs (Hesse, 1980). It is *no longer the agents or the texts that are updated, but the expectations.* The updates can be reflected by agents and in texts.

8.3 The *Differentia Specifica* of Inter-human Communications

Even if dolphins and monkeys were able to use a kind of language for their communication, human analysts would not have direct access to this (quasi-)language. A biologist can reconstruct and interpret "monkey speech"; for example, when monkeys signal danger to one another. However, the biologist herself using biological discourse (for example, about "monkey speech") remains a *super-observer*, to be distinguished from the "languaging" agents under study.

The biologist Maturana (1978, pp. 56 ff.) formulated the specificity of inter-human communications as follows:

> Human beings can talk about things because they generate the things they talk about by talking about them. That is, human beings can talk about things because they generate them by making distinctions that specify them in a consensual domain, and because, operationally, talking takes place in the same phenomenic domain in which things are defined as relations of relative neuronal activities in a closed neuronal network.

What is specifically (re)constructed by the languaging among human beings? What is evolving? Unlike biological code (DNA), the codes of expectations are communication-based. The codes enable us to communicate about what is not the case. *Redundancy* is a measure in the present of these absent possibilities. The future states are analytical specified (in the second contingency), but absent in the first.

The cybernetic hypothesis is that a next-order system is constructed bottom-up (by constructing agents), but the construct tends to take control top-down. In the case of language and languaging, the language that is emerging can be expected to structure the use of language by languaging agents. This cultural domain of evolving expectations is specifically human. Giddens (1976, at p. 144) succinctly formulated his critique of using a meta-biological metaphor for studying society, as follows:

> The process of learning a paradigm or language-game as the expression of a form of life is also a process of learning what that paradigm is not: that is to say, learning to mediate it with other, rejected, alternatives, by contrast to which the claims of the paradigm in question are clarified.

Given this specific capacity to change the reflexive system under study on the fly, there remains little hope of arriving at the illusion of stable pillars of codified knowledge as, for example, seemingly in physics. The dynamics of communication cannot be stabilized in an experimental setting, since both the analysts and the subjects under study communicate and learn. Within the loops, the *cogitantes* (agency) and *cogitata* (constructs) can "learn" from each other. But one can expect an asymmetrical dynamic in the two directions. Furthermore, the different cycles can reflexively interrupt one another.

In summary, from different perspectives both Popper and Husserl argued against logical positivism that insisted on observations and that non-verifiable statements should be discarded as "metaphysical." Pieces of the puzzle of a model of cultural evolution were specified by these authors. However, empirical operationalization and problems of the measurement were beyond the scopes of these philosophers. As Popper (1972, pp. 259f.) put it:

> I cannot, of course, hope to convince you of the truth of my thesis that observation comes after expectation or hypothesis. But I do hope that I have been able to show you that there may exist an alternative to the venerable doctrine that knowledge, and especially scientific knowledge, always starts from observation.

In my opinion, the subjective "consciousness" of individual actors and the inter-objective "communication" were not sufficiently distinguished by these authors as different units of analysis. The dynamics of communication are different from individual learning.

8.4 The Theory and Computation of Anticipations

The theory and computation of anticipatory systems enable us to simulate cultural (that is, non-biological) evolutions, and thus to take next steps using simulation as a possible mechanism of methodological control. The anticipatory perspective radicalizes the inversion of time into a new paradigm: present states can be considered from the perspective of future states.

Anticipatory systems were first defined by Rosen (1985) as systems that entertain models of themselves. The model provides an anticipatory system with a degree of freedom for entertaining internal representations of other possible states. Dubois (1998; cf. Dubois & Resconi, 1992) proposed to model the representations entertained by the anticipatory systems using incursive and hyper-incursive equations. Using these equations, possible future states can be considered as independent variables counter-intuitively driving the present against the arrow of time.

The possibility of incursion as different from recursion follows analytically from the possibility of evaluating a difference equation forward or backward in discrete time. The differential equation in continuous time—e.g., speed as a function of distance over time; $v(t) = \mathrm{d}x/\mathrm{d}t$)—can be formulated in general (for any x) as follows:

$$dx/dt = f(x_t) \tag{8.1}$$

The additional option of a backward and a forward mode finds its origin in the possibility to approach the infinitesimal as a limit transition positively from the previous state or negatively from the perspective of the next state, as follows:

$$x(t + \Delta t) = x(t) + \Delta t\ f(x(t)) \tag{8.2}$$

$$f(x(t) = (x(t + \Delta t) - x(t))/\Delta t \tag{8.3}$$

Or equivalently backward:

$$x(t - \Delta t) = x(t) - \Delta t\ f(x(t)) \tag{8.4}$$

$$f(x(t) = (x(t) - x(t - \Delta t))/\Delta t \tag{8.5}$$

In continuous time, the two tangents can be the same (since $\Delta t \rightarrow 0$); but in discrete time, the one equation is recursive and the other incursive. Drawing the respective tangents, Fig. 8.1 shows that the two approximations may lead to very different results. In other words, there are two pathways for obtaining x_t: one following the arrow of time from the past ($t - \Delta t$) to the present (t), and one developing against the arrow of time from a future state ($t + \Delta t$) to the present.

The recursive equation operates in historical time and the incursive one against the arrow of time, or, in other words, as an intervention. A next state *incurs* on the present one as the expectation of a further selection. This possibility to operate against the arrow of time is akin to the model of information versus redundancy generation discussed above (in Chaps. 4–7). Both redundancy generation and (hyper-)incursive models operate against the arrow of time and therefore with a minus sign, given that the development of entropy in history is by definition positive. The minus sign is needed in order to keep a calculus of redundancy consistent with the Shannon equations: redundancy is generated against the arrow of time (reflexively), whereas entropy is generated with the arrow of time (historically). The algorithmic approach of

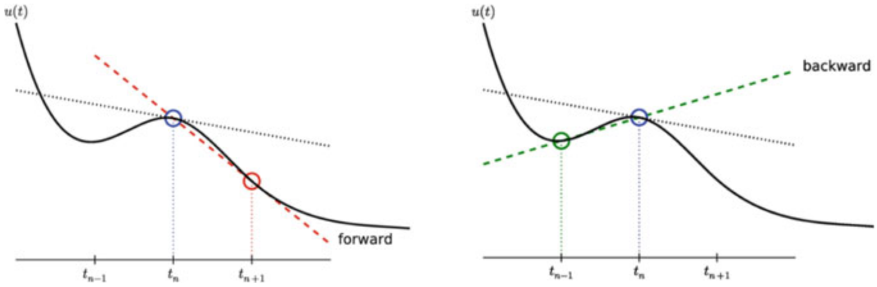


Fig. 8.1 Backward and forward evaluation of the infinitesimal transition. *Source* Linge and Langtangen (2020) Fig. 8.4, at p. 214, and 8.22, at p. 245

anticipatory systems elaborates and adds an algorithmic approach to the geometrical model of redundancy generation and synergy measurement at specific moments or during specific periods of time.

8.5 Incursive and Hyper-incursive Equations

The logistic equation—also known as the Pearl-Verhulst equation—can be used, among other things, for modeling growth in a biological system. The model is based on recursion: each next state is a function of the previous one. Following Dubois (1998), this recursive version of the equation serves me here as a baseline for models using incursive and hyper-incursive variants.

In the biological case, the logistic equation is formulated as:

$$x_t = ax_{t-1}(1 - x_{t-1}) \tag{8.6}$$

This model is *recursive*, since each next stage (x_t) builds on its previous state (x_{t-1}). In Eq. 8.6, the time relation is in accordance with the arrow of time in *both* arguments of the equation. For example, a population first grows with each time step ($x_t \rightarrow x_{t+1}$), but then increasingly selection pressure—written as $(1 - x_{t-1})$ in Eq. 8.6—is generated, bending the system's growth curve into the well-known *S*-shape.

An incursive version of this same equation can be formulated, for example, as follows[7]:

$$x_t = ax_{t-1}(1 - x_t) \tag{8.7}$$

[7]Another incursive equation is $x_t = x_t(1 - x_{t-1})$. This quadratic equation has two roots [$x = (1-a)/a$ and $x = 0$], which correspond to the steady states of Eq. 8.7 to be discussed below (Leydesdorff & Franse, 2009, at pp. 110f.).

For example, the market as a system of expectations does not select commodities, technologies, etc., from among the options provided at a previous moment (that is, using $[1 - x_{t-1}]$); the market selects among options in the present. However, at the same moment the update from x_{t-1} to x_t in the first factor provides the historical (that is, recursive) perspective in Eq. 8.7. In other words: a technology develops historically—that is, with reference to its previous state—but the new technology is selected on the market in the present. We shall see that Eq. 8.7 has solutions that are different from those of Eq. 8.6.

The corresponding hyper-incursive model is:

$$x_t = ax_{t+1}(1 - x_{t+1}) \tag{8.8}$$

I shall argue that (i) the logistic equation (Eq. 8.6) can be used to model a growth process against increasing selection pressure; (ii) the incursive equation (Eq. 8.7) models an instantiation at the present moment t; (iii) this process is hyper-incursively embedded in the structuring of expectations as modeled in Eq. 8.8.

It may seem that one can reformulate recursive equations into incursive and hyper-incursive ones by changing the temporal subscripts: instead of x_t as a function of x_{t-1}, one can also write x_t as a function of x_{t+1}. However, the consequent solutions of the equations can be very different, and so are their interpretations. In the case of the incursive equation (Eq. 8.7), for example, an anticipatory system x_t builds on its previous state (x_{t-1}), but the selection factor $(1 - x_t)$ operates in the present and not in the past, as does $(1 - x_{t-1})$ in the biological model (Eq. 8.6).

In Eq. 8.8, *history (x_{t-1}) no longer plays a role.* This hyper-incursive equation mirrors Eq. 8.6 in terms of the time subscripts. This hyper-incursive system is (re)constructed at $t = \mathrm{t}$ in terms of its future states (t + 1, t + 2, etc.). Such a model without a reference to previous states can be considered *strongly* anticipatory because the expectations are generated internally; the expectations are not in the environment. Weakly anticipatory systems entertain a model to predict future states; a strongly anticipatory one uses future states to reconstruct itself (Dubois, 2002, pp. 112 ff.).

Whereas individuals can be considered as weakly anticipatory systems entertaining a model of themselves reflexively but operating historically (given a life-cycle), systems of rationalized expectations communicate inter-subjectively with reference to horizons of meaning. The communication is continuously restructured in terms of refinements of the expectations, and can be considered as strongly anticipatory while operating at the regime level. Expectations of future states are circulating hyper-incursively in this subdynamic; not the behavior of agents but their expectations are coordinated by these selection mechanisms which are different from "natural selection." Luhmann (1971; 1990a, b, p. 27) conjectured the possibility of "a form of selection that prevents the world from shrinking down." Unlike "natural selection," one can consider this selection mechanism "cultural," since oriented to generating hitherto unrealized alternatives.

8.6 Solving the Equations

Incursive and hyper-incursive equations can be expected to have solutions that are different from recursive equations. As is well known about the logistic equation (e.g., May, 1976), the bifurcation diagram of x plotted against the so-called bifurcation parameter a is increasingly chaotic when $a \to 4$, and cannot exist for $a \geq 4$. In Fig. 8.2, this development is depicted as the left half of the figure. In the case of the *incursive* Eq. 8.7, however, this limit value (for $a \to 4$) loses its relevance. The equation has solutions for $a > 4$.

One can derive on the basis of Eq. 8.7. as follows:

$$x_{t+1} = ax_t(1 - x_{t+1}) \tag{8.7}$$

$$x_{t+1} = ax_t - ax_t x_{t+1} \tag{8.8}$$

$$x_{t+1}(1 + ax_t) = ax_t \tag{8.9}$$

$$x_{t+1} = ax_t/(1 + ax_t) \tag{8.10}$$

By replacing x_{t+1} with x_t in Eq. 8.11, two steady states can be found for $x = 0$ and $x = (1 - a)/a$, respectively, as follows:

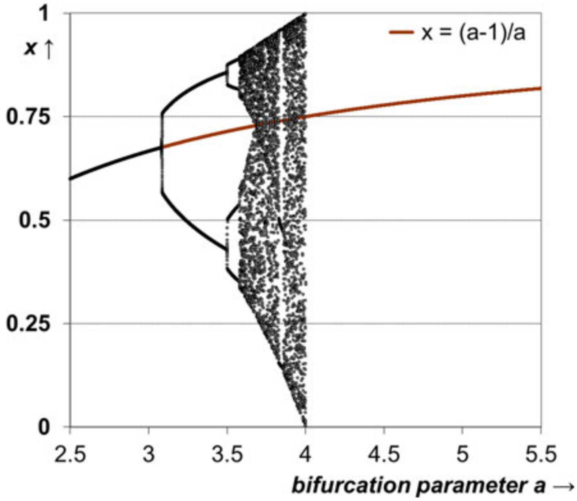


Fig. 8.2 The steady state of the weakly anticipatory system x added. *Source* Leydesdorff and Franse (2009), p. 111

$$x = ax/(1 + ax) \tag{8.11}$$

$$1 = a/(1 + ax) \tag{8.11a}$$

$$1 + ax = a \tag{8.11b}$$

$$\boldsymbol{x = (a - 1)/a} \tag{8.11c}$$

These steady states correspond to (i) the non-existence of the system ($x = 0$) and (ii) the brown line penciled into the bifurcation diagram in Fig. 8.2. Note that this incursive system has values in the domain of $a \geq 4$, which is biologically not possible. An expectation itself cannot be a biological given. However, biologically embodied agents—body-mind systems—are needed to entertain these expectations. The body-mind system, for example, has a presence in both the biological and psychological domains.

The line penciled into Fig. 8.2 represents an incursive system which can provide meaning(s) to events by integrating them into both the biological domain ($a < 4$; e.g., bodily perceptions) and the domain of meaning-sharing and processing ($a \geq 4$). The instantiation of the two arguments in a single receiver integrates the information and meaning processing historically (e.g., in action), and thus can function as a linchpin between weakly anticipatory minds and strongly anticipatory communications in the cultural (i.e., non-natural) domain of meaning-processing ($a \geq 4$). As we shall see below, hyper-incursive uncertainty drives a need to take incursive decisions.

The hyper-incursive equation (Eq. 8.8) is quadratic in x_{t+1} and therefore has two possible roots:

$$x_t = ax_{t+1}(1 - x_{t+1}) \tag{8.8}$$

$$x_t = ax_{t+1} - ax_{t+1}^2 \tag{8.12}$$

$$ax_{t+1}^2 - ax_{t+1} + x_t = 0 \tag{8.13}$$

$$x_{t+1}^2 - x_{t+1} + x_t/a = 0 \tag{8.14}$$

$$x_{t+1} = 1/2 \pm 1/2\sqrt{[1 - (4/a)x_t]} \tag{8.15}$$

This system has no real roots for $a < 4$, but it has two solutions for values of $a > 4$. (For $a = 4$, the two roots are equal: $x_1 = x_2 = ½$; see Fig. 8.3.)

For $a > 4$, two expectations are generated at each time step: one on the basis of the plus and one on the basis of the minus sign in Eq. 8.15. After N time steps, 2^N future states are possible if this system were to operate without historical retention by making decisions. Thus, the system of expectations needs a mechanism for making choices between options, because otherwise the system would rapidly become over-burdened with options. In other words, in short order the communication cannot be

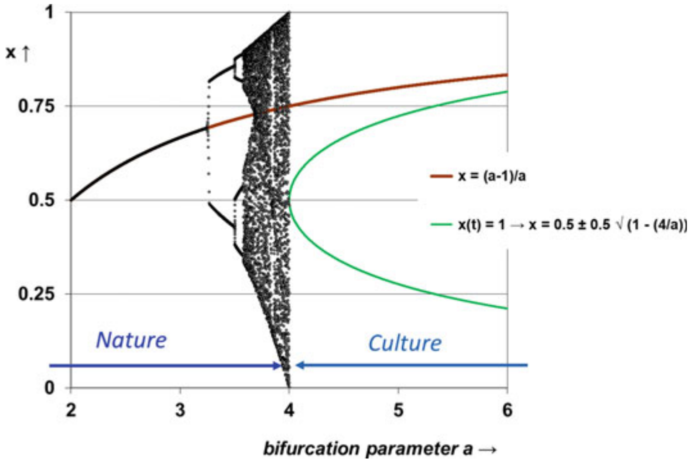


Fig. 8.3 The system of expectations (x) as a result of hyper-incursion. *Source* Leydesdorff and Franse (2009, at p. 113)

further developed without agent(s) able to make choices between options, because of the continuous proliferation of uncertainty by the hyper-incursive mechanism.

Decisions by agents anchor the hyper-incursive anticipations historically in instantiations. Reasoning in another (sociological) context, Luhmann (2000) also suggested considering decisions as the structuring mechanism of organizations. Beyond single decisions, the organization of meaning can also be achieved by institutional agency, using *decision rules* as a codification of decision-making (cf. Achterbergh & Vriens, 2009). From this perspective, the individual can perhaps be considered as the minimal unit of reflection for making choices (Habermas, 1981; Leydesdorff, 2000). Both agency and organizations—institutional agents—are able to *integrate* perspectives by reflexively making choices (and taking action on that basis).

If decisions are socially organized—for example, by using decision rules instead of individual preferences—an institutional layer can increasingly be shaped. The institutional layer provides a retention mechanism for a next round of developing expectations (Aoki, 2001). Thus, the system can be considered as dually layered: (i) as a forward-moving retention mechanism, and (ii) as sets of possible expectations which flow through the networks in the opposite direction, that is, against the arrow of time.

Note that expectations can proliferate much faster than their retention in *res extensa*. Unlike action-based instantiations, "horizons of meaning" are not material or given, but continuously in flux and undergoing reconstructions. While the agents and the texts can both be part of the recursive retention mechanism, the agents as minds can also partake incursively as *cogitantes* in *res cogitans*.[8]

[8]In the semiotic tradition—actor-network theory and the sociology of translation—a distinction is made between agents in sociology and "actants" in the narrative (e.g., Latour, 1996).

8.7 Simulations of Incursive and Hyper-incursive Equations

Hitherto, x was not yet specified. The advantage of this abstractness is that x can be anything about which one is able to specify and entertain an expectation (x_{t+1}). How can one move from these very abstract bifurcation diagrams (in Figs. 8.1, 8.2 and 8.3) to modeling the sciences operating as strongly anticipatory systems? The technique of cellular automata for simulations enables me to develop and illustrate my argument (see Leydesdorff & Van den Besselaar, 1998a, 1998b). The simulation results will be used to refine the theoretical reasoning (in the next chapter.)

8.7.1 *Cellular Automata*

A cellular automaton is a grid of cells with rules for the interactions among the cells resulting in updates for each cell. For example, one can assume that each cell at the coordinates $\{x, y\}$ on a screen can be influenced by the four cells (above, below, to the right, and to the left) in its so-called Von Neumann environment. The coordinates of these four neighbors are: $\{\mathrm{x}, \mathrm{y} + 1\}$, $\{\mathrm{x}, \mathrm{y} - 1\}$,$\{\mathrm{x} + 1, \mathrm{y}\}$, and $\{\mathrm{x} - 1, \mathrm{y}\}$. In Table 8.1, a routine is provided simulating an environment in which the presence of at least three of the four neighbors in this Von Neumann environment induces adaptation in terms of the color of the pixel. I use a simple form of Basic (*QBasic*) in this example for the introduction of the technique.

In the routine of Table 8.1 an array "scrn(321, 201)" is first declared (in line 40) with the same size as a window opened on the screen: 320 cells horizontally and 200 cells vertically. The array is filled randomly with the values $+1$ and -1 (in lines 120–140). The correspondence between the values in the array and the colors on the

Table 8.1 Simulation of Von Neumann Neighborhoods in QBasic

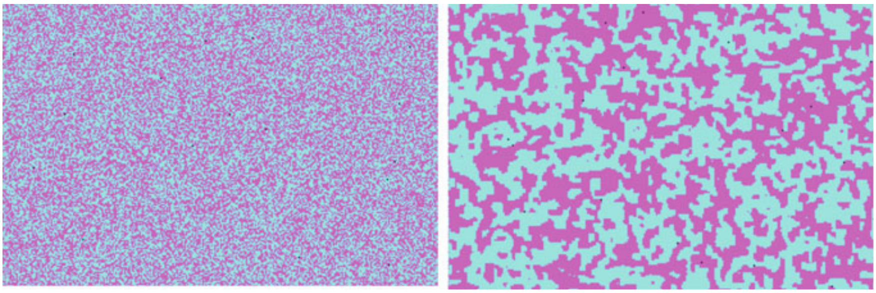
```
10  SCREEN 1: WINDOW (0, 0)-(320, 200): CLS
20  RANDOMIZE TIMER

30  ' $DYNAMIC
40  DIM scrn(321, 201) AS INTEGER

50  FOR I = 1 TO 1000000
60    y = INT(RND * 200)
70    x = INT(RND * 320)
80    IF (x = 0 OR y = 0) GOTO 120              ' prevention of errors
90    z = scrn(x - 1, y) + scrn(x + 1, y) + scrn(x, y - 1) + scrn(x, y + 1)
100   IF z = 0 GOTO 120                         ' random attribution
110   IF z > 0 THEN GOTO 130 ELSE GOTO 140
120   IF RND < .5 THEN GOTO 130 ELSE GOTO 140
130     PSET (x, y), 1: scrn(x, y) = 1: GOTO 150
140     PSET (x, y), 2: scrn(x, y) = -1
150 NEXT I
151 SLEEP 600
160 END
```

screen enables us to study both the micro operations and macro effects in the same passes.

In each run, a pixel is randomly drawn (in lines 60 and 70) from the set of pixels horizontally ($0 < x < 320$) and vertically ($0 < y < 200$). The corresponding cell value in the array is evaluated in line 90 as the sum of the positive and negative values of its four neighbors {x, y + 1}, {x, y − 1},{x + 1, y}, and {x − 1, y}. If the value of z resulting from this summation is positive, the pixel is set to "+1" in line 130; and otherwise to "–1" in line 140. If $z = 0$, the attribution is random (in lines 100 and 120). The system loops, for example, one million times from line 50 to line 150. The routine changes a randomly distributed screen in two colors on the left side of Fig. 8.4 into a pattern as on the right side of this same figure. In other words, a structure is always generated.

Thus, one can both numerically (in the array declared at line 40) and visually (on the screen) follow how the rules affect each element at both the individual pixel level and the aggregate level. The rules can also be made dynamic; for example, by specifying thresholds for the introduction of new routines. In Table 8.1, the drawing of pixels is random (lines 60–70) and structure is emerging. However, this can be defined differently in non-biological models. One can change the perspective without consequences for this methodology.

A cellular automaton allows for intersections among loops, including "strange loops" based on incursions within recursive loops. Such an intersection is not allowed in a formal calculus because loops can be created. Action at one place, for example, may cause an avalanche of changes at other places. In principle, cellular automata enable us thus to simulate the "fractional manifolds" discussed in previous chapters. Different mechanisms and time horizons can be combined into these simulations.



Random attribution of two colors

Von Neumann neighbourhoods after one million recursions

Fig. 8.4 Simulation of Von Neumann Neighborhoods in QBasic on the Basis of Table 8.1

8.7.2 Modelling of Expectations Using Cellular Automata

Cellular automata have been used in the social sciences for modelling bottom-up processes in so-called agent-based modelling (ABM), but the method is more encompassing and abstract, allowing also for units of analysis other than individual agents (Von Neumann & Burks, 1966). ABM has become popular in the social sciences since the publication of Epstein & Axtell's *Growing Artificial Societies: Social Science from the Bottom Up* (1996).[9] On the basis of his work with ABMs, Epstein (2006) formulated what he called a "generative" research program for the social sciences: one cannot explain a social phenomenon until one has "grown" it by simulating the phenomena under study as emerging from the bottom up (cf. Hedström, 2005).

This agent-based research program accords with the strong program in the sociology of science: individuals and their aggregates in institutions—agency—are considered as the units that generate the dynamics of the sciences (Edmonds, Gilbert, Ahrweiler, & Scharnhorst, 2011). The focus is on the "bottom-up" genesis of patterns and not on the validity of the resulting constructs as reconstructions of selection environments. While micro-founded at the level of individuals taking action (or not), the sciences are thus considered as community-based beliefs attributed to agents who can be driven by a blend of socio-epistemic interests (Axelrod, 1997); the intellectual organization of the sciences is considered as an attribute of their social organization; content is defined in terms of the individual cognition of the interacting agents (Payette, 2012; Sun, Kaur, Milojević, Flammini, & Menczer, 2013).[10] Although the agents may be able to perceive and understand the intellectual dimensions of their activities, the interpretation of the results of their interactions remains agent-based (cf. Bloor, 1976).

Edmonds et al. (2011), for example, stated that "science is substantially a social phenomenon." Furthermore, these authors claimed that "agent-based simulations of social processes are able to incorporate lessons from qualitative social science studies of what scientists actually do on a day-to-day level as well as insights from the more naturalistic philosophers of science" (cf. Scharnhorst, Börner, & Van den Besselaar, 2012). McGlade (2014, at p. 295) noted that such an "agent-based ontology" entails problems when simulating mental processes.

How would one be able to visualize the intellectual organization of cognitions? Sun et al. (2013, p. 4) noted that "[f]uture 'science of science' studies have to gauge the role of scientific discoveries, technological advances, and other exogenous events in the emergence of new disciplines against the purely social baseline." Along these lines, Gilbert (1997), for example, replaced the agents at the nodes with interacting "kenes"—the knowledge-based equivalents of genes. This allowed him to show how these analytically hypothesized units of analysis can drive the evolution of the sciences.

---

[9] Biological applications of cellular automata, such as in Artificial Life, preceded this development by more than a decade (e.g., Allen, 1988; Langton, 1989).

[10] Given this focus on agency, references and citations can be understood as rhetorical devices in practices (e.g., Cozzens, 1989; Gilbert, 1977; Gilbert & Woolgar, 1974).

8.7.3 Visualizations of Anticipations

Using communications as units of analysis evolving in cellular automata, let me illustrate the operation of the three layers (A, B, and C) distinguished in Chap. 4 by elaborating an example. Figure 8.5 shows Van Gogh's well-known "Langlois Bridge at Arles" that I will use as an exemplary representation in the routines here below. The height of this reproduction was set to 308 pixels and the width to 400 pixels. However, Visual Basic counts the screen in twips, which are fine-grained and screen-independent. In the simulation of the bridge at Arles, the equivalent of 308 * 400 pixels is (3322 * 4200 =) 13,952,400 twips.

Analogously to Table 8.1, the computer code in Table 8.2 provides an example (in Visual Basic) for a recursive subroutine (Eq. 8.6) of the larger routine to be discussed here below.

Two pictures are first distinguished: PicFrom(0) and PicTo(0). Horizontal (x) and vertical (y) values are attributed to PicFrom(0) in lines 2 and 3, and PicTo(0) in lines 35 and 36. PicTo(0) serves for the reconstruction of the picture after each cycle.

One can find the logistic equation (Eq. 8.6) in lines 17–19 for the red, green, and blue components at each specific position (x, y). I use the traditional red-green-blue (RGB) decomposition for the colors. Since the logistic equation requires values for x between zero and one, the color values (between 1 and 256) are first divided by 256 in lines 11–13, then transformed (lines 17–19) and renormalized into integers before picturing the results in lines 29–31.

This example is only a subroutine of a larger program in which the bifurcation parameter a can be provided interactively by the user. The bifurcation parameter is here labeled "parameter" in lines 17–19. The DoEvents in lines 40–41 makes the program sensitive to switching to other (sub)routines or exiting. The program runs in two loops in order to capture the horizontal variation x (line 32) and the vertical variation y (line 34), respectively; all the pixels are repainted in each cycle. After a

Fig. 8.5 Van Gogh's "Langlois Bridge at Arles" to be used as input to the routines. This image is in the public domain; see at http://commons.wikimedia.org/wiki/File:Vincent_Van_Gogh_0014.jpg

Table 8.2 Transformation of a representation using the logistic equation (Eq. 8.6 above)

```
1  DO
2      For Y = 0 To PicFrom(0).ScaleHeight
3          For X = 0 To PicFrom(0).ScaleWidth
4
5              ' Get the source pixel's color components
6              ' (red, green, and blue)
7              clr = PicFrom(0).Point(X, Y)
8              r = clr And &HFF
9              g = (clr \ &H100) And &HFF
10             b = (clr \ &H10000) And &HFF
11             ' scale the color values between zero and one
12             rt = r / 256
13             gt = g / 256
14             bt = b / 256
15
16             'transform recursively using the logistic equation
17             rt = (parameter * rt) * (1 - rt)
18             gt = (parameter * gt) * (1 - gt)
19             bt = (parameter * bt) * (1 - bt)
20             r = Int(rt * 256)
21             g = Int(gt * 256)
22             b = Int(bt * 256)
23
24             ' possible source of error
25             If r > &HFF Then r = &HFF
26             If g > &HFF Then g = &HFF
27             If b > &HFF Then b = &HFF
28
29             ' Write the new color of the pixel
30             clr = RGB(r, g, b)
31             PicTo(0).PSet (X, Y), clr
32
33         Next X
34         DoEvents
35     Next Y
36     ' Make the changes permanent.
37     ' PicTo(0).Picture = PicTo(0).Image
38     PicFrom(0).Picture = PicTo(0).Image
39     cmdGo.Enabled = False
40     MousePointer = vbDefault
41
42     DoEvents
43     If param2 = 0 Then Exit Do
44 Loop While True
```

cycle, the original picture (PicFrom) is replaced by the newly generated one (PicTo). For example, the representation can be expected to erode in a number of steps towards chaos for values of $a > 3.57$ when using the logistic equation recursively (Eq. 8.6).

In summary, Fig. 8.6 is based on a routine which can be run interactively using the program available at http://www.leydesdorff.net/simulation.2015/netsci.exe. The recursive, incursive, and hyper-incursive routines are combined in a single context so that they can be visually distinguished and compared in terms of their effects.

Figure 8.6 shows the different states of the system after a number of runs when the bifurcation parameter a is set, for example, at $a = 3.6$. Since for $a > 3.57$, the "natural" representation is decaying using the logistic equation in the left-top (PicFrom) and middle-top (PicTo) representations that alternate; after each loop PicTo becomes defined as the next PicFrom, etc. (Table 8.2, line 38).

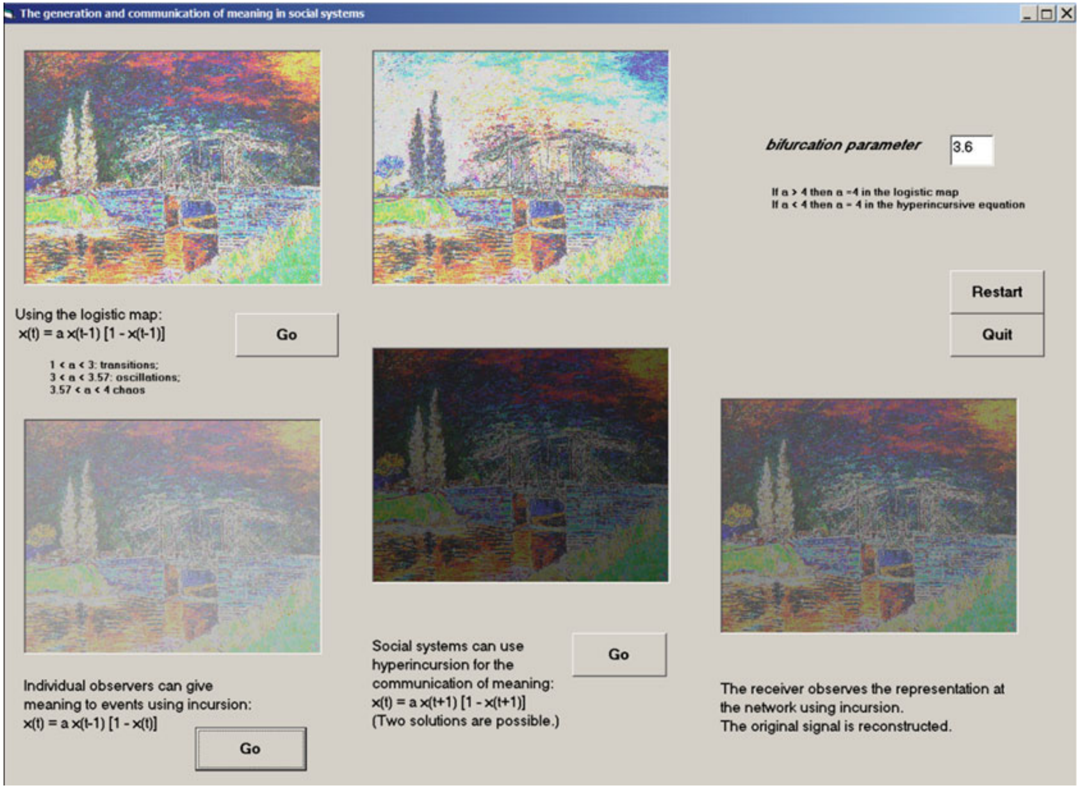


Fig. 8.6 Recursion, incursion, and hyper-incursion in cases of using the logistic equation with Van Gogh's "Langlois Bridge at Arles." Interactive at http://www.leydesdorff.net/simulation.2015/netsci.exe

I have added two reflexive observers using incursive routine. The first observer is generated in the left-bottom screen observing directly the original picture (PicFrom) in the left-top screen.[11] The observer generated in the right-bottom screen, however, does not observe the original picture directly, but only its transformation using the hyper-incursive equation operating in the screen box in the middle at the bottom. Whereas the representation in this latter box seems almost to have disappeared, the receiver at the right-bottom is nevertheless able to regenerate the picture.

The results (in Fig. 8.6) show the possibility of operationalizing reflexive transmissions without invoking a social process. This is a communication process making a specific selection on the underlying social process. The state of mind of the local observers and their social contexts are not relevant to the reception which, instead, is determined by the communication dynamics. The specificity of this process is not the social, but s multi-layered communicative dynamics.

8.8 Sociological Implications and Concluding Remarks

The focus in this chapter has been on how an evolving system of expectations can be simulated without an a priori sociological interpretation. In the next chapter, I shall show the relevance of incursive and hyper-incursive variants of the logistic equation for addressing long-standing problems in sociology, such as how to operationalize "double contingency," the organization of meaning and knowledge, and their further self-organization. These problems could hitherto not be addressed because the conceptualization of the social system of interhuman communications as strongly anticipatory was lacking.

I have argued in this chapter against reification of the cognitive process, but as against Husserl and Luhmann, I argue in favor of *operationalization and measurement*. As Luhmann (1995, at p. 164; 1984, p. 226) formulated: "*communications cannot be observed directly, only inferred.*" (italics in the original). Whereas communications cannot be observed, they can excellently be measured using Shannon's (1948) information theory and simulated using cellular automata. A focus on observations without prior specification of expectations, however, has hitherto blocked this perspective.

The variants of the logistic equation used in Fig. 8.6 enrich the models by showing their limitations. Different ontologies are indicated by using the various time-subscripts in the equations. Whereas the *recursive* version of the logistic equation can be used, for example, to model the development of a biological population in history, the observer at the left-bottom of Fig. 8.4 can be considered as an individual mind using an *incursive* routine for the observation. Among other things, incursion can be used to model the coupling of biological presence with mental representations

[11] For a more extensive discussion of the generation of an observer and observers observing each other, see also Leydesdorff (2006a) and Von Foerster (1982).

of present and future states. Incursive models are needed at the organizational level since like individual action, institutional action remains historical.

The *hyper-incursive* routines refer to evolutionary dynamics that are no longer necessarily historical. This order of conjectures can be elaborated into hypotheses which can be entertained reflexively and further informed by observations. The reference is to an intersubjective communication domain of expectations. In other words, this social order of communications does not *exist* (in history); it remains an order of expectations operating on expectations to which human beings can have reflexive access.

As Popper (1972, pp. 262f.) noted: the knowledge-base is rooted upward. In empirical terms, one can expect both upward and downward dynamics to be continuously invoked as subroutines of cultural evolution. The theory and computation of anticipatory systems provides the tools needed to take a further step: the simulation of structures in systems of expectations. Given my own criteria, I have to complement this "bottom up" genesis with a validation. The genesis shows only the historical process; the validation of these equations and their mutual relations is the purpose of the next chapter.

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Chapter 9
Subdynamics in Knowledge-Based Systems

Using a set of six equations, I propose to model "interactions," the "organization of meaning," and "self-organization" as three coordination mechanisms among expectations; three further equations can be derived to operationalize "double contingency," "identity," and "reflection." One can expect that the subdynamics update one another in co-evolutions as feedbacks and feed-forwards. Interfaces among two (sub)dynamics can be expected to operate with time differences (Δt). Interactions among horizontal and vertical time differences can generate hyper-incursivity in interhuman communications. Hyper-incursion enables us to reconstruct expectations. The social system is probably the only system which can be expected to carry "strong" anticipation while being reproduced as expectations. A system of expectations is not alive, is not constrained by a life-cycle, and does not need to "exist" otherwise than as expectations. The dynamics against the arrow of time are "cultural": they rest on codes as the pillars of discursive knowledge driven upward into horizons of meaning.

In addition to his many discoveries about mental illnesses, Freud carved out the epistemological boundaries of the psychological domain with biology on the one side and sociology on the other. Using the metaphor of *Ego* sitting as a rider on a horse (Freud 1933), *Ego* is not to be considered as an energy system but as a "cybernetic" (Parsons 1958, p. 88, note 16). In relation to sociology, Freud commented (at a workshop in Vienna in 1926) "that he felt like the skipper of a barge who had always hugged the coast, who had now learned that others, more adventurous, had set out for the open sea." He wished them well, but he could no longer participate in their endeavor (Waelder 1958, at pp. 243f.). Parsons (1968), however, argued that Freud himself—approximately at the same time as Durkheim (e.g., 1894, 1912)—had *discovered* the social as the proper subject of sociology. He summarized Freud's demarcation of sociology from psychology, as follows:

> Relatively early, Freud gained the insight that the expression of instinctual need was regulated by the society's moral standards—often, but in no simple sense always, in conflict with instinctual needs—and that these standards were *introjected* into the personality itself, becoming components of its structure. The final form of this conception crystallized about the famous idea of the superego. Later this basic mode of conceptualization was extended to

This chapter is based on: Leydesdorff (2008).

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_9

> the social environment, conceived of as an environment much in the Cartesian-Durkheimian sense. The famous "reality principle" came to focus on "object relations," which for Freud meant relations to other persons, especially the parents, considered as agents of socialization. But these human objects were not only "adapted to" in the sense true for physical objects; they were also introjected—or, as we now usually say, internalized—to form part of the personality structure, particularly of the ego, in Freud's sense. (p. 432).

Why had Freud himself become reluctant to investigate the social at the above-individual level. Parsons (1952) formulated a begin of an answer to this question, as follows:

> The inescapable conclusion is that not only moral standards, but all the components of the common culture are internalized as part of the personality structure. Moral standards, indeed, cannot in this respect be dissociated from the content of the orientation patterns which they regulate; as I have pointed out, the content of both cathectic-attitudes and cognitive-status definitions have cultural, hence normative significance. This content is cultural and learned. (p. 23)

Parsons saw a possibility to relate Freud's concept of internalization to central tenets of American pragmatism. "Society," as Cooley (1902) argued, exists inside the individual in the form of language and thoughts. Action is then based on reflexive selections among options. On this basis, Parsons (1951, p. 94) formulated the concept of double contingency as the cornerstone of social order.

"Double contingency" means that each of us (*Ego*) expects another human being (*Alter*) to entertain expectations as we entertain them ourselves (Elmer 1995; Vanderstraeten 2002). A second contingency among expectations comes on top of the first contingency of empirical processes in the physical and biological domains. In this model, both consciousness and communication develop in substantive and reflexive layers in parallel. The communicative structures are double-layered: they are both actions and pervade actions to various extents. However, the relations between the two contingencies are asymmetrical. The first contingency (*res extensa*) is internalized in the second (*res cogitans*); the second leaves traces (e.g., cultural artefacts at the social level and memory traces at the individual level) in the first.

9.1 "Double Contingency" and Inter-human Interactions

"Double contingency"can elegantly be specified in terms of the theory of anticipatory systems (using Eq. 8.8 in Chap. 8; cf. Dubois 2000, 2003) as follows:

$$x_t = ax_{t+1}(1 - x_{t+1}); \quad 0 \geq x > 1 \tag{9.1}$$

In words: *Ego* (x) operates in the present (as x_t) on the basis of an expectation of her own next state (x_{t+1}) and the anticipated next state of *Alter* $(1 - x)_{t+1}$. Note that the expectation of *Alter* $(1 - x)_{t+1}$ is here defined in terms of *Ego*'s own expectations about *non-Ego*; that is, $(1 - x)$. The expectations constructed in one's mind about oneself and *Alter* precede possible *communication* between *Ego*'s and *Alter*'s expectations about each other. *Alter* is processed in terms of awareness (Husserl, 1931) without necessarily implying externalization into a communication (Nonaka & Takeuchi, 1995).

Not incidentally, Husserl added the word "Cartesian" to the title of his *Cartesian Meditations.* In Descartes' philosophy, *Alter* of the contingent *Ego* is a Transcendency ("God"). *Ego* knows herself to be fallible and uncertain, but *Alter* is Perfect and Infallible from this perspective. In the (Christian) cosmology, God "is" beyond any doubt because absence would be incomplete. Descartes himself thus constructed an ontological proof of God's existence.

More than 150 years later, Kant (1787: B620–B630) refuted Descartes' inference. He concluded that one can remain agnostic about the existence of God. However, one cannot remain indifferent about the secularized Other. The relation to contingent others is discussed by Kant (1788) in the *Critiqueof Practical Reason* which follows upon the *Critique of Pure Reason.* Unlike *Ego*'s relation to God, its relations with others are empirical.

How can relations in the second contingency be analyzed? The specification of relations among expectations generates empty boxes to be potentially filled by observations—in other words, redundancy. Hesitant about the possibility to study these empty boxes empirically, Ulanowicz (2014) proposed calling them "apophatic": a biologist has no instrument to measure or theorize empty boxes which do not "exist." Can one, alternatively, perhaps specify what they are *not* (Bateson 1934), and thus specify ranges of possible expectations?

Double contingency provides a micro-foundation of the social. The expectation of *Alter* precedes the interaction, but cannot be reduced to individual action. Parsons (1968) concluded that society therefore can be considered as a category *sui generis* (Parsons, 1968). Luhmann (1977, at p. 70) added to Parsons' definition that "double contingency" can also be considered as the auto-catalyst of social processes between reflexive individuals. Furthermore, Luhmann added that reflexive relations are possible not only among human beings, but also among the codes of the communications (1995, pp. 105f.; cf. Künzler 1989; Strydom 1999). In another, but similar formulation, Giddens (1979) denoted a "double hermeneutics" between the analyst's and the participant's level of action and accounting. (The participant and the analyst can be the same person embedded in different exchanges and discourses.) Each perspective may lead to new horizons.

In such a complex dynamic, the algorithmic approach—using simulations—can be helpful (Hanneman 1988). Simulations require less ambiguous and more parsimonious definitions. The time subscripts allow us to follow the developments when the referent is changing with the description. Simulations can serve the analysis by pointing to the unexpected or unintended consequences of interactions among subroutines (Hedström 2005).

9.2 Simulations of the Second Contingency

In this chapter, I elaborate on interaction, organization, and the self-organization of meaning using the set of incursive and hyper-incursive equations developed in Chap. 8. Two further equations will be derived which can be used to operationalize “reflection” and “identity,” respectively. As in the case of “double contingency,” these two hyper-incursive mechanisms can be expected to operate “genotypically”; that is, as evolutionary dynamics without reference to a specific and historical state.

1. Eq. 9.1 (above) provided us with a model for double contingency. Double contingency in mutual expectations precedes interaction. The term $(1 - x_{t+1})$ in Eq. 9.1 models a selection of *Ego*’s expectations of *Alter* as non-*Ego*.
2. Interactions imply a historical instantiation. However, one can expect each *Alter* (y) to entertain as another *Ego* an analogous selection term $(1 - y_{t+1})$. The selection terms can operate upon each other and thus lead to the quadratic Eq. 9.2:

$$x_t = b(1 - x_{t+1})(1 - y_{t+1}) \tag{9.2}$$

   Equation 9.2 does not contain any reference to a previous state of the system itself (x_{t-1}). In this model, only *expectations* are operating selectively upon each other. Unlike double contingency, however, this equation models the interactions between *Ego*’s and *Alter*’s expectations.
3. Eq. 9.2 can be extended to more complex configurations by adding a third selection environment. One can add this third (or each next) term as either a hyper-incursive or incursive routine, and thus obtain the following *two* equations:

$$x_t = c(1 - x_{t+1})(1 - x_{t+1})(1 - x_{t+1}) \tag{9.3}$$

$$x_t = d(1 - x_{t+1})(1 - x_{t+1})(1 - x_t) \tag{9.4}$$

Equation 9.3 is a cubic equation which models a “triple contingency” of expectations. The third contingency closes the triad operationally. As argued in Chap. 5, triadic closure is the basis of the system’s morphogenesis. All higher-order configurations (quadruplets, etc.) can be decomposed into triads. Equation 9.3 is thus constitutive of the social system of supra-individual expectations. As shown above, the interactions among three selection mechanisms can generate redundancies.

In a paper entitled “Triple Contingency: The theoretical problem of the public in communication societies,” Strydom (1999) argued that “the increasing differentiation and organization of communication processes eventuated in the recognition of the epistemic authority of the public, which in turn compels us to conceptualize a new level of contingency. A first step is thus taken to capture the role of the public as a code in communication societies. The code mediates and shapes a “triple contingency.” According to Strydom, this differentiation of “public” versus “private” as codes in the communication generated modernity. Note that the public is not considered as a sphere (Habermas 1974) or an audience (Latour 1988), but as a code in the communication.

One can derive that Eq. 9.3 has one real and two complex roots. Since a system cannot continue its operations with the complex solutions, Eq. 9.3 would evolve increasingly into a single value ("eigenvalue") for each value of the parameter *C*. The parameter *C* can thus be considered as a representation of the code of the communication. Horizontal differentiation of this code can then be captured by writing lower-case c_1, c_2, c_3, …, c_n, etc. I elaborate this below.

Note that if only a single fixed code-value *C* would operate, the routine would self-organize "closure" into this value of *C*. In a differentiated system of communications, however, a number of values for the codes (c_1, c_2, c_3, …. c_n) can be expected to disturb tendencies to such operational closure. As argued above in Chap. 5, three (or more) contingencies operating selectively upon one another can shape a fractal manifold containing trade-offs between tendencies to self-organizing closure and organizational interruptions (Ivanova & Leydesdorff, 2015).

4. Eq. 9.4 differs from Eq. 9.3 in terms of the time subscript in the right-most factor. Equation 9.4 can be used to model a specific organization of meanings as an instantiation in the present. The reference to the present in the third factor makes this model historical, whereas the self-organizing system modeled in Eq. 9.3 operates hyper-incursively, in terms of interactions among expectations about possible future states. An instantiation, however, requires (provisional) integration and organization at specific moments of time. In Eq. 9.4, the interaction among expectations is instantiated as a specific configuration at time $t = \mathrm{t}$.

In summary, Eqs. 9.3 and 9.4 model algorithmically the trade-off between the evolutionary and historical perspectives in Triple-Helix relations as discussed in terms of redundancy and information generation in Chap. 5 above.

5. Two more hyper-incursive equations follow as possible members of this family of equations. Analogously to Eq. 9.1, one can formulate as follows:

$$x_t = ax_t(1 - x_{t+1}) \tag{9.5}$$

$$x_t = ax_{t+1}(1 - x_t) \tag{9.6}$$

Equation 9.5 evolves into: $x = (a - 1)/a$ (see Eq. 8.11c on p. 157 for the derivation of this equation as a steady state). It follows that x is a constant for all values of a. I submit, as an interpretation, that this evolution towards a constant value of the system (x) through anticipation can be considered as the self-reference of an expected "identity."

In the second contingency, identity is based not on the history of previous states, but on entertaining the expectation of continuity of the "self." The identity in the network "me" can be distinguished from the "I" (Mead, 1934, at pp. 26f.). Like individuals, organizations can be expected to develop a symbolic identity in the second contingency.

Equation 9.6 can be developed as follows:

$$x_t = ax_{t+1}(1 - x_t) \tag{9.6a}$$

$$ax_{t+1} = x_t/(1 - x_t) \tag{9.6b}$$

$$x_{t+1} = (1/a)[x_t/(1 - x_t)] \tag{9.6c}$$

This model can be simulated (Fig. 9.1): when $x_t > [a/(1 + a)]$, a pulse is generated which first overshoots the value of one (in a virtual domain of possible expectations), but then generates a negative value. This negative value leads to a mirror image of a representation at a specific moment in time, and can thus be considered as a reflection. Reflections enable us to bounce a communication between communication (sub)systems via consciousness (Luhmann, 1988, 1991).

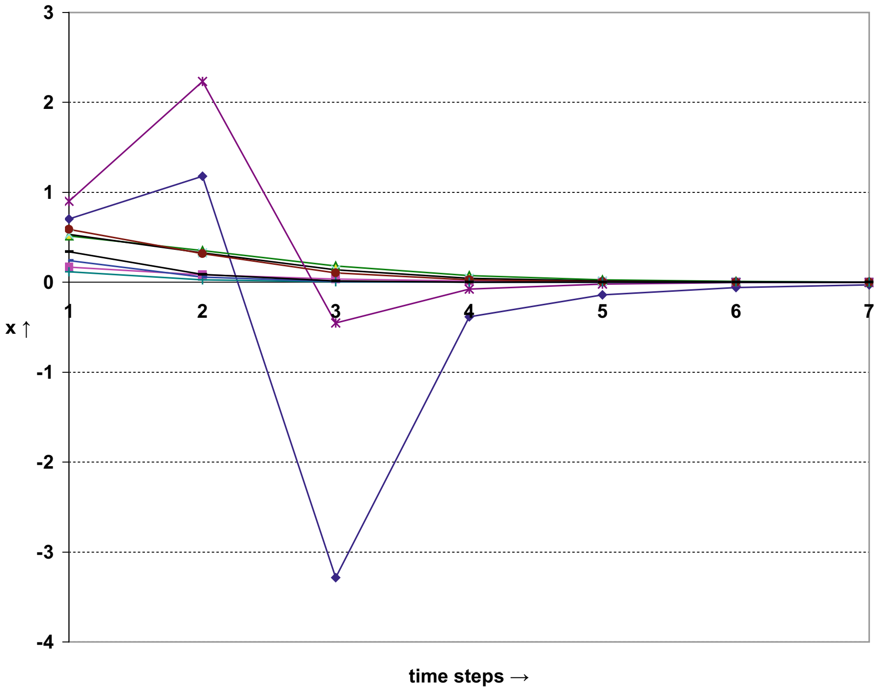

Fig. 9.1 Simulation of Eq. 9.6: the value of x at $t = 1$ is drawn randomly ($a = 4$). (For $a = 4$, the pulse is generated for values of $x_t > 0.8$.)

Dubois (*personal communication*, 16 July 2008)[1] noted that Eq. 9.6 can be derived as the *time inverse* of the incursive (Pearl-Verhulst) equation [$x_t = ax_{t-1}\,(1 - x_t)$]. In Leydesdorff and Dubois (2004), we showed that the sole assumption of social relatedness as a variable among groups of agents provides a sufficient basis for deriving the logistic map as a first-order approximation of the social system. Secondly, I derived the anticipatory formulation of this equation for anticipation in both the interaction term and in the aggregation among subgroups. I will not repeat this argument, but instead follow a more intuitively accessible reasoning based on the *perturbed recursion model* in order first to derive a generalization of the family of logistic equations under discussion here.

9.3 Perturbed Recursions and Incursions

Andersen (2002, at pp. 170 ff.) discussed the logistic equation as a special case of his so-called *perturbed recursion model.* The model can be depicted as follows:

In Fig. 9.2, F is a recursive function that transforms state S_{t-1} into a new state S_t, using a set of parameters $P = p_1, \ldots, p_n$ modelling disturbances. In formula format:

$$S_t = F(S_{t-1}, P) \tag{9.7}$$

Baecker (2002, at pp. 86 ff.) noted that the function F can be considered as the operator of the communication system (S) in Luhmann's model; he used the word "eigen-function" for this recursive loop (cf. von Foerster, 1960). However, more than a single such eigenfunction (i.e., code) can be expected in a differentiated system. Each code structures variation differently. In other words, the recursive selections can be expected to codify different meanings along the main axes of the network.

[1] Dubois added to this communication the following derivation as evidence:

$$x_{t+1} = ax_t(1 - x_{t+1}) \tag{n9.6a}$$

is equal to the following equation for dt = 1:

$$x_{t+dt} = ax_t(1 - x_{t+dt}) \tag{n9.6b}$$

The time reverse of this equation is obtained for dt → –dt, with the negative discrete time –dt:

$$x_{t-dt} = ax_t(1 - x_{t-dt}) \tag{n9.6c}$$

or, with –dt = –1:

$$x_{t-1} = ax_t(1 - x_{t-1}) \tag{n9.6d}$$

So with a time translation of t → t + 1 for the whole equation, one obtains:

$$x_t = ax_{t+1}(1 - x_t) \tag{9.6}$$

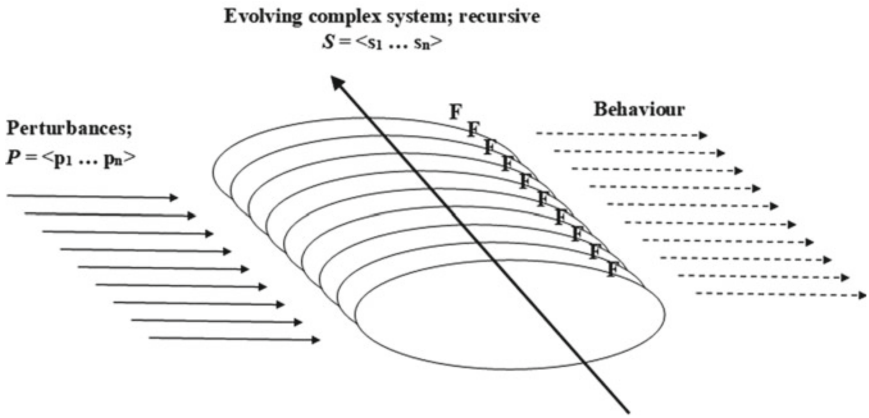

Fig. 9.2 The perturbed recursion model (Adapted from Andersen, 2002, at p. 170 and Leydesdorff, 2001, p. 102.)

Following Baecker (2002), one can add a subscript c (of *coding*) to the operation and use the E of environment as the source of disturbances; one can then rewrite Eq. 9.7 as follows:

$$S_t = F_c(S_{t-1}, E) \tag{9.8}$$

When differentiation prevails, the environment E of each subsystem is composed of the other subsystems, with a remaining term ε as representation of the residual (that is, as yet undifferentiated) environment. Using the lower-case f and s for the *sub*systems, one can then rewrite Eq. 9.8 as follows:

$$s_{i,t} = f_i\left(s_{i,t-1}, s_{j,t-1}, s_{k,t-1}, s_{l,t-1}, \ldots, \varepsilon\right) \tag{9.9}$$

The windowing of the subsystems upon each other is based on horizontal differentiations. Each subsystem (i) codes (using f_i) its own previous development and the development which it finds in its (selection of) relevant environments. However, meaning can be provided to this development by the other (selecting) subsystems from the perspective of hindsight. This adds a vertical differentiation between historical recursion and reflexive incursion, as follows:

$$s_{i,t} = f_i\left(s_{i,t-1}, s_{j,t}, s_{k,t}, s_{l,t}, \ldots, \varepsilon\right) \tag{9.10}$$

The vertical differentiation between recursion and incursion is based on the dynamics of meaning and codification; the horizontal one is based on functional differentiation. The state of a specific subsystem ($s_{i,t}$) can now be dependent both on the previous state of this subsystem ($s_{i,t-1}$), and on the previous and the current states of the other subsystems. Systems and subsystems continue to operate historically (Eq. 9.9) and to provide meanings to one another (Eq. 9.10). In discrete time, however, the recursive and incursive operations are not *ex ante* synchronized and can therefore be expected to differ with a Δt at each interface. One can expect the routines to update one another.

At all these interfaces one can thus expect asynchronicities. Using these asynchronicities from the backward perspective of incursion, meanings can be propelled both horizontally and vertically. The incursions can be formalized in a manner analogous to that of the incursive formulation of the logistic equation provided in Eq. 9.5, but multiplied by references to the selection requirements of other subsystems *j*. In formula format:

$$x_{i,t} = ax_{i,t-1}\prod_{j=1}^{n}(1 - x_{j,t}) \cdot \varepsilon \tag{9.11}$$

In Eq. 9.11, *n* represents the theoretically expected number of subsystems. While this number was analytically restricted in Parsons's structural-functionalism—using his so-called *four*-function paradigm—this number can vary in Luhmann's (1997) theory with the historical development of the media of communication and their symbolic generalization into codes (Distin, 2010; cf. Merton, 1938, 1948). As noted, Simon (1973) conjectured that there may be an alphabet of possible codes in interhuman communications.

On the basis of this general model one can consider, for example, the incursive and recursive version of the Triple-Helix model as special cases. Incursively, three relevant selection environments operate on the development of the resulting arrangements, as follows:

$$x_{it} = ax_{j,t-1}\left(1 - x_{j,t}\right)\left(1 - x_{k,t}\right)\left(1 - x_{l,t}\right) \cdot \varepsilon \tag{9.12}$$

In other words, the evolutionary TH model is incursive; the institutional one focuses on historical recursions, such as trajectories and historical transitions following the arrow of time.

9.4 Transversal and Longitudinal Propagation of Meanings

Because the differentiation can lead to asynchronicities and therefore ΔT-values specific for each interface, some models can be expected to advance more rapidly than others. For example, the market can be expected to operate faster than a research process; the difference in speed may lead to delays at each interface. Interface management in a knowledge-based corporation is meant to align time horizons: "whichtechnology can be introduced on the market at which moment in the future?" The models are synchronized at $t = \mathrm{t}$ by decisions about future options and historical constraints at interfaces. This synchronization is based on an expected time difference at interface.

While vertical differentiation—in terms of interactions, organization, and self-organization—was already available in pre-modern societies (High Cultures, as in the Middle Ages), updates over time provide *modern* societies with another, that is, second mechanism for organizing reflexive communications in an anticipatory mode. The horizontal differentiation is subordinate to the vertical in pre-modern societies; in modern societies, however, the horizontal differentiation is coded, and this coding provides another degree of freedom. The acceleration by organization in a High Culture is replaced by one based on trade-offs between stabilizing organization and globalizing self-organization in the communications.

Each interface—both in the horizontal and vertical dimensions—can contain a time difference Δt. The two incursive terms in the corresponding equations can also operate upon each other. This may lead to hyper-incursion. Hyperincursion at the regime level cannot be historically manifest, but the feedback of hyperincursion on the incursion can leave a footprint. The hyper-incursive regime and the historical trajectory co-evolve in terms of providing (potentially different—local and global) meanings to the events.

Each incursive equation contains a reference to the historical dynamics and another to the evolutionary one. Interactions between vertical and horizontals incursions can generate a quadratic incursion or, in other words, next-order hyper-incursion (Fig. 9.3). Since a hyper-incursive system operates against the arrow of time, *one can expect this routine to generate redundancy instead of information*, since the arrow of time is inverted.

Incursions contain both a reference to the current and the previous state. When historical incursions interact *recursively,* a variation (entropy) is generated. However,

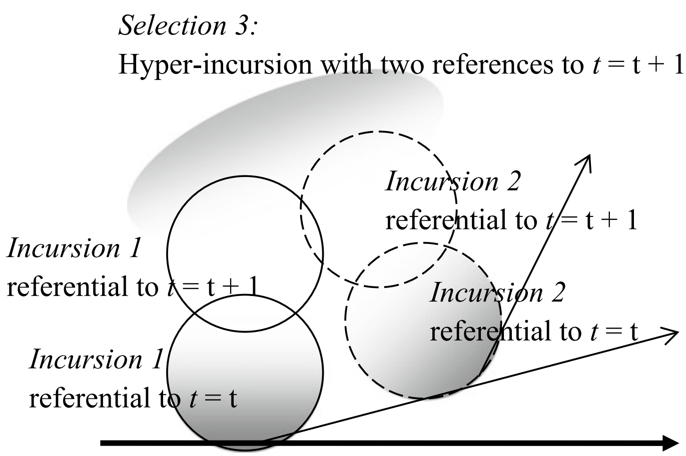

Fig. 9.3 Hyper-incursivity at the interface emerging at $t = \mathrm{t} + 1$ between two incursive routines. *Source* Laydesdorff (2009, p. 21)

when two different incursions are interfaced *incursively*, hyper-incursion can be expected. Each incursion generates both information and meaning, and thus becomes organized both historically (with reference to t = t) and reflexively (with reference to t = (t + Δt)). However, a hyper-incursive equation cannot be organized and materialized at t = t because it only contains references to future states [at t = (t + Δt)]. The resulting hyper-incursion builds on the interactions between references to present or future states in two (or more) underlying incursions. Since this hyper-incursion no longer contains a reference to historical time, *an incursive subdynamic is additionally needed for making the (interactions among) expectations historically relevant* (Eq. 9.4).

Luhmann (2000) hypothesized that self-organization among the differently coded fluxes of communication can be brought under organizational control by decisions. This formulation may sound action-based, but this inference would be too fast. The third contingency can be provided by another code operating incursively; for example, by taking decisions.

9.5 Decisions and Decision Rules

In Chap. 8, the hyper-incursive formulation of the logistic equation (Eq. 8.8) was elaborated into:

$$x_{t+1} = 1/2 \pm 1/2\sqrt{[1 - (4/a)x_t]} \tag{9.13}$$

Depending on the plus or the minus sign in the equation, two future states are generated at each time step. Since this formula is iterative, the number of future states doubles with each next time step. After N time steps, 2^N future states would be possible. For $N = 10$, the number of options is more than one thousand.

Dubois (2003, at p. 115) proposed a decision function u(t) for making a choice between one of two options:

$$u(\mathrm{t}) = 2\, d(\mathrm{t}) - 1 \tag{9.14}$$

It follows that $u = +1$ for the decision $d = 1$ (true), and $u = -1$ for the decision $d = 0$ (false). In a social system, however, more choices than these two extremes may be possible. Social systems operate in a distributed mode with a probability distribution of preferences. In distributed systems, decisions can be organized and codified into decision rules (Bertsekas & Tsitsiklis, 1989). Luhmann (2000) argued that organizations can be considered as the results of codifications in the dynamics of decision-making. The stabilization of decisions in rules, for example, can generate an institutional layer of the social system in which decision-making can develop routines and thus follow trajectories.

Note that the decisions (at the individual level) or decision rules (at the organizational level) do not determine the hyper-incursive dynamics of the self-organizing regime, but only guide these dynamics historically as instantiations along trajectories. *Autopoiesis* controls its own operation (Varela, 1979); decisions do not have to be taken at each step. The distribution of decisions and non-decisions changes the historical conditions by inducing reorganization. Without this historical opportunity to anchor the routines, the interfacing of expectations would remain in an elusive realm of expectations operating on expectations.

9.6 Inter-human Coordination in the Second Contingency

I distinguished three coordination mechanisms above: interaction, organization, and self-organization. I will now discuss these three equations in more detail.

9.6.1 Interactions

As noted, anticipatory interaction can be modeled based on the mutual selections of *Ego*'s and *Alter*'s expectations of each other, leading to Eq. 9.2 (above):

$$x_t = b(1 - x_{t+1})(1 - x_{t+1}) \tag{9.2}$$

Equation 9.2 does not include a term referring to previous states; only expectations are operating selectively upon each other. Unlike "double contingency," interaction is a social dynamic and no longer an individual (mental) one. (I use "*b*" instead of "*a*" for the parameter in order to highlight this difference.)

Equation 9.2. can be elaborated as follows:

$$x_t = b(1 - x_{t+1})(1 - x_{t+1}) \tag{9.2}$$

$$x_t/b = 1 - 2x_{t+1} + x_{t+1}^2 \tag{9.2a}$$

$$x_{t+1}^2 - 2x_{t+1} + (1 - x_t/b) = 0 \tag{9.2b}$$

$$x_{t+1} = 1 \pm \sqrt{x_t/b} \tag{9.2c}$$

This interaction system can be simulated as the following oscillation (Fig. 9.4):

The interactions oscillate in Fig. 9.3 around the value of one. The system reaches its largest fluctuations (between zero and two) for $b = 2$.[2] On each side, the interaction

[2]The system vanishes for $b < 2$ because the term under the root can then become larger than one, and therefore $x_{t+1} < 0$ in case of the (possibly) random choice of the minus sign in Eq. 9.2c.

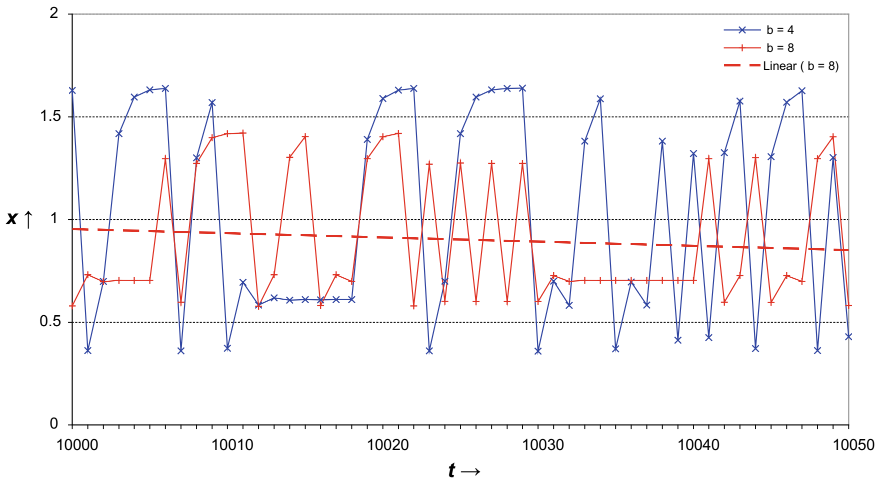

Fig. 9.4 Simulation of hyper-incursive interactions

can be continued for a number of iterations before the alternate resumes its operation. I modeled this here (in Excel) by using a random number to choose the plus or minus sign in the evaluation of Eq. 9.2c. The (potentially random) variation warrants the continuation of the interaction. In other words, these hyper-incursive interactions serve to generate variation in the *cogitatum*, such as, among other things, the communication of newness supporting and inducing the *morphogenesis* of organization and self-organization (Achterberg & Vriens, 2009).

9.6.2 Organization versus Self-organization

Whereas two selection environments are needed for interactions, one can add either a hyper-incursive or an incursive subroutine to Eq. 9.2 (above) for modelling organization and self-organization. At each addition, one obtains two possible equations:

$$x_t = c(1 - x_{t+1})(1 - x_{t+1})(1 - x_{t+1}) \tag{9.3}$$

$$x_t = d(1 - x_{t+1})(1 - x_{t+1})(1 - x_t) \tag{9.4}$$

As noted, Eq. 9.4 differs from Eq. 9.3 in the time subscript of x in the third factor. The reference to the present in this third factor bends the system back to its present state and thus makes this model historical, whereas the self-organizing system of Eq. 9.3 operates hyper-incursively. In the case of Eq. 9.4, however, the interaction among expectations can be instantiated by a specific historical organization at $t = \mathrm{t}$.

The roots of Eq. 9.4 can be derived (analogously to Eq. 9.2) as follows:

$$x_t = d(1 - x_{t+1})(1 - x_{t+1})(1 - x_t) \tag{9.4}$$

$$x_{t+1}^2 - 2x_{t+1} + 1 - x_t/[d(1 - x_t)] = 0 \tag{9.4a}$$

$$x_{t+1} = 1 \pm \sqrt{x_t/d(1 - x_t)} \tag{9.4b}$$

Simulation of this system shows that the organization of communications vanishes after a variable number of steps for all values of the parameter d (Fig. 9.5).

Figure 9.5 shows this development using Excel for the simulations. However, Excel depicts the historical end of the organization of communications as zeros, while these zeros may be based on values of $x > 1$ which lead to a negative value of the denominator of the term under the root in Eq. 9.6b. In this case, the root of this equation is complex and can no longer be evaluated. In other words, the organization does not disappear in the sense of "dying," but its historical development can be insufficiently complex to instantiate self-organization among the fluxes of communication. Note that the self-organizing dynamic does not have to be instantiated at each step.

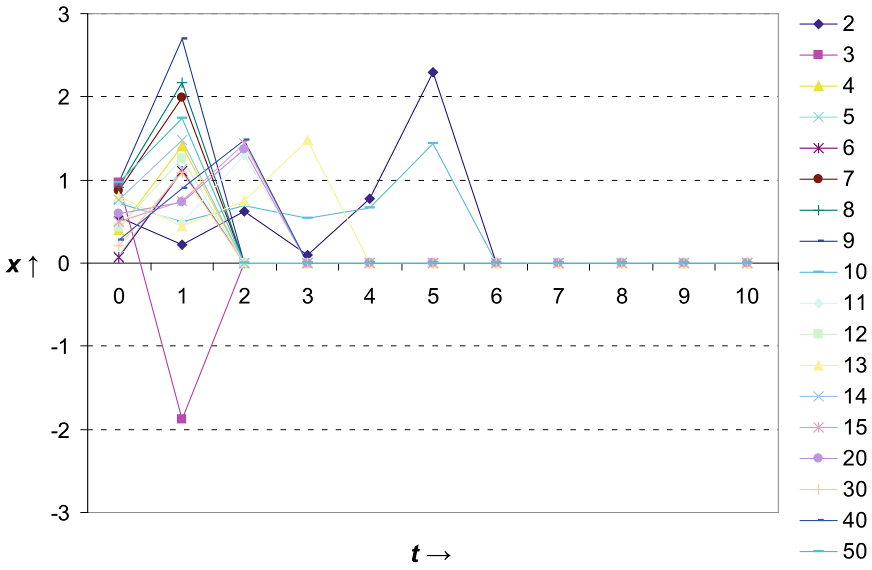

Fig. 9.5 *Organization* of interactions for different values of the parameter d

9.6.3 *Self-organization*

Equation 9.3 can be developed as follows:

$$x_t = b(1 - x_{t+1})(1 - x_{t+1})(1 - x_{t+1}) \tag{9.3}$$

$$\frac{x_t}{b} = (1 - x_{t+1})^3 \tag{9.3a}$$

$$\left(\frac{x_t}{b}\right)^{1/3} = (1 - x_{t+1}) \tag{9.3b}$$

$$x_{t+1} = 1 - \left(\frac{x_t}{b}\right)^{1/3} \tag{9.3c}$$

Equation 9.3 has three roots of which two are complex (Mike Burke, personal communication, 10 October 2008). The real solution of Eq. 9.3c can be denoted as:

$$x_{t+1} = 1 - \sqrt[3]{\frac{x_t}{b}} \tag{9.18a}$$

and the two complex roots are:

$$x_{t+1} = 1 - \sqrt[3]{\frac{x_t}{c}}\left(\frac{-1 \pm i\sqrt{3}}{2}\right) \tag{9.18b}$$

Since the further operation cannot evaluate the complex solutions in a next time-step, the system in this case can be expected to continue with the real solution. This leads to a single and stable solution for each value of *b*. At the level of subsystems, these relative constants can be considered as the codes of the communication.

9.7 Discussion and Conclusions

In this chapter, I have related Dubois' incursive and hyper-incursive equations modeling anticipatory systems (Dubois, 1998, 2000, 2003) to Luhmann's (1995 [1984]) social systems theory. I used both theories heuristically; the construction of a relation between Luhmann's theory and Dubois' computations required a translation of the one theory into the other, and therefore minor changes.

Luhmann (1984, p. 605; 1995, pp. 446f.) noted that "[s]elf-referential, autopoietic reproduction would not be possible without an anticipatory recursivity." However, he did not specify the anticipatory mechanisms. In his final and summarizing book, Luhmann (1997) returned to this issue and provided two references to Rosen's (1984) book entitled *Anticipatory Systems*. However, these references were framed in a biological context ([1997, pp. 206 and 820] 2012, Vol. 1, p. 123 and Vol. 2, p. 137). Luhmann added (at p. 821) that in the domain of meaningful processing of information one cannot avoid a reference to the present when defining the relation between past and future. This time-dimension with the present at its origin is elaborated as a degree of freedom in the theory and computation of anticipatory systems. In other contexts, Luhmann (e.g., 1990a, b, p. 98, n.10) developed a semantics for the discussion of "time."

Relevant for this study is furthermore his distinction between social differentiation and systems differentiation (Luhmann, 1997)which accords to a high degree with Simon's (1973) distinction of horizontal versus vertical differentiation. Social differentiation is possible in the communication because communications can be coded in a variety of ways in language, and codes of communication can be generalized symbolically (Distin, 2010).

The different subsystems operate in parallel, but not necessarily synchronously. As Luhmann (1984, at p. 128) formulated: "*Social* differentiation serves as an uncoupling mechanism. It divides the time-orientations in the different systems and therefore accepts that things can be urgent in one system, while another system can take its time" (italics added, L.). *Systems* differentiation, however, organizes the social system at different levels. This differentiation of micro-level interactions, meso-level organization, and macro-level self-organization in the processing of meaning could be elaborated in this chapter in terms of six equations.

Furthermore, the model of recursive perturbations could be used to consider the various formulations of the logistic map as a family of equations. The spanning of the time dimension enabled me to reformulate some "paradoxes" in Luhmann's social-systems theory as questions amenable to empirical research about trade-offs: is positive entropy or redundancy (negative entropy) generated by self-organization prevailing? The duality of structure in social systems (Giddens, 1979, 1984) could thus be considered as a consequence of the difference between the forward and backward arrows represented as time-subscripts of Eqs. 9.3 and 9.4 (above), respectively.

Unlike interaction and self-organization, the *organization* of meaning is historically constrained; specific organizational forms can be replaced with other organizations in relation to (i) the ongoing interactions—generating variation from below—and (ii) the hyper-incursive self-organization of the communication into codes at a relatively global level (Eq. 9.4). Luhmann (1995, at p. 600n.[1984. at p. 551n.]) expressed the relationship among the three coordination mechanisms of expectations as follows:

> […] in all social relations, under all circumstances a difference between society and interaction is unavoidable, but not all societies are acquainted with organized social systems. We therefore exclude organizations, but only from treatment on the level of a general theory of social systems. On the next level, that is, of concretizing the theory, one would perhaps need to distinguish between societal systems, organizational systems, and interaction systems and develop separate theories for each type because these three separate ways of forming systems (i.e., dealing with doubling contingency) cannot be reduced to one another.

Organization structures communication at specific moments of time by using incursion and thus remains rooted in history. As against double contingency as the micro-foundamental operation at the level of the mind participating in communication, organizations can entertain different expectations synchronously because organizations are interfacing expectations (in the first two terms of Eq. 9.4) and looping into the present state x_t (in the third term of Eq. 9.4). From this perspective, the individual *cogitans* might be considered as a minimal form of organization among expectations. Agents can take decisions on the basis of trade-offs between differently coded considerations.

Organization in the communication of meaning is historical and can therefore be expected to develop along a trajectory for a number of time-steps. However, without further variation as input from below or codification from above, any specific organization of communications can be expected to erode in due time because the construction remains a superstructure on an underlying *information* flow generating uncertainty (Schattschneider, 1975). The organization of communication provided us with a basis for measurement. Meaning is historically instantiated in organizations; the imprint of self-organization at the organizational level can be measured as mutual *redundancy* (Chaps. 4–6 above). The suggested calculus of redundancy would enable us to test theoretical expectations empirically—and thus to obtain counter-intuitive results—whereas the calculus of anticipations in terms of incursions and hyper-incursions can be elaborated in terms of simulations which may enrich the intuitive understanding.

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Chapter 10
Cultural and Biological Evolution

Although there is no necessary relation between “big data” and “monism”—the program of reducing cultural and mental processes to computational and biological principles—both these programs reject a dualism between *res extensa* and *res cogitans*. Opposing this philosophy of science, I have argued in the above chapter that a second contingency of possible relations and expectations feeds back on the manifest relations. This second contingency cannot be studied from a natural-science or life-sciences perspective, but is the proper domain of the social sciences, where the focus is on what things *mean* as different from what they *are*. Next-order selection mechanisms can take evolutionary control. The complexity of the communication evolves against the arrow of time in terms of interacting codes, which generate redundancies and therefore new options. As human beings, we can follow the potentially unintended consequences of the communication dynamics reflexively. Both consciousness and communication are self-organizing and thus resilient against steering.

10.1 Monism versus Dualism

In his book *Descartes' Error*, Antonio Damasio (1994) made an argument for monism. In this author's opinion, Descartes' statement *Cogito ergo sum* (“I think therefore I am”) has been a major source of error in Western philosophy. Damasio formulated as follows: Taken literally, the statement illustrates precisely the opposite of what I believe to be true about the origins of mind and about the relation between mind and body” (p. 245).

Although there is no necessary relation between “big data” and “monism”—the program of reducing cultural and mental processes to computational and biological principles—both these programs reject a Cartesian dualism between *res extensa* and *res cogitans*. In a paper entitled “The End of Theory,” Anderson (2008), for example, formulated the program of “big data” as follows:

This chapter is partly based on: Leydesdorff, L., & Hoegl, F. (2020). The Evolutionary Dynamics of Expectations: Interactions among Codes in Inter-Human Communications. Biosystems, 198, 104236. https://doi.org/10.1016/j.biosystems.2020.104236

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_10

> This is a world where massive amounts of data and applied mathematics replace every other tool that might be brought to bear. Out with every theory of human behavior, from linguistics to sociology. Forget taxonomy, ontology, and psychology. Who knows why people do what they do? The point is they do it, and we can track and measure it with unprecedented fidelity. With enough data, the numbers speak for themselves.

In a similar spirit—but with another methodology—Ramstead, Badcock, and Friston (2017), for example, presented "a hierarchical multiscale free energy formulation […] that offers the sciences of life, mind, behaviour and society with a principled, computationally tractable guide to discovery" (p. 13). In this ontology, the system levels self-organize into a hierarchy. *Homo sapiens sapiens* is then placed at the top of this hierarchy as "the world's most complex living system." Humans are said to generate "(epi)genetically-specified expectations that have been shaped by selection to guide action-perception cycles toward adaptive or unsurprising states" (p. 12; cf. Leydesdorff, 2018).

These various authors have in common that their program is to *reduce* cultural phenomena to biological and computational principles (Porankiewicz-Żukowska, 2017). My argument in this study has been that the exchanges of and interactions among expectations are *not* epi-genetic, but shape a cultural layer with a dynamic operating as a feedback on the (human) carriers of this cultural evolution. Unlike biological evolution which follows the entropy flow, codes in the communication can generate redundancies; for example, by refining distinctions. In this model, however, humans are not at the top of "the" hierarchy, but can function as infra-reflexive linchpins among hierarchies and heterarchies of variably codified communications. Not *Homo sapiens sapiens* but the complexity of the communication among humans is further evolving in terms of new recombinations and differentiations among codes.

10.1.1 Descartes' Error

In my opinion, Damasio's rejection of *Cogito ergo sum* in favor of monism is based on a misreading of Descartes (cf. Gluck, 2007). This misreading, however, is more wide-spread: the sociologist Schutz (1975, at p. 82), for example, criticized Husserl's ([1929] 1960) *Cartesian Meditations* in a similar vein, as follows:

> […] As a result of these considerations we must conclude that Husserl's attempt to account for the constitution of transcen-dental intersubjectivity in terms of operations of the consciousness of the transcendental ego has not succeeded. […] As long as man is born of woman, intersubjectivity and the we-relationship will be the foundation for all other categories of human existence. The possibility of reflection on the self, discovery of the ego, capacity for performing any epoch, and the possibility of all com-munication and of establishing a communicative surrounding world as well, are founded on the primal experience of the we-relationship.

Schutz (1975, p. 72) opposed Husserl's position that all communication is constituted by communication. Schutz argued that the "we-relationship" remains fundamental. In other words, one can consider Schutz's (micro-)foundation as existential—grounded in relations—whereas Husserl grounded intentionality in interpersonal expectations.

In my opinion, both Schutz and Damasio misread Descartes from a present-day perspective: the words are provided with empirical meanings that are different from their philosophical meanings at the time. Descartes did not wish to make an empirical inference about thinking and being, or the genesis of consciousness in the mother-child ("we"-)relationship. *Cogito ergo sum* is meant to be the formulation of a "first principle" in Descartes' philosophy. Although Damasio (1994) mentioned this alternative interpretation as possible (at p. 249), he did not elaborate on it.

Descartes (1637) specified *Cogito ergo sum* in *Discourse on Method* (Part 4), and formulated as a conclusion[1]:

> […] the mind by which I am what I am, is wholly distinct from the body, and is even more easily known than the latter, and is such that even if the latter were not, it would still continue to be all that it is."

The "mind by which I am what I am" is not an empirical subject of study, but a philosophical grounding which "is even more easily known" than the body, because the body can be an empirical object of study. *Cogito*, however, is not empirical; it belongs as a first principle to what the Greek philosophers characterized as "the mathematical." *Cogito ergo sum* is a statement with a status similar to "two plus two is four" (cf. Hoegl, 2003). The statement can be made on the basis of a priori reasoning. Heidegger ([1962], 1970, p. 70), for example, explained the text as follows:[2]

> The formula […] "*Cogito ergo sum*" suggests the misunderstanding that it is here a question of inference. That is not the case and cannot be so, because this conclusion would have to have as its major premise: *Id quod cogitat, est*—"that which thinks, exists." […] Descartes himself emphasizes that no inference is present. The *sum* is not a consequence of the thinking, but vice versa; it is the ground of thinking, the *fundamentum.* In the essence of positing lies the proposition: I posit. […] The I is the *subjectum* of the very first principle. Before Descartes everything present-at-hand for itself was a "subject"; but now the "I" becomes the special subject, that with regard to which all the remaining things first determine themselves as such. ([at p. 82], p. 69f.)

Descartes' ontological proof of the existence of God became unconvincing with the further development of the sciences, epistemology, and the precursors of the philosophy of science in the course of the eighteenth and nineteenth centuries. As noted in Chap. 9, Kant concluded that one can remain agnostic about the existence of God or a transcendental reality. However, one cannot remain indifferent in one's relations to others. The relation of *Ego* to other human beings is discussed by Kant (1788) in the *Critique of Practical Reason* from an ethical and moral perspective.

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[1] https://www.literatureproject.com/discourse-reason/discourse-reason_4.htm. I have used this translation with minor changes.

[2] On the moral issue of using Heidegger's writings, see, for example, Bernstein (1995, pp. 79–141).

10.2 The Secularization of Alter

Can the contingent *relations* with *Alter* as "another human being" offer an alternative foundation of *Ego*? Can "God" be replaced with "intersubjective intentionality"? By thus secularizing the transcendental relation to God into expectations of contingent relations with other human beings, the domain which transcends the individual becomes a *second contingency* in which human beings provide meanings to things and events.

As against the study of behavior in the first contingency, interactions of judgements and expectations in the second contingency are not directly observable. However, these second-order relations can be expected to leave observable effects in the first contingency, such as cultural artefacts. In the first contingency one can touch, feel, observe, and directly relate to other human beings. In the second, one provides meanings by *partaking* in the social (re)construction of meanings among humans.

Meanings can be expected to loop in cycles on top of the entropy flow. The two contingencies can operate in parallel or in an intermingled process; the repetition in the loops can be expected to generate redundancy, and thus span another domain. A number of authors from approximately 1900 onwards (Durkheim, Freud, and others) began to formulate theories about the social as a qualitatively different domain. The constitutive role of the *Other* in the shaping of the *I* was elaborated, for example, by the American pragmatists. George Herbert Mead (1934), for example, formulated as follows:

> If one is to speak of a transcendental "consciousness in general," if I, this singular, individual ego, cannot be the bearer of the nature-constituting understanding, must I not ask how I can have, beyond my individual self-consciousness, a general, a transcendental-intersubjective consciousness? The consciousness of intersubjectivity, then, must become a transcendental problem; but again, it is not apparent how it can become that except through an interrogation of myself, [one that appeals to] inner experience, i.e., in order to discover the manners of consciousness through which I attain and have others and a fellow mankind in general, and in order to understand the fact that I can distinguish, in myself, between myself and others and can confer upon them the sense of being "of my kind."

In my opinion, this second contingency of expectations is *the proper domain of the social sciences and humanities*. In parallel with investigating events in the natural and life-sciences, one can always ask "what do things mean?" Attempts to make this domain the subject of the natural and life sciences in the name of ideals such as "the unity of science," "monism," or a "grand synthesis" tend to reduce the social sciences to a relatively irrelevant commentary to the "real" world of science and "hard" scientific facts. On the basis of the philosophical a priori of "monism" and "big data," the social sciences would no longer be developed as theoretical research programs in their own right; our knowledge about the dynamics of expectations would then remain poorly developed. Accordingly, policy advice about the knowledge-based economy would be based on political economy instead of a model with requisite variety (Ashby, 1958).

10.3 Habermas' Knowledge Interests

The discussion about monism repeats in many respects the older one about positivism (e.g., Adorno et al. 1970; Popper, 1959 [1935]). As mentioned in Chap. 1, Habermas (1968b), for example, distinguished among *three* epistemologically different knowledge interests: (i) the *technological* one of the natural sciences, (ii) the historical-hermeneutical one of *understanding* in the humanities, and (iii) an *emancipatory* interest in social change on the basis of reflection and critique. According to Habermas, one would expect scholars working in these three domains to develop different criteria for "objectivity," namely: nomothetical, hermeneutic, and ideology-critical, respectively.

The Habermas-Luhmann discussion in the early 1970s made clear (at least to me) that the three epistemic domains of science were not yet properly specified by Habermas (1968a; 1971a and b). While the historical perspective is embedded and its method accordingly hermeneutic, the critical position is potentially *disruptive*. "Critical" refers to "crisis:" the crisis makes it necessary to revise.

The distinction between the second and third knowledge interests can also be framed in terms of historicism *versus* the commitment to value-freeness (e.g., Popper, 1967; Weber, 1917). Value-freeness serves the analysis of values because the analyst avoids an a priori commitment to the values of the subject(s) under study. This distancing does not imply a reduction to explaining behavior; "understanding" (*Verstehen*) can be methodologically secured by value-freeness. Without commitment to value-freeness, "understanding" tends to engagement with the normative and historical perspectives of the subjects under study, and thus to be subjective.

The third (emancipatory) interest is based on distancing oneself from the historical givens on the basis of reflection and reasoning, and is thus part of the second layer of Giddens' so-called "double hermeneutics." The analytical discourse is theoretically constructed as a system of rationalized expectations feeding back on the communications under study. The substantive and the reconstructing layer can couple on each other. However, these couplings are empirical and thus leave room for empirical research in science and technology studies. The expectation is that the sciences are in important respects different from each other. This includes differences in the relevant couplings with professional practices (Whitley, 1984).

In sum, I suggest reading Habermas—despite his intentions at the time—as committed to values and operating in an historical-hermeneutical approach. The Habermas of the debate in the 1970s was still committed to the neo-Marxist values of the Frankfurter Schule (Horkheimer & Adorno, [1947], 1969). In his later theory of communicative action (Habermas [1981], 1987), other commitments such as unrestricted discussion ("*herrschaftsfreie Diskussion von allen mit allen*") became normative objectives of the theorizing, leading eventually to a discussion with Pope Benedikt XVI (Benedikt XVI & Habermas, 2006).

Despite his aversion to formal methodology and statistical testing, Luhmann, however, sided with an analytical approach against historicism; for example, he formulated that "[science] cannot offer basic principles, arguments or even certainty.

It can no longer be understood as a theory of the founding of knowledge. The opposite is true: it analyzes the uncertainty of knowledge and gives reasons for it" (Luhmann, 1990a, at p. 81). From this perspective, organized knowledge production does *not* have binding implications, whereas the critique of the technocratic implications of systemic developments was crucial and normatively binding, for example, in Habermas' (1968b) critique of Marcuse's (1964) book *One-Dimensional Man.*

Both approaches—historical-hermeneutical understanding and a commitment to value-freeness—go back to Weber, but the commitment to value-freeness is central to Weber's epistemology of the social sciences; this commitment drives the differentiation between scholarly and normative discourses in social theory. This distinction and the corresponding one between cognitive and normative learning by the carrying agents can be considered as the *differentia specifica* of a cultural evolution that is knowledge-based.

10.4 Meta-Biology and Reification

More than a decade after the Habermas-Luhmann discussion, Habermas (1987) returned to this debate with the argument that Luhmann's (1984) *magnum opus* had made clear to him that social-systems theory can be considered as a meta-biology. Habermas commented as follows:

> In this way, subject-centered reason is replaced by systems rationality. As a result, the critique of reason carried out as a critique of metaphysics and a critique of power, which we have considered in these lectures, is deprived of its object. To the degree that systems theory does not merely make its specific disciplinary contribution within the system of the sciences but also penetrates the lifeworld with its claim to universality, it replaces metaphysical background convictions with metabiological ones. (p. 385).

Following Gumbrecht's (2006) distinction between Luhman I, II, and III (see Chap. 1), this critique addresses "Luhmann II" as the author of the (1984, 1995) book entitled *Soziale Systeme: Grundriß einer allgemeinen Theorie* [Social Systems: Foundations of a General Theory]. At the time of the discussion between Habermas and Luhmann in the early 1970s, however, "Luhmann I" (1971) made an argument for distinguishing between "meaning" and "information." Luhmann proposed "meaning" as the basic concept of sociology, when formulating as follows:

> What one person takes for granted might be surprising to someone else; and the same is true across time: a book that today is hard to understand and full of needlessly complicated sentences may seem quite informative tomorrow.

In my opinion, this program of studies is dualistic, since a dynamic of understanding ("meaning") is distinguished from the dynamics of the historical events ("information"). However, Habermas' (1987) characterization of Luhmann's work as "metabiology" was a reaction to Luhmann II's (1984) book which opened upfront by stating the assumption *daß es Systeme gibt* (1984, p. 30; 1995, p. 12). From this perspective, biological, psychological, sociological, and organizational theories of *autopoiesis* were considered as species of *a general theory of autopoietic systems* (Luhmann, 1984, p. 16; 1995, p. 2),[3] and an evolutionary tree was sketched as a hierarchy among them.[4]

A decade later (that is, after 1990), Luhmann III argued that his general theory could be grounded in a theory of "observation" based on Spencer Brown's (1978) *Laws of Form*. In my opinion, this argument contains a number of steps which are problematic.

1. Spencer-Brown's *Laws of Form* is a mathematical study. The laws of form therefore are content-free (as is "information" in Shannon's mathematical theory of communication; cf. Baecker, 2017). On the last page (p. 76) of this study, however, Spencer Brown formulated as an implication and example that "an observer, since he distinguishes the space he occupies, is also a mark." Whereas an observer can be considered as a mark, not all marks are also observations.
   For example, a predator observes its prey by distinguishing and identifying it. As against biology, however, a distinction that is identified in a discourse specifies only *an observational category*. The value of the observation has still to be determined empirically, for example, by measurement (De Zeeuw, 1993). In other words, by identifying a distinction only an *expectation* is specified, but not yet an observation. Since empty, the new boxes add only to the redundancy.
2. The biologist Maturana (1978) stated explicitly that his studies of "the biology of language and knowledge" focus on *observable "languaging" as behavior* and not on the content of *what* is communicated. Human language, in Maturana's opinion, is used by "super-observers" (1978, pp. 56f; cf. Maturana, 2000), who are able to take part in a scientific discourse that is *different from* the biological communications under study such as among "languaging" monkeys, ants, or whales.[5] Maturana could thus avoid having to argue at the meta-biological level of sociology.

When the communications under study are human, reflexive participants and analysts are able to change roles. This "double hermeneutics" is specific for the study of inter-human interactions (Giddens, 1976, at p. 162). When sociology is reduced to a meta-biology studying observables without the surplus of theoretical understanding, however, the surplus of the social sciences, that is, the study of this *double* hermeneutics and therefore the option to translate meanings among discourses, is lost; the communicative translation is reduced to action.

Biological metaphors are not only misplaced but potentially confusing; the sociological finesse in distinguishing among texts and subtexts disappears. For example, these metaphors may lead to research designs in which observations and expectations are no longer clearly distinguished. Furthermore, the application of biological theory to social systems in "social Darwinism" and socio-biology has historically been a

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[3] A general theory of social systems was suggested by Luhmann (1981).

[4] This tree was further elaborated in Luhmann (1986a, b, pp. 172f.).

[5] Dodig-Crnkovic (2014) argues that theoretical biology has nowadays reflexively abandoned the focus on observing in favor of computational modelling of the construction.

disaster. In the German context, Habermas' critique using the attribution of "meta-biological" is almost offensive. As noted in Chap. 1, Giddens (1984, at p. xxxvii) stated that he deemed it "necessary to repudiate the newer versions of Parsonianism," including both Habermas and Luhmann, for similar reasons. The noted risk of an invocation of "magical explanatory properties of social reproduction" is based on a meta-biological reading of these authors.

Undoubtedly aware of these critiques, it is somewhat surprising that Luhmann never[6] problematized the abuse of biological metaphors in Nazi Germany (e.g., Weingart, Kroll, & Bayertz, 1988).[7]

10.5 Towards a Calculus of Redundancy

In an email to the list of the American Cybernetics Society, Krippendorff (9 June 2010) distanced himself from systems theory as a theory of everything with roots in biology; he claimed another *epistemology* for cybernetics (Ashby, 1947), when he formulated as follows:

> […] cybernetics starts with conceptualizing all possible systems, *regardless of whether they exist*, and it is informed when some of them cannot be built or found in nature. […] Conceptualizing all possible systems before enacting some of them implies both creativity and action in a circular relationship. […] Cybernetics paints a reflexive picture of the world of active participants, not of a holistic system of subsystems. (italics added, L.)

Cybernetic models are content-free; they allow for translating models developed in one substantive domain into another as *hypotheses*. On the basis of specific hypotheses, observations can corroborate the assumptions. In other words: analytical distinctions have priority, and the hypothetical status of knowledge remains assumed. As Popper (1972, pp. 259f.) put it: "observation comes after expectation or hypothesis."

The empty boxes generated by distinctions add redundancy to the maximum capacity. The empty boxes can be filled with values on the basis of observations. In his book *Incomplete Nature*, Deacon (2012, at p. 3) called for a focus on the zeros:

> What is absent matters, and yet our current understanding of the physical universe suggests that it should not. A causal role for absence seems to be absent from the natural sciences.
>
> […] This something-not-there permeates and organizes what is physically present in these phenomena. Its absent mode of existence, so to speak, is at most only a potentiality, a placeholder. […] Zero is the paradigm example of such a placeholder. (p. 10.)

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[6]The exception are some statements about antisemitism in interviews (Klaus Dammann, *personal communication*, 8 November 2019; cf. Dammann, 2014, p. 171). Of course, the issue is sensitive.

[7]Luhmann was obliged to enlist the Hitlerjugend in 1944 at the age of 17. Before that date, he applied (perhaps non-voluntarily) for membership in the NSDAP with the number 9935113, 20 April 1944; that is, on the occasion of Hitler's 55th birthday (*Der Spiegel,* 25 July 2007, pp. 134 f.; Dammann, forthcoming).

The biologist Ulanowicz (2014) argued that the *apophasis* (A)—redundancy—cannot teach us anything about historical events. A biological system with more options than are realized ($A > D$) is vulnerable to perturbations to the extent that a catastrophe would be unavoidable (Ulanowicz, 2014, p. 26; see also Ulanowicz, 1986, p. 92). In my opinion, the codes in the communication provide support to psychological and social systems and enable them to operate with volatility "at the edge of chaos" on top of biological systems such as bodies and populations.

Unlike biological systems, systems of expectations do not need to be materialized. Reflexivity can provide these systems with other types of operation (e.g., incursivity; see Chap. 8) and next-order buffering capacities (hyper-incursivity) so that their identities can be maintained beyond the historically observable stability or instabilities. Whereas psychological (action) systems are supported by their carrying bodies, the codes in inter-human communications provide additional stability by structuring the communications from above (at the supra-individual level). The codes refer to horizons of meaning. Beyond stabilization in history, globalization can operate as a selection mechanism in a regime of expectations.

Ulanowicz's "*apophasis* minus *didactics*" ($\Phi = D - A$) can perhaps be considered as another formulation of the trade-off between information and redundancy generation discussed as the Triple-Helix indicator in Chaps. 4–7. However, I have taken these programmatic statements further by proposing a calculus of redundancy in analogy to Shannon's (1948) calculus of information (Bar-Hillel, 1955). Against the idea that the zeros and the missing cases are not informative, I submit that the social sciences not only construct the empty boxes and fill out the zeros by specifying values; they can also provide us with insight into the potentially negative values of the intangibles that organize our understandings into discourses.

10.6 Consequences for Evolutionary Economics

When selection is no longer considered as "natural selection," selection mechanisms have to be specified on theoretical grounds. Case descriptions by historians—or, in the terminology of evolutionary economics, "stylized facts" (e.g., Malerba, Nelson, Orsenigo, & Winter, 1999)—and indicators generated in quantitative science and technology studies provide mainly descriptive statistics. However, one is not allowed to infer from observable variation to selection mechanisms.

The specification of selection mechanisms other than the market has been central to evolutionary economics. Nelson and Winter (1977, 1982) first specified the interactions between market and non-market selection environments. In these models, however, selections are made by agents (firms) who are bounded by the rationality of the selection environments (Alchian, 1950; Simon, 1955). If the firms themselves were selecting as agency, however, a theory of the firm would eventually be the unavoidable result (Casson, 1997). In other words, Nelson and Winter (1982) did not specify selection mechanisms, but the selection *environments* of firms.

With a reference to Hayami and Ruttan (1970), Nelson and Winter (1982, pp. 258f.) distinguished these selection environments as production functions at the trajectory level from meta-production functions at the regime level. In their earlier article entitled "In Search of a Useful Theory of Innovations," Nelson and Winter (1977, p. 49) had taken this broader perspective and distinguished between structures on the technological side (such as trajectories and regimes) *versus* selection environments, 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.)

In my opinion, the feedbacks, which were literally bracketed in the above quotation, can be elaborated into a hitherto missing third selection dynamic of communication-based translations and controls. I argued in Chap. 5 how recombinations among differently codified communications can transform political economies into knowledge-based ones (Arthur, 2009). Instead of endogenizing the hypothesized feedbacks into their theory—as was originally the intention—these authors put the knowledge-based transformations between brackets—as an external given—and eventually formulated normative policy-oriented instead of theoretical conclusions. For example, as follows:

> We have put forth the proposition that underlying natural trajectories there is a certain body of knowledge that makes the traverse relatively easy, and that in the recent half century formal science has been an important part of that knowledge. The *key question* then becomes: to what extent are the directions in which science advances inevitable, and to what extent can these be molded by conscious policy. (p. 73; italics added, L)

In a critique of these "post-Schumpeterian contributions," Andersen (1994, pp. 188f.) argued that the main and largely unresolved question remains to specify "What evolves?"

> The question (of "what evolves," L.) is so important that we repeat it in an unforgettable way which is recorded by Boulding, a contributor to post-war non-formalized evolutionary economics, who got fascinated by Schumpeter and economic evolution while he was a pre-war student at Oxford University:
>
> My Oxford philosophy tutor, who had the curious habit of crawling under the table while giving his tutorials, commented in a high British voice coming from underneath the table on a paper I had given on evolution, "It is all very well to talk about evolution, Mr. Boulding, but what evolves, what evolves, what evolves?" (Boulding, 1978, 33) […]
>
> Forty years after this conspicuous form of pedagogics, Boulding had a 'glimmering' of an answer: 'What evolves is something very much like knowledge.' (ibid.) While this answer is undoubtedly correct, it is also radically incomplete in relation to the development of an analysis of economic evolution. Especially, we would like to find an evolving substance which has a much less amorphous character than the common-sense kinds of 'knowledge.' To be able to give rise to an evolutionary process, the 'thing' we are studying should have an aspect of preservability, mutability and selectability.

I have argued in this study that *the complexity of the communication* evolves, and not the bounded rationality in the *behavior* of firms or other agency (Alchian, 1950).

Agents and their behavior are historical phenomena; they make choices and generate new variants. The bounded rationality of their decisions depends on their capacity to learn reflexively and recognize opportunities. However, evolution is taking place in terms of what is genotypically binding (the codes of the communication) and not in terms of variation phenotypically bounded by the codes (Hodgson & Knudsen, 2011). The coordination mechanisms of society have become knowledge-intensive and therefore increasingly transparent and available for reconstruction.

On the basis of the distinction between historically observable developments and the evolutionary dynamics in the background, I distinguished (in Chap. 5) two Triple-Helix variants (Eqs. 9.3 and 9.4): an entrepreneurial and a neo-evolutionary one. The entrepreneurial model shares with Nelson and Winter's models a focus on institutional arrangements and entrepreneurship. The neo-evolutionary Triple-Helix model of wealth generation in industry, novelty production in academia, and governance can be further specified as a manifold—in which synergies can be generated as a result of interactions among both horizontally and vertically differentiated communications. The relationship between innovation and entrepreneurship can be further analyzed from this evolutionary perspective.

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Chapter 11
Summary and Conclusions

Three themes have been central to my research program: (1) the dynamics of science, technology, and innovation; (2) the scientometric operationalization and measurement of these dynamics; and (3) the Triple Helix (TH) of university-industry-government relations. University-industry-government relations provide an institutional infrastructure carrying the potential of self-organization in the knowledge base of an economy. I elaborated these themes into the problem of relating (i) Luhmann's sociological theory about meaning-processing in communications with (ii) information-theoretical operationalizations of the possible synergies in Triple-Helix relations, and (iii) anticipatory mechanisms in cultural evolutions.

11.1 The Sociocybernetics of Scientific Knowledge

How are meaning and information processing related, and how are they re-combined in the shaping and self-organization of discursive knowledge? Whereas knowledge is often attributed to individuals in the history and philosophy of science or, from a sociological perspective, to communities as belief structures, a perspective on the sciences using communications as units of analysis enables us to proceed to measurement. The aggregated citation relations among journals, for example, can be used to visualize disciplinary structures (Chap. 2, Fig. 2.3). The journal network, for example, can be considered as a construct at the supra-individual level structuring the variation. A cognitive structure can be revealed that operates as a selection mechanism on the historical (bottom-up) generation of knowledge claims that feed the publication process. The knowledge claims in articles provide the variation; the cognitive, social, and textual contexts operate as selection environments.

When both variations and selections can operate upon each another and among themselves, one can expect the generation of both information (that is, uncertainty) and redundancy (that is, reduction of uncertainty). The evolutionary dynamics of

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5_11

interactions between selection environments are different from interactions among historical agents. The variations generate uncertainty (along the arrow of time). Interactions among selection mechanisms can also reduce uncertainty by generating redundancy (against the arrow of time).

In Chap. 3, I discussed how "heterogeneous networks" have been studied in terms of *practices* and *actor-networks* in the sociology of scientific knowledge and the sociology of translations, respectively. From these perspectives, authors, texts, cognitions (and in the case of the sociology of translation even the objects under study) have been analyzed as symmetrical sources for the construction of techno-scientific artefacts (e.g., Callon, 1986).

In my opinion, scholarly practices are intellectually structured by codes emerging in the communications. The codes operate as selection mechanisms by spanning horizons of meaning as selection environments. Different from the symmetry principle used as a normative yardstick in the constructivist sociologies of science, selections can be expected to generate *asymmetries* between selected and de-selected variations. Cognitive structures thus interact and co-construct the organization of scholars and discourses into research programs, specialties, and disciplines. In other words: the intellectual organization of the sciences adds to and asymmetrically feeds back on the configurations of authors and texts.

In Chap. 4, I proceeded to the operationalization and measurement of the interacting dynamics of communications and meanings using information theory. Shannon's co-author Weaver (1949, p. 8) warned against confusing information and meaning. He distinguished three layers which I further elaborated in a model: (i) at level A, events are sequenced historically along the arrow of time, generating uncertainty; (ii) the incursion of meanings at level B is referential to (iii) horizons of meaning spanned by codes in the communication at level C. I propose to distinguish accordingly: the interactive communication of information at level A, the organization (e.g., sharing) of meanings at level B, and the generation and self-organization of discursive knowledge at level C.

The three levels can be operationalized in a measurement theory, as follows: *relations* (at level A) can be distinguished from *correlations* among patterns of relations and non-relations at level B. The correlations span a vector space on the basis of a network of relations. Relations and relating nodes are positioned in this vector space and can then be provided with meaning. Different positions provide other horizons of meaning spanned by codes in the communication. The codes can interact and overlap (for example, in university-industry-government relations.) Overlapping codes may generate new codes and therefore redundancies—that is, options which are still open for realization. From this (evolutionary) perspective, the realized—that is, historically observable—networks can also be considered as retention mechanisms.

11.2 Synergy in Triple Helix Models

The Triple Helix of university-industry-government relations provides an empirical model combining the *vertical* differentiation among the levels in terms of relations, correlations, and eigenvectors (as operationalizations of the codes) with *horizontal* differentiation among the codes (e.g., markets, technologies, politics, etc., operating in parallel). The institutional TH model focuses on the observable relations among horizontal differentiations in the networks and the neo-evolutionary on interactions among selection mechanisms. The relative weights of the historical and evolutionary dynamics in generating information and redundancy can be measured as a trade-off in empirical configurations. The generation of redundancy in interactions among latent codes is a measure of the additional synergy in configurations of relations; options reduce uncertainty, as in a niche. In a knowledge-based economy, one can exploit this synergy as a source of wealth.

In Chap. 6, regional and national systems of innovations in Italy were analyzed as an empirical example. The Italian systems of innovation are interesting because the Italian economy is both knowledge-based and knowledge-intensive. Using firm-level data collected by Statistics Italy for 2008, 2011, and 2015, synergies among the geographical and size distributions of firms and technology classes can be measured at both national and regional levels. As against the statistical classification into twenty regions, or into Northern, Central, and Southern Italy, the greatest synergy is retrieved by defining the country in terms of Northern and Southern Italy as two sub-systems, with Tuscany included as part of Northern Italy.

Different innovation strategies could be developed for these two parts of the country. The current focus on twenty regions for innovation policies may to some extent be an artefact of EU policies. In terms of sectors, both medium- and high-tech manufacturing (MHTM) and knowledge-intensive services (KIS) are integrated proportionally in the various regions in Italy. In Spain, for example, the knowledge-based sectors are highly concentrated in Madrid and Barcelona as two metropolitan innovation systems (Leydesdorff & Porto-Gomez, 2019).

In Chap. 7, the Triple-Helix synergy indicator was formalized and generalized as a methodology for the measurement of synergy and systemness. A routine for this measurement is made available at https://www.leydesdorff.net/software/synergy.triads. The routine evaluates all possible permutations among three column vectors in terms of their contribution to synergy generation. This enables us to compare configurations in terms of possible synergies. Since the routine is based on the Shannon formula, synergies can be summed (after proper normalization). For example, one can compare two regions in Italy—e.g., Tuscany and Piedmont—in terms of the Triple-Helix dynamics of geographical, technological, and organizational variety (e.g., of firms). One could ask, for example, how much a change in one of these distributions would increase the number of options.

When policy-makers call for “interdisciplinarity,” they often mean “synergy.” In collaborations with third parties, however, “interdisciplinarity” can also be considered a means for creating “synergy. Synergy is generated when the whole offers more possibilities than the sum of its parts. I discuss recent advances in the operationalization and measurement of "interdisciplinarity" and propose a methodology for measuring "synergy." An increase in the number of options above the sum of the options in subsets can be measured as redundancy, that is, the number of not-yet-realized options. Increasing redundancy reduces the relative uncertainty. The operationalization of the two concepts—"interdisciplinarity" and "synergy"—as different outcome indicators enables us to distinguish between the effects and the effectiveness of interventions in research priorities.

11.3 Anticipatory Dynamics and Simulations

Knowledge bases can drive the transformation in the present from the perspective of expected states. In Chaps. 8 and 9, I analyze the *feedback* of an emerging communication dynamic as a local inversion of the arrow of time in terms of the theory and computation of anticipatory systems. Using a set of recursive, incursive, and hyper-incursive equations derived in Chap. 8, I specify *six* subdynamics of anticipation operating in the second contingency of knowledge-based systems in Chap. 9: (i) three coordination mechanisms among expectations at different levels of aggregation (interactions, the organization of meaning, and self-organization), and (ii) three further equations that operationalize "double contingency," "identity," and "reflection," respectively.

These subdynamics update one another dynamically in co-evolutions of historical recursions and anticipatory incursions. In this complex dynamics, vertical and horizontal differentiations can be expected to generate time differences (Δt) at interfaces. Interactions among time differences in horizontal and vertical *incursions* can be multiplied and generate hyper-incursivity. Hyper-incursion drives the layer of rationalized expectations. The social system of communications is unique in its ability to build on interactions among meanings in the second contingency.

11.4 Against Monism

In an epilogue (Chap. 10), I discuss, among other things, the differences between the dualistic sociology of science and the monistic program claiming a research perspective for a meta-science based on "big data." Both "big data" and "monism"—the program of reducing cultural and mental processes to computational and biological principles—reject a dualism between a physical and biological reality (*res extensa*) and our knowledge of this reality (*res cogitans*). However, I have argued throughout this study that on top of the manifest relations, a second contingency of possible relations and expectations can be envisaged. This second contingency is the proper domain of the social sciences, where the focus is on what things *mean* and how these appreciations can change. In other words, I have argued against monism and historicism.

In my opinion, a major contribution of this study is the focus on redundancy as a measure of the number of cases that could have occurred or the meanings that could have been provided. The possible meanings refer to "horizons of meaning." These horizons are contingent (for example) upon positions and perspectives. However, the second contingency operates differently from the first contingency, with a minus sign. A complication is the time factor; the linear arrow of time accords with the entropy law in thermodynamics, and thus with Shannon's probabilistic entropy. However, the *possible* states of a system cannot be learned from its history because a system's history is by definition only its genesis in a lower dimensionality. If one wishes to envisage the range of possibilities, one first has to specify expectations. In most boxes one finds a zero, indicating redundancy.

Furthermore, this study contributes to the construction of a relation between social theory, on the one hand, and the specification of a measurement theory in terms of information, redundancy, and meaning, on the other. The relations between these discourses have hitherto been scarce. In artificial intelligence, the main focus has been on relating biology and psychology at the level of individuals and with the purpose of explaining agency. Agency can be observed as behavior (of, for example, persons, institutions, or principal agents). Behavior provides us with a point of entrance to study individual intentions. However, the relations between science, technology, and society are structural at the above-individual level. Structures can be expected to operate as selection mechanisms on both variation (e.g., actions) and on interactions among differently coded structures (e.g., co-evolutions, Triple- and Quadruple-Helix models, etc.). Since one can no longer expect a single ("natural") selection, the interactions among selection mechanisms can also become sources of variation in a complex dynamic.

At the level of above-individual expectations, selection mechanisms can also be considered as coordination mechanisms. Codes can be expected to emerge in the communications when selections operate on other selections or previous selections, Selections which operate on selections, may lead to stabilization and also globalization. Codes provide meta-stable selection criteria which operate in parallel. In addition to a horizontal differentiation in terms of codes, structures are differentiated vertically in layers (e.g., information, meaning, and knowledge). Organization is a specific function and a layer, and thus links the vertical and horizontal differentiations.

Simon (1973, pp. 19f.) hypothesized that there might be an alphabet of possible codes. For example, other dimensions of the communication are backgrounded when we focus in scholarly discourse on substantive issues or in policy-making on choices. The routines can be interrupted by otherwise coded communications. The interruptions disturb system-building and thus shape a "fractal manifold" (Ivanova & Leydesdorff, 2014). In sum, one expects neither Triple nor Quadruple helices of co-evolutions (Carayannis & Campbell, 2009), but one can expect fractals and fragments; for example, a dimensionality of 3.1. In this domain of incompleteness, the derivatives from the Latin verb *esse* ("to be," "exist," and "ontology") are superseded by derivatives of *frangere* such as "fractal," "fragment," "fragile."

Add to the dynamics of the second and first contingencies—and their interactions—the possibility to invert the time-axis to different degrees in each receiving systems. Meanings incur on events against the arrow of time, and interactions among incursions can induce hyper-incursive operations (Chaps. 7 and 8). For example, expectations organized in models enable us to add new dimensions to the communication. Whereas agency constructs piecemeal, along historical trajectories, the social can be expected to self-organize and hyper-incursively reconstruct virtual structures of expectations.

The codes emerge over time in a morphogenesis, but when sufficiently populated, the next-order can take over control *because it is based on selections.* These asymmetrical transformations of contents between the level of incursive individuals and hyper-incursive expectations show the operation of communications as mediating structures with the potential of control. Measurement is needed for the specification of the extent to which organization or self-organization prevail.

I have used the three, in my opinion, most relevant theories for addressing these dynamics at the supra-individual level: Luhmann's sociology, Shannon's information theory, and Rosen's and Dubois's theory of anticipatory systems. These theories enabled me to approach the problems from different angles. However, the objectives of these theories are very different: information theory is operational and provides primarily a measurement theory (Theil, 1972); Luhmann's (1997a, 1997b, 1984, 1995, 2012) sociology has remained theoretical and sometimes even speculative. In my opinion, the latter has been hitherto the most systematic effort to remain at the level of a *second-order* cybernetics of communication while specifying a sociological dynamics; Rosen's (1985) theory and Dubois' (1998) computation of anticipatory mechanism are expressed in algorithms that can be simulated.

I submit that only the social system can be hyper-incursive—that is, without historicity, since operating hyper-incursively from the perspective of the future. In the computation of anticipatory systems (CASYS), one may therefore need this focus on the social as a unique example of strong anticipation. A research program can here be envisaged.

The objective of this study has been to make the three perspectives of communication theory, information theory, and socio-cybernetics relevant for one another. Reading these sociological and computational theories together can broaden the scope for each of them. The focus shifts from explaining what "is" to what "might be" or "could have been"; that is, from information to redundancy. However, the surplus of combining these approaches is first analytical; the focus is on the specification of expectations. The purpose is to provide suggestions for further research. These theories had not yet been brought together with a perspective on further research—operationalization and measurement—because of their very different theoretical backgrounds and respective semantics.

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
https://doi.org/10.1007/978-3-030-59951-5

Subject Index

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
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