Institutional Interfaces of the Science System and the Economic System: Science-Based Technologies, Organizations and Networks.

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Introduction [1]

Although institutional interfaces between the science system and the economic system represent important structural features of developed societies, sociology has not given these interfaces due attention so far (exceptions are Schimank 1988; Stichweh 1999; Kaufmann/Tödtling 2001). One reason for the continued lack of interest is that technology plays but a marginal role in sociological theory. Two influential theoretical sociologists, Talcott Parsons and Niklas Luhmann, place technologies outside society (Parsons 1977; Luhmann 1997). Another reason is that the discussion on institutional interfaces between functionally differentiated social systems has remained relatively abstract in as far as these are only being dealt with at the level of functional systems. Organisations as the basis of functional system capacities and networks have not been analysed systematically. As a result, the empirical potential of *structural coupling* – the theoretical concept that describes institutional interfaces between social systems in Luhmann's theory – has not yet been utilised. Although Luhmann's work contains a few hints, there is no systematic treatment of this topic. However, it is argued here that Luhmann's theory provides an appropriate frame for conceptualising the institutional inferface of the science system and the economic system. Based on earlier works (Heinze 2005, 2006), this paper outlines how science-based technologies, organisations and networks contribute to the structural coupling of science and economy.

1 I am grateful to Arlette Jappe for her helpful comments on the manuscript.

In *innovation studies,* the institutional interface of scientific research and value creation in the economy is usually dealt with under the headings of "innovation process", "knowledge and technology transfer", "technological change" or "science-based industries". Studies on technological innovation are interested in identifying the factors and mechanisms that influence the competitiveness of companies on national and international markets. Industrial competitiveness in high-technology markets also attracts considerable attention from science and technology policy. There is an abundance of empirical findings as to the relationship of scientific research, innovative activities, technology development and the production of goods and services. However, the field of innovation studies failed to come up with a powerful theory capable of systematising the wealth of empirical findings. Although the *National Systems of Innovation* (NIS) approach has become widespread during recent years and has opened up an interesting field of research (Fagerberg et al. 2005; Edquist 1997; Freeman 1995; Nelson 1993; Lundvall 1992), it has several theoretical weaknesses that impede better understanding of the institutional interface between scientific research and economic value creation (Miettinen 2002; Edquist 2005). The two most critical dimensions here are the relationship of organisations and societal systems, and networks connecting different system capacities. Therefore, introducing the concept of *structural coupling* from Luhmann's theory to *innovation studies* is an important step in improving the theoretical understanding of available empirical data on the process of technological innovation.

The paper introduces first the concept of structural coupling and argues that science-based technologies are *boundary structures* that facilitate interchange between the science and economic systems (section 2). This argument is illustrated by innovation indicators, such as publications, patent applications and company turnover for the field of biotechnology; they illustrate the various interconnections between scientific knowledge production, technology development and market operations (section 3). Then, the relationship between organisations and functional systems is explored. It is argued that, because these two system levels are loosely coupled, one can distinguish between *type-1 and type-2 organisations*. These two organisational types have co-evolved with *fundamental and applied research* on the part of the science system and *technology markets* with either *high* or *low research intensity* on the part of the economic system (section 4). Furthermore, I demonstrate that collaborative ties across system boundaries are more common among type-2 rather than type-1 organisations. Empirical data on the domain of nanotechnology shows that applied research capacity and high-tech market pressure are both preconditions for network formation between organisations, whose predominant institutional anchor is either the science or the economic system (section 5). The concluding section summarises the arguments and findings (section 6).

1 The concept of "structural coupling"

Functional differentiation is always to be thought of, both theoretically and empirically, in terms of interconnected social systems. Luhmann argues that

> "if one were to describe modern society simply as a number of autonomous functional systems that, owing no consideration to each other, only follow the reproduction of their own autopoiesis: this would be a very one-sided picture. It would then be difficult to understand why this society does not implode very quickly or collapse [...] In fact, all functional systems are linked with each other and maintained in society." (Luhmann 1997: 776, translation TH)

In Luhmann's theory structural couplings are conceived of as selective channels of mutual influence – ways in which social systems are able to influence each other. Influence means, on the one hand, that systems restrict each other's operations, without however being able to directly interfere in the other system's operations. On the other hand, influence means reciprocal transfer and flows of capacity. These two types of influence are selective because they are restricted to designated paths and do not affect the operational autonomy of the social systems. Structural couplings are historically contingent and contribute to the integration of society (Luhmann 1997: 776-788).

Luhmann's examples for structural couplings include, amongst others, *constitutional law* (political system and legal system), *educational certificates* (educational system and economic system) and *contracts* (legal system and economic system) (Luhmann 1990, 1997: 776-788; Lieckweg 2003: 80-87). Let us consider the example of contracts in more detail. How do contracts interconnect the legal system and the economic system? Contracts warrant two types of transactions: transfer of payments as an element of the economic system, and transfer of property rights to goods and services as an element of the legal system. Although these two types of transactions are analytically separate, they are interconnected in practice, because the transfer of payments can only be carried out successfully if, first, one knows the owners of the property rights and, second, the conditions under which the transfer of property rights should take place. Both preconditions are regulated by contracts. Therefore, contracts *enable* payments by providing legitimate expectations about the way in which economic transactions are processed. Without such a legislative frame, it would be difficult to organise payments on a regular basis. The provision of contracts is a particular capacity, which the legal system provides to the economic system. At the same time, however, contracts *restrict* the ways in which economic transactions are expected to take place, because they demand that payments comply with the conditions specified in the contract. Payments that do not conform to the legal code, as spelled out in the contract, will be regarded as unlawful and illegitimate.

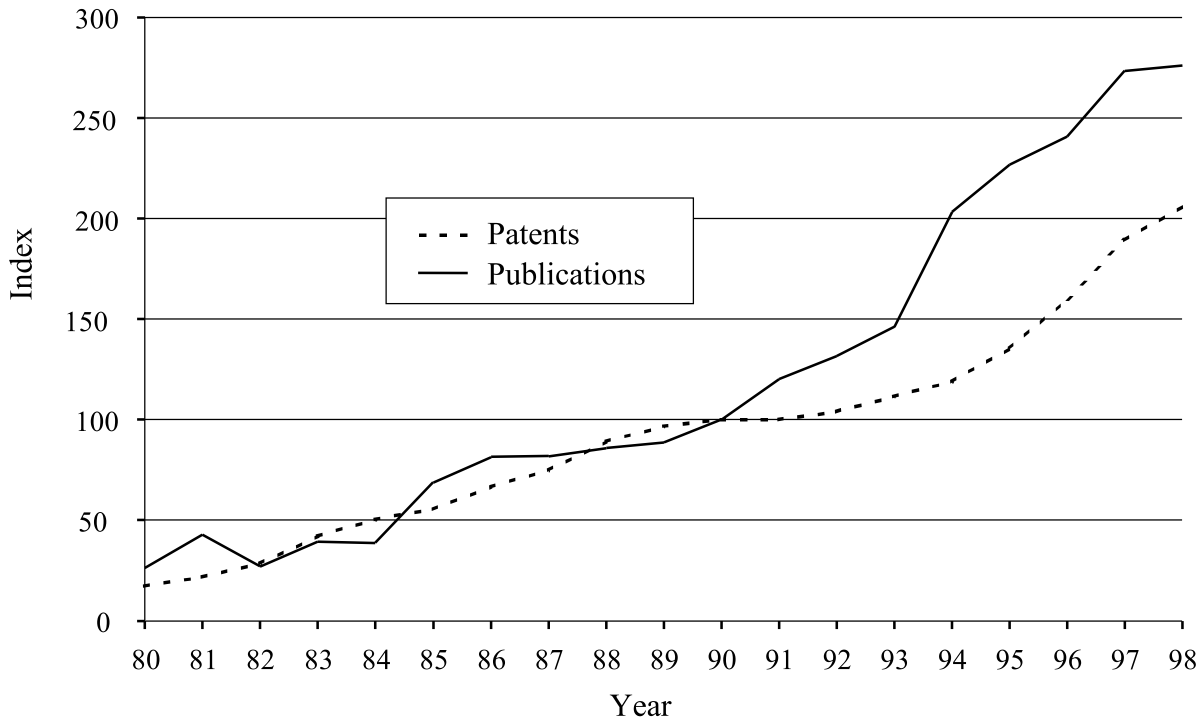
Structural coupling is also important in the domain of technology. By definition, *technology* is understood as the entirety of material and immaterial methods and mechanisms that increase the effectiveness of activities, extend the spectrum of perception and make sure that operations are carried out reliably. Technologies also include the repertoire of knowledge and skills necessary to achieve desired results and to avoid undesired ones (Rammert 1998, 2000). The term "technology" is often used to distinguish between *science-based technologies* and *traditional techniques*. Science-based technologies are more complex and, in contrast to traditional techniques, dependent to a greater extent on advances in scientific research. Therefore, the emergence of science-based technologies indicates a growing influence of scientific knowledge production on the development of new technical solutions and artefacts (Freeman/Soete 1997). Since new technologies are developed and used in the production and marketing of goods and services, economic transactions are related to advances in scientific knowledge production. Therefore, science-based technologies are a *boundary structure* that facilitates the coupling of the science system and the economic system.

2 Indicators for science-based technologies

An important objective of innovation studies is to quantify the relationship between the production of new knowledge, the emergence of new technologies and cash flows on technology markets. Quantitative indicators are constructed in order to inform innovation policy about knowledge-based sectors of the economy (Grupp/Mogee 2004; Barré 2004). While the *production of new scientific knowledge* is typically measured by publications in scientific journals, the invention and *development of new technologies* and the *improvement of existing technologies* is measured by patent applications or granted patents at patent offices. Scientific papers are the most important output of scientific research, at least for science and engineering. Patent applications are a typical output in many fields of technology which are well suited to illustrate the productivity and dynamics of innovative activity. So, publication and patent data is among the most important indicators of innovative activities (Bassecoulard/Zitt 2004; Narin et al. 2004).

Innovation indicators are an important means to describe the structural coupling of functional systems through science-based technologies. One example of the combined use of publication and patent statistics is depicted in Figure 1. For the domain of biotechnology, the graph shows a typical curve for science-based technologies: strong growth in scientific publications is accompanied by similarly strong growth in patent applications. The almost parallel increase in publications and patents can be interpreted as evidence of considerable knowledge transfer between research organisations and industrial companies. One can observe similar patterns in other science-based domains of technology, for example in nanotechnology (Hullmann/Meyer 2003; Heinze 2004).

Figure 1: Worldwide Patent Applications and Scientific Publications in Biotechnology



Note: Index 1990 = 100. Patent data acc. to year of first application (priority), publication data acc. to publication year. WPI = World Patent Index. SCI = Science Citation Index

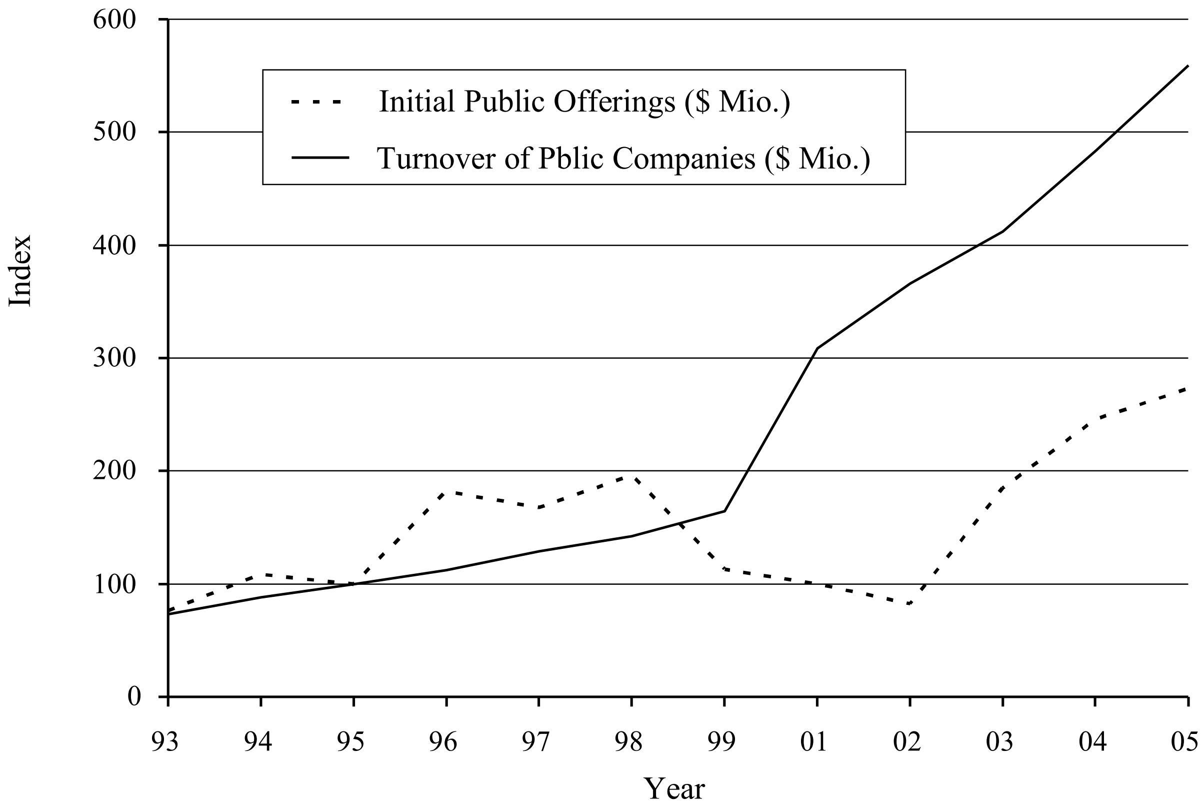
Source: Heinze (2005)

The structural coupling of functional systems via science-based technologies as boundary structures can be shown in a more direct way by analysing patent citations. When examining new patent applications, it is common practice to refer to already issued patents, because the main technical characteristics are documented here in a systematic way. If no suitable patents can be found, however, patent examiners will resort to publications in scientific journals, so-called non-patent literature (NPL). Citations to NPL are also made if it is impossible to judge whether an issued invention meets the patentability criteria (novelty, distinctness, uniformity, and commercial applicability) without reference to the state of the art of scientific research. NPL citations are therefore interpreted as indicators of technical developments that cannot be patented without reference to the scientific body of knowledge (Carpenter et al. 1983; Narin 1997).

Innovation studies literature maintains that linkage to science is an inherent characteristic of technological domains, independent of the national origin of the patents and the period considered. It has also been shown that the science linkage varies strongly between different technologies. For example, biotechnology is among the fields with the highest share of NPL citations. In the United States, biotechnology patents have about ten NPL citations on average, the majority of which refer to publications of public research organisations (McMillan et al. 2000). In the domain of nanotechnology, similar patterns have been observed (Meyer 2000, 2001).

The quantitative description of innovative activities using publications and patents as indicators is an important step to examine system coupling, yet patents per se are not indicators of market transactions. How is the production of new scientific knowledge (publications) and new technologies (patents) translated into cash flow in the economic system? The *cash flows on technology markets* can be described by two indicators: statistics of the value added in economic sectors and the turnover or number of start-up companies. Figure 2 shows the turnover of all listed biotechnology enterprises worldwide (public companies) and the profits from initial public offerings. Since the mid-1990s, the enormous volume of publications and patenting (as shown in Figure 1) has been translated into a remarkable increase in economic opportunities (Figure 2). Biotechnology is a striking example of how closely interlinked knowledge production, technology development and market cash flows can be. These findings are supported by the results of Harhoff et al. (2003) who report that the economic value of patents in science-based fields of technology increases with the number of NPL citations: the more new inventions draw on scientific knowledge, the greater the possible cash flows in the economic domain.

Figure 2: Worldwide Turnovers and IPOs of Biotechnology Companies



Note: Index 1995 = 100. Turnovers of all listed biotechnology enterprises worldwide (public companies) and the profits from worldwide IPOs (=Initial Public Offerings). Two indices were formed in order to depict the different scales of both variables together. In enterprise turnovers the index value 100 in 1995 means $11.3bn. For the profits from IPOs, the value amounts to $935m. for 1995.

Source: Ernst/Young (1994-2006)

3 Organisations and functional systems

Any meaningful account of the institutional interface between functional systems requires an appropriate description of the organisations involved. Unfortunately, innovation studies have not come up with a convincing theory so far that adequately relates the three system levels relevant in processes of technological innovation: functional system, organisation and networks. As a result, it is common practice to place universities and other public research institutes in the "science system box" and companies in the "economic system box", as if these organisations were each parts or subsystems of these two functional systems of society. This has a major conceptual drawback: One cannot distinguish the organisational and the functional system levels. Yet the functional orientation of organisations can be more complex than a one-to-one relation. Since multiple organisations are involved in the innovation process, their actual relation to science, economy and other social systems needs to be explored first.

In the debate on sociological systems theory, it has become widely accepted that functional and organisational systems are *loosely coupled* (Kneer 2001; Lieckweg et al. 2001; Simsa 2001). Organisations relate their operations to more than one functional system. Companies, for example, not only operate on markets, but in doing so they also enter into contracts (legal system), they educate apprentices (education system), and they are involved in research and development (science system). These multiple operative references give rise to questions about the fundamental system references of organisations.

Tacke (1999) argues that organisations often assign themselves to *one predominant functional system* through their own decisions. Organisational procedures and routines are systematically linked to the institutional code of one functional system. Thereby, they develop a distinct functional system identity on the basis of which they then provide functional systems capacities (Tacke 1999). For example, schools, parliaments, courts and hospitals are examples of organisations where one institutional code predominates. However, this idea only describes *one possible relationship* of the co-evolution between organisations and functional systems. I describe this case as type-1 organisation.

Embeddedness in one predominant institutional environment is also possible when organisations develop a secondary functional system orientation. I describe this case as type-2 organisation. Although organisations of this type provide primarily capacities of one functional system, such as the production of scientific knowledge (science system) or the provision of goods and services (economic system), their secondary orientation shapes these capacities according to another functional system. Consider that the historical change to more complex and knowledge-intensive technologies was accompanied by two internal differentiations within both the science and economic systems that made it possible for organisations to systematically link their routines and capacities to more than one functional system: *fundamental and applied research* on the part of the science system and *technology markets* with either *high* or *low research intensity* on the part of the economic system. These internal differentiations on the functional system level allow for more complex orientations on the part of organisations, as will be shown below.

Fundamental research is knowledge production aimed at extending the existing body of knowledge irrespective of potential utilisation or application. In contrast, *applied research* represents knowledge production that satisfies a knowledge demand outside the science system. Both Luhmann and Stichweh have argued that these two types of research fulfil different societal functions. While the disciplinary and often theoretical focus of fundamental research produces highly selective chains of specialised communications within scientific communities, the often interdisciplinary focus of applied research is a means to integrate science into society (Luhmann 1992; Stichweh 1994). In terms of societal evolution, applied research (as separate and socially differentiated activity) reflects increased expectations from the environment of the science system to provide useful knowledge, here from the economic system with respect to technology development. Stokes (1997) has argued that there is a third type of research where fundamental research and applied research intersect: *use-inspired fundamental research*. Stokes' distinction is particularly useful to capture the various types of research in science-based technologies, such as biotechnology (Evans 2004) and nanotechnology (Heinze 2006). In terms of the two-tiered organisational typology introduced above, organisations conducting either use-inspired fundamental or applied research would qualify as type-2 organisation.

There is an extensive discussion in innovation studies concerning the internal differentiation of the economic system in *technology markets* with either *high* or *low research intensity* (Smith 2005; Tunzelmann/Acha 2005). Research intensity describes the degree to which research and development (R&D) contribute to the value added, either in a given category of goods or services, or across industrial sectors. In his classical analysis of British firms, Pavitt (1984) identified the chemical and electro-technical industries as research-intensive economic sectors. Pavitt finds relatively large *science-based companies* whose competitiveness is dependent on appropriate R&D capacities. Pavitt's taxonomy has often been applied and extended. For instance, Marsili (2001) gives a modified taxonomy that is more geared to the technological paradigms in different economic sectors.

Another typology, introduced by the OECD, divides industrial markets into four main groups based on the empirical distribution of R&D intensity: high-tech industries (R&D > 5 %), medium high-tech industries (3 % > R&D > 5 %), medium low-tech industries (0.9 % > R&D > 3 %), low-tech industries (0 % > R&D > 0,9 %) (OECD 2001). Differentiating markets and companies based on R&D intensity means that competitive relations between the producers of goods and services are co-determined by their capabilities to continuously develop and improve technologies in order to stay in the market. High-tech companies, which would be qualified as type-2 organisations, need to develop search and evaluation routines that help them identify and absorb new technological knowledge. Among the prerequisites for maintaining their technological competitiveness, high-tech companies conduct R&D activities in specialised departments or collaborate with research organisations. Cohen and Levinthal (1990) coined the term “absorptive capacity” for this.

4 Interorganisational networks

Recent research on interorganisational collaboration documents a strong positive relationship between alliance formation and innovation across such diverse economic sectors as chemicals (Ahuja 2000), semiconductors (Stuart/Podolny 1999), telecommunications (Godoe 2000) and biotechnology (Powell et al. 1996, 2005; Owen-Smith et al. 2002; Gittelmann 2000; Liebeskind et al. 1996). Most studies, however, rely on networks within the corporate sector and do not expand their perspective to research organisations. Although several studies mention that collaborative ties with research institutes give companies access to new knowledge and that tie characteristics are important for their capability to exploit these collaborations (for an overview see Powell/Grodal 2005), little is known about network structures across the science and economic system, nor how the strength of collaborative ties depends on the type of organisation involved.

The fact that research organisations develop capacities in either fundamental or applied research, or both, and that companies operate in technology markets with high or low research intensity (as shown in the preceding section) has consequences for the likelihood that they will engage in mutual interaction and establish collaborative relationships. It is postulated here that collaborative ties and network formations between companies and research organisations are more common among type-2 than type-1 organisations. Because high-tech companies need access to latest developments in science, they are more likely to interact and collaborate with research organisations than low-tech companies. Likewise, research organisations with capacities in applied research are more likely to be partners for companies because they have expertise not only in fundamental research problems but also in advancing technological know-how. In other words, applied research capacity and high-tech market pressure are both preconditions for interaction between organisations whose predominant institutional anchor is either the science or the economic system. This consideration is summarised in Table 1.

To put the two-tier organisational typology and the propositions in Table 1 to an empirical test, Heinze (2006) examined the patent network in the emerging domain of nanotechnology in Germany. The analysis of patent ties is based on the methodological consideration that while the majority of patent applications are filed by companies, patent inventors are often found in public research organisations, too. In order to fully capture public research sector involvement in patenting, inventor names have to be matched with SCI authors, a method that significantly increases the number of public research units in the patent database (Noyons et al. 2003; Heinze 2006: 142-81). Consequently, patent ties between companies and research institutes are in most cases applicant-inventor relations. Since research organisations sometimes also file patents, applicant-applicant ties are possible as well.

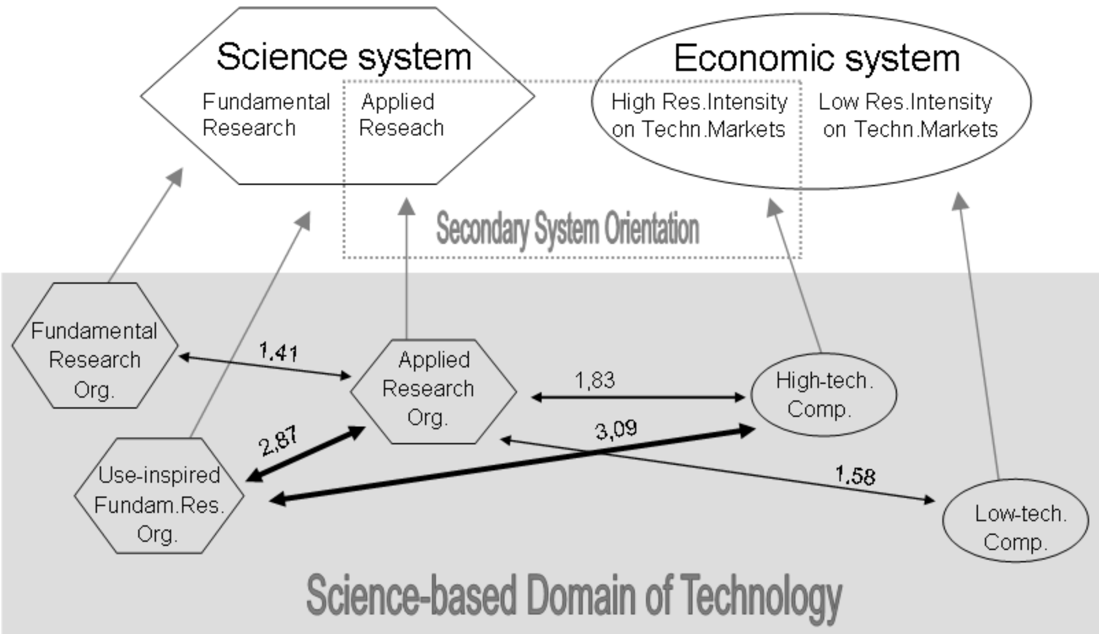
Table 1: Probability of Network Ties between Type-1 and Type-2 Organisations

	Type-1 Organisation: Companies in technology markets with *low* research intensity	*Type-2 Organisation:* Companies in technology markets with *high* research intensity
Type-1 Organisation: Research organisation with *fundamental* research focus	low	medium
Type-2 Organisation: Research organisation with *applied* research focus	medium	high

Source: Heinze (2006)

For the time period of 1996-2000, Figure 3 shows the empirical distribution of patent ties between the different organisational types in German nanotechnology. The three types of research institutes correspond to Stokes' typology: They are operationalised by measuring the balance of fundamental and applied research activities; the company types correspond to the OECD definition using NACE codes, but they are simplified to high-tech (> 5 % research intensity) and low-tech company (< 5 % research intensity) tiers (Heinze 2006: 154-161). Figure 3 illustrates that the strongest relations exist between use-inspired research institutes and high-tech companies. These are about three times more dense ("thicker") than the patent network as a whole. In contrast, low-tech companies possess relations to applied research units only. Use-inspired research institutes are mostly universities and some Max-Planck Institutes (MPIs), while fundamental research units are most often MPIs followed by universities. Fraunhofer Institutes, which are in most cases classified in the applied research category, have collaborative ties to high-tech companies too, though to a lesser extent than institutes of the use-inspired fundamental research category.

Figure 3: Collaboration in German Nanotechnology Patent Network



Note: The graph shows all co-patent relations in the German nanotechnology network in 1996-2000, mostly applicant-inventor relations, but also applicant-applicant ties. Numbers on arrows indicate collaboration density factors as multiples of average network density; only factor values greater than 1 (above average network density) are shown. Data cover 251 organisations and are derived from EPO and WPI patent databases, and from author-inventor matches in SCI.

Source: Heinze (2006)

The empirical meaning of *structural coupling* can be further demonstrated by examining the impact of collaborative ties to research institutions on companies' technological performance, measured as patent output. Multivariate regression models show that the number of firms' patent applications increases with the number of ties to public research institutes. Over a period of ten years, i.e. 1991-2000, companies' patent output grows along with the number of external collaborative ties, in particular with respect to patenting. Hence, companies benefit from the science base of their collaborators. This effect is particularly strong for ties to highly central public research units and multiple types of relationships (Heinze 2006: 121-122).

In sum, the nanotechnology data presents evidence on interorganisational patent ties in an emerging domain of science-based technology. It is shown that high-tech companies are only able to operate successfully in their market environment if they institutionalise routines through which they get access to and can make use of knowledge from research organisations. Likewise, universities and non-university institutes involved in applied research projects possess the capacities to identify and work on problems relevant to the corporate domain. Although these research organisations are still embedded in the communication and reputation structure of the science system, their capacities in more applied research questions provide entry points for collaborative relations with high-technology companies.

5 Conclusion

The arguments presented in this paper shall be summarised in three points. First, science-based technologies are a boundary structure that facilitates the coupling of the science system and the economic system. This means that economic transactions are dependent on advances in technology development, and – due to the latter's dependence on advances in science – are also conditional on advances in the scientific domain. Science-based technologies can be conceived of as selective channels of mutual influence between science and economy. Both systems influence each other by flows of capacity: scientific knowledge and expertise on the part of the science system; additional research funding on the part of the economic system. Mutual influence is not in every case beneficial to the organisations involved, but can have adverse effects too. As demonstrated by Evans (2004), industrial partnerships can make science less novel and more commercial; also, such collaborations may influence scientists to be less persistent in their inquiry and less apt to share research with their colleagues.

Second, organisations play a vital role in the coupling process. It is argued that organisational procedures and routines are either linked to producing the capacities of one functional system (type-1 organisation) or that organisational capacities are aligned to a secondary functional system orientation (type-2 organisation). The second type of organisation has co-evolved with internal structures of both the science and economic system which facilitate the process of technological innovation: fundamental and applied research on the part of the science system and technology markets with either high or low research intensity on the part of the economic system.

Third, the two organisational types are relevant for innovation networks, especially where the transfer of implicit and non-codified knowledge is concerned. However, while collaborative ties between companies and research organisations are common among type-2 organisations, this is less so for type-1 organisations. Because high-tech companies need access to latest developments in science, they are more likely to engage in interaction and collaboration with research organisations than low-tech companies. Likewise, research organisations with capacities in applied research are more likely to be partners for companies, because they have expertise not only in fundamental research problems but also in advancing technological know-how. Organisational routines are selectors for whether interactions between companies and research institutions take place or not. Applied research and high-tech markets are structures that increase the probability for interaction among firms and research institutes.

The considerations in this paper are based both on *Luhmann's systems theory* (Luhmann 1997) and several studies on knowledge transfer, technological change and science-based industries in the domain of *innovation studies*. To put these considerations to an empirical test, various data are presented on two worldwide significant fields of science-based technology. Using publication, patent and cash flow indicators for biotechnology, it is shown how closely interlinked knowledge production, technology development and market cash flows are. For nanotechnology, patent data on the total set of relevant organisations in Germany confirm that the strongest relations exist between use-inspired research institutes and high-tech companies, and that companies increase their technological performance by collaborating with research institutions.

In his recent review of the National System of Innovation approach, Edquist (2005) acknowledges several theoretical problems with pivotal concepts, such as "institution", "system boundaries" and "functions of its constituents". He also reports that the NIS approach has been criticised in particular as "undertheorised". The present paper has argued that the empirical literature on technological innovation can be linked with concepts and ideas of Luhmann's theory in a fruitful fashion. While Luhmann's theory itself needs further development and specifications in order to guide empirical research, as is shown for the concept of *structural coupling* in this paper, it represents a powerful analytical framework with a wide range of possible applications. One contribution of this theory to understanding processes of technological innovation is that functional systems, organisations and networks are autonomous yet interconnected levels of system formation, and that hypotheses about relationships between these levels can be proposed and tested empirically. This contribution is meant to stimulate a broader discussion on how to overcome the current lack of theory in the study of science-based innovation and research governance.

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