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

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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

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[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]).

[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.

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[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?

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[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

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[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

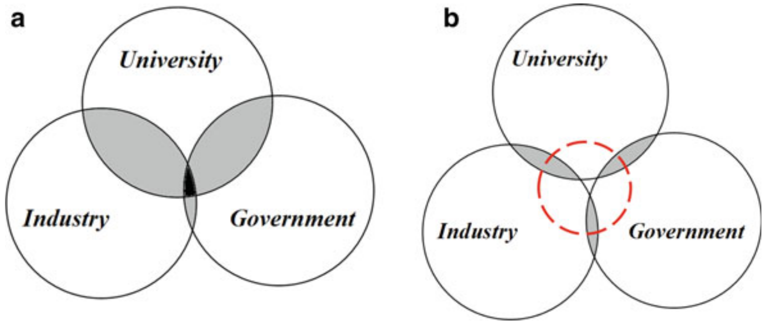

Fig. 1.2 **a** Integration in the overlaps among the three helices of a Triple Helix. **b** Differentiation and hypercyclic integration at the next level

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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