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KNOWLEDGE IN SCIENCE AND INNOVATION

A Review of Three Discourses on the Institutional and Cognitive Foundations of Knowledge Production

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Abstract: Modern society is said to be a knowledge society. Yet the academic discourse on the topics of learning and knowledge production is fragmented. In order to build bridges between different traditions, we review three discursive formations on contemporary knowledge production in science and innovation: *the social shaping of science (SSS) discourse*, *the knowledge in innovation (KNOWINN) discourse* and *the analogy in science (ANALOG) discourse*. We argue that the three discourses should be seen as complementary; and that a more comprehensive approach to the study of knowledge production in contemporary society can be developed by combining them. We illustrate this with an empirical example from the field of biotechnological science and innovation, and end the paper with a few proposals for fruitful ways of combining and juxtaposing the perspectives developed within the three discourses.

1. Introduction

According to a large body of literature, knowledge is becoming increasingly important as a driver of modern society. The claim is that knowledge is replacing, or at least strongly supplementing, capital as "the principle for social hierarchies and stratification, for the formation of class structure, for the distribution of chances of social and political influence and for the nature of social life" (Stehr, 1994, p. 14). Further, knowledge is said to have become the primary source of productivity and competitive advantage in the economy, which is reflected in notions such as "the learning economy" (Lundvall & Johnson, 1994). These trends have led social scientists to call for a more thorough analysis of the texture of the knowledge society (Stehr; Knorr Cetina, 1999). The significance of knowledge for socio-economic change has, in fact, been discussed since the end of the 1960s when authors such as Daniel Bell (1999) and Alain Touraine (1974) wrote about the transformation of the industrial society into a post-industrial society. Since then, different authors have tried to capture the essence of change with labels such as "the information society" (Toffler, 1980; Lyon, 1988), "the network society" (Castells, 2000), "the risk society" (Beck, 1993) and "the knowledge society" (Stehr). Others have analyzed the new, emerging culture in terms of "late modernity" (Giddens, 1994), or "postmodernity" (Lash & Urry, 1994), and described the character of social change as "reflexive modernization" (Giddens), or "extension and enlargement" (Stehr). Despite the differences in emphasis, all these notions share the view that immaterial human capacities – knowledge, values, emotions, reflection, communication and so on – are playing an increasingly important role for socio-economic and cultural change. A similar viewpoint entered economic and organizational research in the mid-1900s as the role of routines and tacit knowledge for corporate decision-making was discovered (Simon, 1945; March & Simon, 1958; Nelson & Winter, 1974; 1977), and gained significant force with the renewed interest in innovation and learning in the 1980s and the early 1990s (e.g., Freeman, 1974; 1991; 1994; von Hippel, 1988; Lundvall & Johnson, 1994; Rosenberg, 1994; 1999; von Hippel & Tyre, 1995; Lundvall, 1995).

As the production of knowledge accelerates, so does the fragmentation of knowledge into bodies of specialized knowledge. This development is not restricted to scientific knowledge production, but concerns all kinds of knowledge. *Exploitation* of knowledge, in the senses of application, refinement and further specialization of existing knowledge frameworks, is a natural tendency, because it leads to a more efficient use of resources.

On the other hand, exploitation also contains a risk of becoming trapped in "suboptimal stable equilibria" (March, 1991, p. 71); that is, of missing opportunities as a result of too narrow problem definitions or too limited searches. Economists use the term "lock-in" for describing organizations that have been trapped in some particular trajectory of production, despite signs indicating that other trajectories could be more profitable in the long run. Lock-in can be avoided through *exploration*, that is by variation, experimentation and other attempts to go beyond existing knowledge frameworks. From the societal perspective, exploration is just as important as exploitation, because it is the source of renewal and adaptation to new circumstances. The negative side of exploration is that it necessarily leads to a high degree of failure, which means inefficiency in resource use, at least in the short time perspective. As March has pointed out, in any organization, exploitation and exploration compete for scarce resources, and decisions have to be made about priorities.

One particular form of exploration consists of building connections between two or more lines of exploitation. In the context of knowledge, we call this "transepistemic exploration." We propose that knowledge exploitation and transepistemic exploration are key components in the texture of any knowledge society. Yet, both phenomena are poorly theorized in the human and social sciences. Or, to be more precise, there are many attempts to analyze and conceptualize particular forms of knowledge exploitation and exploration, but few, if any, efforts to bring together the various discourses on them. This paper is a step in that direction. We review three discursive formations on contemporary knowledge production: *the social shaping of science (SSS) discourse*, *the knowledge in innovation (KNOWINN) discourse* and *the analogy in science (ANALOG) discourse*. Our review is reflective rather than purely descriptive. In other words, we actively construct the discourses as more or less coherent bodies of knowledge, and permit ourselves to develop our own positions on various issues. Important criteria for inclusion or exclusion of texts as parts of a particular discourse were cross-citation and logical connection. The point of our effort is not empirical, in the sense of a comprehensive and neutral description, but conceptual and theoretical.

The three discourses differ by attending to distinct aspects of knowledge production and learning – from now on called "knowledge production"— in contemporary society. The SSS discourse focuses on the structure of scientific knowledge production, with "local research site," "discipline," "research program," "interdisciplinary collaboration," "boundary object" and “standardized package” as some of the key concepts. The KNOWINN discourse deals with the structure of knowledge production in firms and applies a different set of key concepts, even if some overlap exists: “core competence,” “absorptive capacity,” “functional integration,” “boundary object” and “boundary infrastructure.” These two discourses share a social and institutional approach to knowledge production. Their analyses range from aggregate studies of discipline formation or firm performance to micro-level research on the collaboration between individuals. The third discourse to be reviewed here, the ANALOG discourse, brings our attention to the individual level of knowledge production and to the role of analogy as a cognitive tool for explorative thought. Key concepts are “analogy,” “metaphor,” “mental model,” “conceptual change,” “abduction,” “problem solving” and “reasoning.”

By bringing order into a relatively fragmented landscape of thought and research, we hope to raise researchers’ awareness of the proximities and complementarities of work done in different fields of enquiry. All three perspectives have strengths and weaknesses. Together they form a rich basis for a more general theory of the epistemic texture of knowledge society. We argue that the three approaches should be seen as complementary; and that a more comprehensive theoretical framework for the study of knowledge production in contemporary society can be developed by combining them. More importantly, we also illustrate how this can be done. This is, in our view, the true task of *integrative scholarship* (Boyer, 1990; Awbrey & Awbrey, 2001).

The paper is structured as follows. There is a separate section for each discourse: the social shaping of science discourse in section 2, the knowledge in innovation discourse in section 3 and the analogy in science discourse in section 4. Each review is quite extensive and delves deeply into its respective topics. We do not discuss the links between the various discourses during the reviews. That discussion is postponed to the final section, which brings the three reviews together and explicates the strengths and shortcomings of each discourse.

2. The Social Shaping of Science (SSS) Discourse

The SSS discourse includes all scholarly interest in “the history of disciplines, the dynamics of science as a social institution, and the philosophical basis for scientific knowledge” (Hess, 1997, p. 1). However, we restrict ourselves to those parts of the SSS discourse that focus on the formation of knowledge perspectives and on the collaboration between different perspectives in scientific knowledge production. We bring together texts from a broad range of traditions within the discourse, such as science studies, the sociology of science and interdisciplinary studies. Yet, there are strong logical connections between the viewpoints that are presented below, and any lack of citation and communication across the traditions, whenever they occur, cannot be blamed on their authors' cognitive or epistemological difficulties.

What are Disciplines?

The basic unit of analysis in most discussions about science is the *discipline*. Practicing scientists often see the existence of disciplines and their derivatives, sub-disciplines, as a logical outcome of a cognitive division of labor. According to this understanding, discipline formation is driven by research, the results of which are "packed down and distilled into the teaching wing of science" (Lenoir, 1997, p. 53). The implication is that there is a complete – or at least a high degree of – overlap between the cognitive content of research and the discipline or sub-discipline as an academic institution. This is often taken for granted, with the effect that the opposite of disciplinary research is then understood to be *interdisciplinary* research (Gibbons, et al., 1997). Yet, many scholars have pointed out that disciplines are actually quite heterogeneous, from a cognitive and epistemological perspective, and that research seldom follows any strict disciplinary boundaries (Fujimura, 1996; Klein, 1996; Lenoir, 1997). Stephen Turner (2000, p. 56) has even argued that "interdisciplinarity precedes or is a more fundamental phenomenon than disciplinarity."

Definitions of the discipline can be positioned along a spectrum, ranging from cognitive to institutional approaches. One of the more elaborate analyses of the discipline as a *cognitively based unit* is that of Heinz Heckhausen (1972; see also Hemerén, 1986). He defines disciplinarity as the "specialized scientific exploration of a given homogeneous subject matter producing new knowledge and making obsolete old knowledge," and suggests seven criterion levels for identifying a discipline. Five of the seven criteria are cognitive, epistemological, or methodological, in character. The last two criteria, however, point in another direction. They are: a) the application of a discipline in fields of practice, and b) the historical contingencies of a discipline. Heckhausen (p. 86) notes that "every discipline is a product of historical developments" and that disciplines are always "in a transitional state." He also contends that disciplines are "under the sway of extradisciplinary and changing forces, such as public reputation, sociocultural values, political ideologies and economic conditions" (p. 86). Yet he fails to see that this feature of the discipline does not fit well with the idea of its being an exploration of a *homogeneous* subject matter, or, in Tony Becher's (1993, p. 42) words, that "disciplines comprise an untidy level of analysis in certain respects, in that the boundaries between them are constantly shifting and sometimes poorly demarcated, and that there are numerous apparent gaps and overlaps in their pattern of coverage of knowledge domains."

At the opposite end of the spectrum, there is the notion of the discipline as a *social institution* and, thus, a historically contingent construct, without strong causal links to the cognitive, epistemological and methodological contents of research. From that perspective, disciplines are seen, for instance, as "cartels that organize markets for the production and employment of students by excluding those job-seekers who are not products of the cartel" (Turner, 2000, p. 51). Turner argues that disciplines are effects of a standardization of training and the creation of markets for the recruitment of those who are trained. This is attained through a "disciplinary organization" (Ziman, 1999) of the academic world[1] and through the establishment of service roles in relation to the broader society.[2] Disciplines are thus the result of organizational and political[3] activity, and their function is to "demarcate areas of academic territory, allocate privileges and responsibilities of expertise, and structure claims on resources" (Lenoir, 1997, p. 56). As a result, disciplines tend to be based on "relatively broad theoretical vision, methods … techniques and instruments capable of sustaining research on a wide front of problems" (p. 56). From the cognitive, epistemological and methodological perspective, they are heterogeneous families rather than monolithic structures. This, of course, has implications for our understanding of interdisciplinarity, because it suggests that, in a cognitive sense, disciplines can be quite interdisciplinary in themselves (Klein, 1996). The opposition between disciplinary and interdisciplinary work becomes problematic, and consequently also the notion of "interdisciplinarity," which is based on that opposition (Bruun, 2000; Weingart, 2000). This leads us to the question about what we mean by interdisciplinarity and the attribute "interdisciplinary."

What is Interdisciplinarity?

Rainer Bromme (2000, p. 124, our italics) argues that the constitutive feature of interdisciplinary work is "the *distinctiveness of perspective* in the scientists concerned." However, if the discipline is not the basis for such cognitive, epistemological and methodological distinctiveness, one must ask whether there is any other foundation for it. The sociological, anthropological and historical literatures on science offer several other potential candidates. Despite there not being any consensus on how to use terminology in this matter, most conceptualizations seem to boil down to two levels of knowledge production; a) the local site of the research, such as the laboratory, research group or department, and b) the paradigm or the research program. There are, in other words, several competing theories of the institutional origin of the distinctiveness of scientific perspectives. Some approaches emphasize the influence of local interaction, others that of disciplinary formation, and still others that of large research programs or paradigms that cut across disciplines.

In science studies, there is a tradition of investigating local sites of scientific knowledge production, and several studies emphasize the role of local practices and negotiation for the stabilization of interpretations (Latour & Woolgar, 1986; Hess, 1997; Knorr Cetina, 1999). On the other hand, other scholars have complained that this gives too fragmented a picture of the making of science, because it neglects that science is often organized in broader paradigms or research programs, which are defined by a cognitive, epistemological and methodological core that the participating (local) research sites share (Fujimura, 1996; Kuhn, 1996; Lenoir, 1997). Inter- or extra-disciplinary paradigms or research programs can eventually give rise to disciplines, as did the sociological research program in the early 20th century (Turner, 2000) and the phage research program in the 1930s and onwards.[4] There is, however, no inevitability to such a development. Some research programs never become disciplines. Cancer research, for instance, is widely distributed in the disciplinary sense, although it has been argued that a relatively coherent cancer research program, based on the use of DNA recombinant technology, emerged in the latter part of the 20th century (Fujimura). Note that both local research sites and research programs can be, and often are, interdisciplinary in the sense of combining the work of people with different disciplinary training.

What are we to do with the notion of interdisciplinarity in the face of the surprisingly modest degree of relevance that disciplines seem to have for the differentiation of scientific content? We suggest making a distinction between the collaboration between representatives of different disciplines, on the one hand, and the collaboration between scientists with distinctive cognitive, epistemological and methodological perspectives, on the other.

The former could be called interdisciplinary, since it involves the crossing of the boundary of disciplines as institutions, while the latter should be labeled differently, for instance, as "transepistemic" (Knorr-Cetina, 1982; Bruun, Langlais, et al., 2002). On the basis of these definitions, we contend that interdisciplinary research is not necessarily transepistemic, just as transepistemic research does not need to be interdisciplinary. Thus, the question of the appropriate level for identifying scientific knowledge regimes – that is, systems for reproduction of more or less coherent cognitive, epistemological and methodological perspectives (Bruun, et al.) – is, in the end, an empirical one.

Finally, we want to point out that local research sites and research programs do not operate independently from the institutional formation of disciplines. On the contrary, the epistemic and the institutional realms of science are in constant interaction (Lenoir, 1997). The perspectives of research sites and programs can be developed and maintained only in an institutional context, just as disciplinary institutions seek legitimacy by attachment to scientific contents. Thus, builders of local and more global research programs use the institutional structure of science as a resource for mobilizing researchers, guaranteeing funding, etc., while, at the same time, discipline-building scientist-entrepreneurs use the authority and esteem generated by research as resources for molding the institutional structure of science. In other words, disciplines do have a stabilizing effect on scientific content at a global level, across the "numerous, diverse local practices" (Lenoir, p. 51), but this effect is, on the one hand, limited, because it does not make local sites homogeneous, and on the other hand, is not restricted only to "monodisciplinary" research sites and programs, but extends also to interdisciplinary sites and programs.

Various Forms of Interdisciplinarity

There have been many efforts to distinguish between different forms of collaboration and knowledge integration across disciplinary boundaries. The most common approach is to distinguish between different degrees of integration. Heckhausen (1972), for instance, identifies six types of interdisciplinarity,[5] Joseph Kockelmann (1979) five,[6] and Margaret Boden (1999) six.[7] A comparison of these three categorizations reveals the state of art in the research on interdisciplinarity: there is no consensus on the labels to be used or even on the logic that should underlie categorization (see notes 5, 6 and 7). In addition, most of this literature fails to distinguish between epistemic and disciplinary boundaries, and therefore proceeds from what Klein (1996) has called “the standard model of disciplinarity.” It is assumed that epistemic and disciplinary territories coincide, and that interdisciplinarity is a relatively straightforward matter of integrating existing theories, models, and contents through collaboration. The focus is on integration, and the mapping of interdisciplinarity is based on the form that integration takes. Yet, as collaboration between scientists with different perspectives, interdisciplinary, or more properly, transepistemic, knowledge production is not primarily an act of integration, but an attempt to solve a particular problem. Integration as such is not an important criterion for success, but the resolution of the problem is. Integration is just an instrument, and demands for complete integration are actually quite rare in science. In contrast, “most scientific work is conducted by extremely diverse groups of actors – researchers from different disciplines, amateurs and professionals, humans and animals, functionaries and visionaries” (Star & Griesemer, 1989, p. 387). We therefore suggest that transepistemic knowledge production should be analyzed from the perspective of communication or encounter, not integration (see Lattuca, 2001 for a similar argument).

Transepistemic communication occurs across various kinds of interfaces between knowledge regimes. There are many such interfaces in science: generic methods, theories, themes, concepts, instruments, practices, etc. (e.g. Ben-David, 1960; Mullins, 1972; Nilstun, 1986; Fujimura, 1987; Bechtel, 1993; Hübenthal, 1994; Bugliarello, 2000). There are also many methodologies for establishing links between different perspectives: hierarchical ordering, systems thinking, complexity theory, modeling, simulations, semiotics, hermeneutics, phenomenology, analogies, metaphors, and so on (e.g. Darden & Maull, 1977; Bechtel, 1986; Burian, 1993; Kincaid, 1997). In a seminal article, Susan Leigh Star and James Griesemer (1989) identify two major factors contributing to successful communication between distinct social worlds – or what we call knowledge regimes – in the case of building a natural history research museum in the early 1900s in Berkeley, California: standardization of methods and creation of boundary objects.

The standardization of methods is crucial for enabling transepistemic communication in scientific knowledge production, because a common standard facilitates understanding across local contexts. At the same time, it reduces uncertainty at the local level and thereby allows researchers to concentrate on solving new problems. Boundary objects, on the other hand, are “scientific objects which both inhabit several intersecting social worlds … *and* satisfy the informational requirements of each of them” (Star & Griesemer, 1989, p. 393). They function as a lowest common denominator that “satisfies the minimal demands of each world,” thereby allowing each social world to integrate the boundary object into its own range of activities. Boundary objects, according to Star and Griesemer, must be both plastic enough to allow divergent uses according to local needs, and robust enough to maintain a common identity across local contexts. In Star and Griesemer’s study of the establishment of a research museum, four kinds of boundary objects are identified: 1) *Repositories*, or stocks of standardized objects (the museum); 2) *ideal types*, or abstract objects that can be interpreted differently by different social worlds (the concept of species); 3) *coincident boundaries*, or “common objects which have the same boundaries but different internal contents” (the state of California as a geographical focus); and 4) *standardized forms*, that is, the embodiment of the method to be standardized in instructions, manuals, protocols, forms, etc., (the forms that amateur collectors were required to fill out when obtaining a specimen).

Transepistemic communication comes in varying forms and intensities. When integrative ambitions are low, that is, when coordination is based on division of labor rather than the formation of common perspectives, boundary objects can remain highly abstract. However, as Joan Fujimura (1992; 1996) points out, if the ambition is to stabilize more or less fixed common understandings, then boundary objects have to be more specific and also combined to constitute a network of mutually reinforcing objects. “Such codefinition and corestriction narrows the range of possible actions and practices but does not entirely define them” (Fujimura, 1992, p. 170). Fujimura’s research (1996) on the formation of the cancer research program based on recombinant DNA technology identifies the existence of a mutually reinforcing network of theory, concepts, methods, instruments and materials. This “standardized package” was attractive to researchers independent of disciplinary background, because it allowed them to “construct and solve ‘doable problems’” within their own knowledge framework. In this sense, the standardized package has the same kind of function as the boundary object: it serves as an interface between multiple social worlds (Fujimura, 1992). Fujimura also shows that the formation of a standardized package, such as that of this particular kind of cancer research, occurs in continuous interaction with the institutional dimension of both science – disciplines, funding agencies, scientific journals, etc. – and society at large.

Barriers and Opportunities

Much of the literature on interdisciplinary knowledge production focuses on identifying various kinds of disincentives and barriers for working across disciplinary boundaries. Klein (in press) provides the following, extensive list: territoriality and turf battles; disciplinary pecking order; status problems; resistance to innovation; insecurity and mistrust; lack of integrative skills; constraints of time and budget; avoidance of complexity, leading to reductionism; unfamiliarity with interdisciplinarity; rigid budgetary and administrative categories; inadequate forms of exchange; accommodating tactics that inhibit change; inertia and marginality; equipment cost and access; defaulting to individual and disciplinary perspective; opposition to interdisciplinary research and teaching; lack of incentives; inadequate reward system and performance measures; personal insecurity; and restrictive legal mandates and policies. Many of these barriers occur in disciplinary research, too.

Barriers and disincentives to communication across epistemic boundaries have multiple origins. *Epistemic barriers* have their origin in the differences between perspectives. Theories are sometimes contradictory; methodologies can be based on different, perhaps even mutually exclusive, assumptions; concepts often differ, overlap only partly, or have diverging meanings; and methods, techniques and instruments that have been adapted to particular kinds of problem solving might be unsuitable for solving other kinds of problems (Bruun, 2000). *Knowledge barriers*, on the other hand, originate in the unfamiliarity of researchers with each other's perspectives and practices. Communication becomes difficult, unless significant efforts are made to increase participants' knowledge about each other. Knowledge barriers consist not only of cognitive problems – those related to grasping the theories, etc., that the other refers to – but also of the social challenge of understanding the behavior and motives of the other. Unfamiliarity often leads to stereotypic conceptions of the epistemic contents (such as the myth of the mainstream, see Ziman, 1999) of other disciplines (Becher, 1993, pp. 27-31).

Cultural barriers emerge as a result of the distinctive practices in different research sites or disciplines. Becher's (1993; 1994) research suggests that there are many potential sources for such differences: the type of reasoning that is valued, norms for setting up experiments or field research, the type of language that is used, ways of giving a presentation, ways of organizing research (alone or collectively?), frequency of publication, types of publications that are valued, the degree of openness about research results, collaboration with industry or the public sector, the attitude toward popularization of science, etc. A common cultural barrier seems to be the stereotypic understanding of other disciplines; in this case, the simplifying conceptions do not originate in the unfamiliarity of other disciplines only, but in the identity that is cultivated by the researcher's own research site or discipline. Identities are shaped by demarcating boundaries to what one is not, or to what one does not want to be.

Administrative barriers reside in the formal organization of research and education, and relate to resource distribution, staffing, curricula, promotion and tenure, reward systems, performance measures, etc. (Klein, 1996; van der Laan, 1999; Lattuca, 2001). A common complaint is that positive valuation of interdisciplinarity by researchers, policy makers, financiers, etc., in public is not paralleled with changes at the level of formal organization. "Today's universities remain locked in academic and administrative silos that have little genuine ability to communicate or to recognize the interdependence of knowledge" (Awbrey & Awbrey, 2001, p. 270; for a deviating view, see Lattuca). Thus, while knowledge production is increasingly based on transepistemic communication, collaboration and integration, disciplinarity seems to maintain its strength as an institutional basis of scientific activity. This can give rise to tensions between the epistemic needs of research and education, on the one hand, and the formal incentives in the academic system, on the other.

Finally, there are *psychological barriers* to transepistemic communication, as a result of the personal cognitive and social investments that researchers make in disciplinary knowledge and status (Ziman, 1999). Psychological barriers are highly related to the institutional structure of academia, since the latter defines many of the opportunities and costs involved in deviations from the disciplinary path. At a personal level, pressures to work outside the customary knowledge framework can cause a sense of insecurity and fear of losing what one has gained over the years, i.e., professional identity, position, job security, salary, and esteem of peers. On the other hand, for those who do not fit well in the disciplinary framework, interdisciplinarity offers opportunities to find a new niche as well as a multidisciplinary social reference group (Lattuca, 2001).

The mere amount of disincentives and barriers might seem discouraging. Are interdisciplinary activities viable at all? Fortunately, the literature has registered several reasons for optimism, too. Starting with the *epistemic barriers*, there are many examples of successful linking of different knowledge frameworks, and there is no reason to believe that this will not continue (see, for instance, Bechtel, 1986; 1993; Fujimura, 1996; Miettinen, Lehenkari, et al., 1999; Mey, 2000). *Knowledge barriers* and *cultural barriers*, in their turn, are lowered by the educational system in most countries. Students are, almost without exception, required to choose one or two secondary subjects as a part of their education. There is also generally an introduction to a range of disciplines in the beginning of undergraduate studies. Further, multidisciplinary approaches seem to have become increasingly common in both educational programs and research. The present practices of allocating external funding to collaborative research projects increase researchers' contacts across disciplines, and thus their familiarity with each other. A closer look reveals that there are indeed a huge number of arenas for transepistemic communication: seminars, conferences, courses, journals, Internet chats, etc. (Lattuca, 2001). Further, one should be careful not to overemphasize the role of disciplinarity in shaping individual behavior and motivation. Disciplinary identity is just a part of the full personal identities of individuals. As a result, the meaning of disciplinary identity varies from researcher to researcher. As Collini (1998) has pointed out, "... we need to think in terms of degrees of participation in these shared worlds rather than in terms of simple inclusion or exclusion."

Administrative barriers to interdisciplinary collaboration do exist, but there are also many examples of administrative arrangements that encourage boundary crossing – for instance, multidisciplinary research and education programs in universities, the Sixth Framework Programme of the EU, NSF's Engineering Research Centers Program (ERC) and its Science and Technology Centers, national research and technology programs, multidisciplinary graduate schools and interdisciplinary institutes such as the Santa Fe Institute in the U.S. and the Centre for Interdisciplinary Research at Bielefeld University in Germany (see, for instance, Roy, 2000; Weingart & Stehr, 2000; Tuomaala, Raak, et al., 2001). *Psychological barriers*, finally, may be decreasing in the late modern, or post-modern, culture, in which complex identities that mix various dimensions and levels of social life are commonplace. The contemporary economy, in which short-term employment and occupational mobility are normal phenomena, and which emphasizes continuous learning, adds to the intricacy of individual identities.

In sum, then, the reality of interdisciplinary learning and knowledge production in contemporary science is a complex outcome of inhibiting as well as excitatory factors. Some scholars emphasize the growing role of exploration across boundaries (Gibbons, Limoges, et al., 1997), while others dispute the existence of such trends (Weingart 1997). Much depends on what one chooses to see: the barriers, restrictions and failures in collaboration, or the opportunities, supportive measures and successes.

3. The Knowledge in Innovation (KNOWINN) Discourse[8]

The notion of innovation is used in many different ways. Common for most usages, however, is a stress on the production and successful commercialization or application of novelty, whether as new products, new manufacturing methods, new organizational structures or new strategies. Innovation processes and innovative activity are studied within several academic fields, including organization theory, evolutionary economics, neoclassical economics, science and technology studies, technology management, knowledge management and industrial management. In this paper, we focus on the organizational and economic research on innovations – more specifically, on the segment that attends to the problem of knowledge production and integration in innovation. We begin with a review of some of the reasons for the interest in knowledge integration among organization theorists and economists. Then we turn to some of the theoretical concepts that have been used within the KNOWINN discourse to analyze the challenges that innovating organizations face with respect to knowledge.

Knowledge and Organizational Capability

Most of the innovation literature reviewed here proceeds from a resource-based theory of the firm. This approach, which sees *knowledge* as a key asset for firm competitiveness, was developed as a response to what was considered to be deficiencies in the dominant, neoclassical approach to economics. Neoclassical economics conceptualizes economics in terms of decision-making and market mechanisms. Decision-making is seen as a process involving two main elements: information about supply, demand, prices and so on, on the one hand; and rational processing of this information so as to maximize the present value of some utility function, on the other. In the early days of neoclassical analysis, the availability of information was not seen as a problem. Implicitly, information was assumed to be generic, accessible at no cost, codified and context-independent (Cusmano, 2000; Cohendet & Meyer-Krahmer, 2001). Thus, the focus was on the rational processing of information rather than on information itself.

Subsequently, however, economists began to realize that the assumption of perfect information is not only a simplification, but is misleading, because it gives a false picture of how economic decisions are made. Nelson and Winter

(1974; 1977) were among the first to point out that firms often face situations in which information is restricted, not only because of the costs – in time and money – of acquiring it, but more importantly because of uncertainty about future developments of markets and technologies. Their argument is that the effect of these restrictions goes beyond a mere complication of the maximization of utility functions. Firms cannot rely on thorough, rational analysis in such situations. Instead, they use decision-making heuristics or routines that have turned out to be successful during the previous history of the firm. From that theory, the new approach that emerged, which is often associated with "evolutionary economics" and "institutional economics," emphasized the *differences* between economic agents rather than the similarities. Routines, norms and rules for behavior accumulate in a path-dependent way and are therefore firm specific. If decision-making is based on contingent rules rather than universal rationality, then organizations will have distinct decision-making capabilities.

The two ways of thinking about firms have different implications for firm strategy. The first, the neoclassical approach, leads to strategy theories that emphasize choice of markets, positioning in the markets and strategic moves to deter entry or raise prices. The resource-based perspective, which is based on the institutional understanding of firm behavior that was described above, proceeds instead from the idea that competitive advantage rests on the firm's idiosyncratic and difficult-to-imitate resources (Teece, Pisano, et al., 2002), and therefore emphasizes the role of firm-specific factors in contrast to industry and market effects. Strategy should then focus on identifying the firm's unique resources, and on making decisions about in which markets these can best be used. It should also deal with the need to maintain and/or develop the organization's *capabilities* so as to achieve and sustain competitive advantage. As Teece and his colleagues argue, "… if control over scarce resources is the source of economic profits, then it follows that such issues as skill acquisition, the management of intangible assets, and learning become fundamental strategic issues" (Teece, et al., p. 337).

To be capable of something is "to have a generally reliable capacity to bring that thing about as a result of intended action" (Dosi, Nelson, et al., 2002, p. 2). Capabilities are, in this sense, *constitutive* (Bruun & Langlais, 2003) for the actions and activities that organizations such as firms perform. In our understanding, the concept of capability refers to the whole range of skills, routines, assets and contingent factors that build up that reliable capacity to act in particular ways. Thus, capability can be a result of a number of factors such as particular problem-solving procedures, technical skills, management skills, understanding of demands and users' requirements, mastery of technology, licensing agreements, close position to raw material supplies, location in a low-wage cost region and infrastructure. In the present context, however, we are mainly interested in the role that knowledge has for capability and that capability has for knowledge production.

Core and Peripheral Competence

One of the most influential concepts for linking knowledge and capability is that of "core competence." Hamel and Prahalad (1996, pp. 223-233) define core competence as "a bundle of skills and technologies" that is "competitively unique," "makes a disproportionate contribution to customer-perceived value," and is generic in the sense that it can "form the basis for entry into new product markets." Hamel and Prahalad emphasize that the key to understanding knowledge generation within a company is to go beyond discrete skills, technologies or disciplines to study how these combine to form larger wholes. For instance, in the 1990s, Federal Express possessed a core competence in routing and delivery, which rested on the integration of bar-code technology, wireless communications, network management and linear programming (Hamel & Prahalad).

Hamel's and Prahalad's (1996) major point is that firms need to focus their activities around a limited number of competencies so as to avoid dilution of attention. Their argument is, first, that a distinction should be made between "core" and "non-core," or peripheral, competencies. The latter might be important for the normal functioning of the firm, but they should not be a major focus in corporate strategy. Their second argument is that the core competencies should be limited in number, preferably four or five. There are costs associated with the building and maintenance of competencies, and too broad an approach may undermine the focus and coherence needed. If one keeps the number of competencies small, however, this can create long-term leadership and competitive strength for the successful corporation (Dosi, Nelson, et al., 2002, p. 6).

There is, though, debate about the kinds of knowledge that affect firm performance. Hamel and Prahalad have been criticized for neglecting the fact that in rapidly changing sectors companies also need to have *complementary competencies*, so as to be able to understand threats and opportunities in the development of relevant fields outside the core competencies (Tidd, Bessant, et al., 2001). Further, the two authors have been said to focus too much on *technical knowledge* in the organization, at the neglect of the *organizational knowledge* that is also needed, or "… how to organize and manage projects, coordinate different problem-solving activities, determine goals and incentives, allocate resources and assign personnel, and resolve disputes ..." (Pisano, 2002, p. 132). There remain important questions about how firms should structure their portfolios of core and complementary competences in order to build up a capability for absorbing new knowledge and changing their ways of operation whenever needed. Absorptive capacity and cognitive distance are important concepts for achieving that.

Absorptive Capacity and Cognitive Distance

Cohen and Levinthal (1990, 128) define *absorptive capacity* as "the ability to recognize the value of new, external information, assimilate it, and apply it to commercial ends." The authors emphasize the role of investments in internal learning within organizations for the ability to absorb new knowledge. Much of the literature on absorptive capacity is quantitatively-oriented and aims at measuring the relation between absorptive capacity and the performance of the firm (Cohen & Levinthal, 1989; Cockburn & Henderson, 1998; Cusmano, 2000). In this context, however, we prefer to use the concept in the more qualitative, hard-to-measure sense of routines, norms and rules that shape knowledge production in organizations. This set of practices forms a *context of interpretation* for the members of the organization, a context that affects the knowledge framework through which individual people interpret new information.

There are many dimensions to knowledge absorption. From the cognitive perspective, knowledge absorption involves at least two basic components: the knowledge framework of the people within the "absorbing" organization, on the one hand, and the knowledge framework that is implied in the knowledge to be absorbed, on the other. The difference between the two can be described in terms of *cognitive distance*. When the cognitive distance is large, the degree of novelty is high, but comprehensibility is low. A small cognitive distance, on the other hand, makes comprehension easier, but restricts novelty (see Nooteboom, 2001). Difficulties in comprehension translate into costs and risks for the firm, while novelty is related to potential profits.[9] The proper choice between novelty and comprehensibility depends on the aims of the firm. However, as a result of the trade-off, there is a range of solutions that are optimal in the sense that they balance novelty and comprehensibility in an efficient way for each situation.

Knowledge absorption is a complex process. Zahra and George (2002) distinguish between four aspects of knowledge absorption: 1) the acquisition of knowledge, as measured by intensity, speed and direction; 2) the assimilation of knowledge, which refers to “the firm’s routines and processes that allow it to analyze, process, interpret, and understand the information obtained,” (p. 189); 3) the transformation of knowledge, for instance by building linkages between knowledge that already exists in the firm and the new, assimilated knowledge; and 4) incorporation of the acquired, assimilated and transformed knowledge into the firm’s operations (exploitation). Zahra and George also point out that a distinction should be made between *potential* absorptive capacity (PACAP), on the one hand, and *realized* absorptive capacity (RACAP), on the other. PACAP refers to the firm’s “capability to value and acquire external knowledge,” which should be distinguished from its ability to exploit this knowledge in its business activities. Thus, firms that invest in, for instance, research and development (R&D) and as a result increase their PACAP might fail to transform it into economic value (RACAP). Zahra and George’s point is important, because many scholars have used the size of R&D investments (as share of turnover) as an operationalization of absorptive capacity, thus neglecting the potential problems in turning PACAP into RACAP.

Van den Bosch, Volberda, et al. (1999) point out that a high level of absorptive capacity has no value in itself for firms, but depends on the “knowledge environment” of their activities. The value of absorptive capacity is highest in turbulent knowledge environments, where competitiveness, or even pure survival, requires an ability to rapidly adapt to new circumstances and new knowledge demands. In stable knowledge environments, on the other hand, knowledge production tends to be incremental. The knowledge base for competitive advantage in mature industrial sectors tends to be in exploitation rather than exploration, which means that absorptive capacity is of secondary significance – at least until the sector becomes subjected to some sudden, radical change.

Practices of Knowledge Generation

The research on absorptive capacity emphasizes the need for firms to absorb external knowledge. Equally important is, however, the capability to integrate knowledge *within* the firm. Some scholars even argue that “the primary role of the firm is the integration of knowledge” (Grant, 1996, p. 377). Knowledge is needed for a whole range of activities in firms, and it seems, as suggested in the introduction, that its importance for the creation of value and the competitiveness of firms is growing. However, as Grant points out, there are constant pressures to specialize the knowledge within the firm, because, given the restrictions of human cognition and communication, this is the only way to reach depth. At the same time, good performance – in the sense of creating value "through transforming input into output" (Grant, p. 377) – requires that knowledge is coordinated and integrated across specialized functions (Tidd, Bessant, et al., 2001). Grant suggests that knowledge integration in firms is organized hierarchically. At the base there are individuals with specialized knowledge related to their tasks. At the middle level are departments or functions in which the specialized knowledge of individuals is integrated into "functional capability": R&D, design, manufacturing, finance, marketing, etc. At the top of the hierarchy are activities that require "wide-ranging, cross-functional integration," such as new product development. From a management perspective, this is the most complex level, because integration of middle level capabilities – that is, departments with functional expertise – can only be achieved through the interaction of individuals, whose cognitive performance is carried out at the bottom level of the hierarchy. Cognitive and communicative constraints restrict the number of individuals that can be directly involved in advanced, integrative activities, yet there is a need to integrate "an extremely broad basis of knowledge" (Grant, p. 378). It is therefore, according to Grant, important that the organizational hierarchies of authority and control correspond to the knowledge integration needs of the firm. Often, however, this is not the case. Grant points out that many top management capabilities are quite specialized – for instance, capital budgeting, strategic planning and government lobbying – and thus involve "a limited scope of knowledge integration."

Much of the literature on innovation treats knowledge integration at a rather abstract level, focusing on structural issues and on the firm at an aggregate level. There are, however, a few scholars who have gone deeper into the question of knowledge formation within firms. The approach has been similar to that of science studies: it is assumed that individual knowledge is shaped in an institutional context, and that people perceive the environment as a function of the mental constructs they use to interpret the world. Consequently, the crucial question concerns the level at which the relevant institutional context should be identified. Margherita Turvani (2001) argues that spatial and cultural proximity are crucial for creating shared behavioral models. This is also the assumption of Wenger (2002), who coined the notion of *community of practice*. Communities of practice are formed by people who are involved in a shared activity – such as research, product development, accounting, marketing, selling – and who share an understanding of that activity (see also Dougherty, 1992, p. 182). A practice is shared when it becomes the structured context within which the activities of individuals are performed, and within which they are interpreted (Cook & Brown, 1999, pp. 386-387). Such practices are normative: they set standards for procedures, judgments and methods, and define competence as the capability of the agent and the department as a whole to live up to those standards. At the same time, communities of practice also touch upon the *identities* of people: e.g. “This is what I do”; “This is what I am good at”; “I feel at home doing this” (Brown & Duguid, 1991; Dougherty, 1992; Wenger, 2002).

To summarize, there is, just as in the SSS discourse, an emphasis on the local site of knowledge production. On the other hand, there is also a common conception that there is continuity across local sites that perform similar functions. Dougherty (1992), for instance, identifies common patterns in the “thought worlds” of functionally similar *departments*, independent of firm (see also Carlile, 2002). Such similarity seems to be greater than the similarity between functionally distinct departments within one and the same firm. According to Dougherty, the thought worlds of functional departments are distinguished by three “themes”: a) what people see when they look into the future; b) how they interpret the product development process; and c) how they understand the development task itself. As an example, Dougherty found that “technical people” – people involved in research or engineering – differed from “field people” who work in sales and customers relations. When looking into the future, for instance, technical people focused on technological trends, problems and opportunities. Field people, in contrast, saw the future in terms of user trends and shifts. Further, the two groups had different understandings of the product development process. For technical people, the critical aspect was the specification of what the product should do, or what users want to have, while field people were concerned with the continuously changing needs of users. As a result, field people were often unable to give the specification of customer needs and product requirements that the technical people wanted to have. Another interesting discovery in Dougherty’s study was that all other departments had difficulties in understanding the output of planners – people in market research or business analysis – who operate at an abstract, conceptual level that is difficult to align with the more hands-on approaches of the other departments.

The organizational function and its embodiment in the department can be seen as analogs to the discipline and the university department in science. Dougherty’s study seems to confirm what most innovation scholars take for granted when they talk about "the challenges of functional integration." Considering, however, the complexities of the discipline as a designator of the institutional context for the formation of scientific contents, one should also be careful with the use of "department." Departments are units in the formal structure of authority and command and do not necessarily constitute knowledge regimes. They should therefore be treated as formal institutions, or organizational units, while the question about the relation between the department and the actual formation of knowledge frameworks in the firm remains an empirical one. The operations of companies are often significantly more complex than the organizational charts suggest, with task forces, cross-functional project teams, virtual teams, job rotation, company level routines, knowledge management systems, informal networks and collaboration with other firms, universities or authorities as potential sources of complexity in the epistemic texture of the firm.

Knowledge Integration in Firms

In innovation research, the notion of knowledge integration in firms is a matter of creating competitive advantage. According to Grant (1996), the relation between knowledge integration and competitive advantage can be analyzed from three perspectives: efficiency of integration, scope of integration and flexibility of integration. *Efficiency of integration* is crucial, because "competitive advantage depends upon how productive firms are in utilizing the knowledge stored within individual organizational members, which is dependent upon the ability of the firm to access and harness the specialized knowledge of its members" (Grant, p. 380). According to Grant, integrative efficiency is influenced by the level of common knowledge in the firm, the frequency with which tasks are performed, and the extent to which organizational structure reduces the need for communication. The second factor affecting competitive advantage is the *scope of integration*, that is, the span of specialized knowledge that is integrated. Scope is relevant because it makes replication by competitors more difficult, and because it increases the absorptive capacity of the firm. On the other hand, the greater the scope is, the more complex the knowledge integration. This is a problem not only for competitors who want to imitate, but also for the firm itself as it is faced with significant management challenges. Scope is not, however, enough in itself. Firms must be *flexible*, too, being able to change their knowledge base and integrate new knowledge. They should also be able to reconfigure the specialized knowledge they already have, by finding new ways of integrating it (Van den Bosch, Volberda, et al., 1999).

The three sources of competitive advantage – efficiency, scope and flexibility – do not necessarily reinforce each other. For instance, flexibility and efficiency stand against each other, because changes (flexibility) imply that more time must be spent on communication and the search for new integrative mechanisms (Grant, 2001).

What mechanisms are there for knowledge integration in firms? Suggestions abound, and are presented at various levels of organization and abstraction. At the firm level, Grant (2001) identifies two main mechanisms: "direction" and "organizational routines." Direction is achieved through documents, such as operating manuals or protocols that provide explicit rules and instructions for action, and in effect align the performance of different people or units (Orlikowski, 2002). Various tools and methodologies have been developed for enabling alignment. On the other hand, many activities are too complex or too context-dependent to be codified in any straightforward way. In those cases, one has to rely on organizational routines that develop over time. Integrative routines emerge as "individuals develop sequential patterns of interaction which permit the integration of their specialized knowledge without the need for communicating that knowledge" (Grant, p. 379). Teams, for instance, can develop tremendous efficiency over time by developing informal routines based on commonly-understood roles and interactions (Orlikowski). Normally, firms utilize both direction and routines to effect knowledge integration across people and departments. A third mechanism for knowledge integration is "socialization," that is, the production of "a shared ideology that offers members an attractive identity as well as collective interpretations of reality" (Van den Bosch, Volberda, et al., 1999, p. 557). Socialization produces social cohesion and increases the capacity of the firm to exploit knowledge. Its negative side is that it can create "mental prisons that prevent people from seeing important changes, for instance, in the market" (p. 557).

Communication across knowledge boundaries creates transepistemic knowledge networks. Such networks can have different characteristics, depending on how the different perspectives are aligned with each other. A common strategy is to decompose tasks into several sub-tasks – for instance, sequential phases, functions, or product segments – with the effect of creating a set of semi-independent systems for problem solving. The output from these can then be coordinated in time and/or space. These modular knowledge networks can be contrasted with two other types of knowledge network, translational and pioneering (Bruun, Langlais, et al., submitted).

Translational knowledge networks use standardized interfacing devices, such as CAD software, to enable direct communication between people with specialized knowledge. In industrial manufacturing, such software is used, for instance, to create virtual prototypes that are available for direct manipulation by several departments. All manipulations can be observed by the other functions that can in turn respond with new manipulations. The interfacing device reduces the problems of communication and understanding that otherwise tend to occur between people with different knowledge (D'Adderio, 2001). On the other hand, standardized interfacing devices work only if they are functional from the perspective of communication, and if people learn to translate their own knowledge into the language of the device (Henderson, 1991).

Modular and translational knowledge networks are proper solutions when the task to be performed is relatively well known and when principles for division of labor or standards for interfacing devices are at hand. Sometimes, however, this is not the case; then, communication across knowledge boundaries must be more open-ended and explorative in orientation, the requirement being that participants are prepared to move outside their normal frame of thinking and be open for influences from other perspectives. Without an established semantics for communication, boundary objects have to be developed. Innovation scholars have used the term "boundary object" in the same sense as Star and Griesmer (1989) have in science studies. The former have developed the concept, however, by adapting it to the analysis of less scientifically oriented activities. Consequently, Carlile's (2002) categories of boundary objects differ slightly from Star and Griesmer's original ones (see above). They include: 1) *repositories,* such as databases and libraries, which "supply a reference point of data, measures, or labels across functions;" 2) *standardized forms and methods*, which "provide a shared format for solving problems across different functional settings;" 3) *objects, or models*, such as sketches, assembly drawings and prototype assemblies, which "can be observed and then used across different functional settings;" and 4) *maps of boundaries*, such as process maps, workflow matrices and computer simulations, which "represent the dependencies and boundaries that exist between different groups or functions at a more systematic level" (see also Henderson, 1991; Carlile, p. 451).

Boundary objects facilitate communication across knowledge regimes in the absence of standardized interfacing devices. Yet, as Carlile (2002) points out, they are no "magic bullet," because they depend on active maintenance and are hard to sustain. In isolation, the effect of a particular boundary object on knowledge generation is limited, but taken together, they can form a mutually reinforcing "boundary infrastructure" for exploration in a pioneering knowledge network.

4. The Analogy in Science (ANALOG) Discourse

Among the many approaches to the study of science, we may distinguish one that has a special focus on the cognitive aspects of scientific knowledge production: mental structures and processes relating to concepts, representations, reasoning, etc. Scholars of the cognitive studies of science have criticized the philosophical and socio-cultural accounts for ignoring the workings of human cognition in knowledge production. Philosophy of science has traditionally operated within a logical positivist understanding of knowledge, while human cognition involves a much broader range of structures and processes than logic describes (Nersessian, 1992; 1999; Thagard, 1994). Socio-cultural accounts, in turn, have established the importance of interests, motivations, culture and social context, but have treated cognition as a "black box" (Nersessian, 2004) and have left questions of the impact of social context on the scientist's knowledge unanswered (Dunbar, 1995). For example, some authors in the discourses above have emphasized the role of metaphor and analogy in borrowing insights from other perspectives in interdisciplinary communication (Bromme, 2000; Nooteboom, 2001), but these analyses have remained rather shallow.

In the present review, we attempt to improve the situation by depicting a discourse that involves one of the cognitive components in use in scientific knowledge production, namely that of analogical thinking. Cognitive science, in general, and research on analogy, in particular, have been acclaimed as model examples of successful interdisciplinary research (e.g. Thagard, 1997; Gentner, 1998; Schunn, Crowley, et al., 1998; Holyoak, Gentner, et al., 2001, p. 10). In fact, current views on analogy are the result of converging interests between cognitive psychology, artificial intelligence, cognitive neuroscience, linguistics, philosophy and the history of science. Some branches of history and philosophy of science have taken a cognitive turn after becoming influenced by cognitive psychology and artificial intelligence, and cognitive scientists have found the domain of scientific thinking and discovery a fruitful object for the study of human cognition.

Analogy and Metaphor in Human Cognition

Analogies are partial, highly selective similarities between different situations that support further inferences (Gentner, 1998). Analogical thinking is a creative process in which existing modes of representation are abstracted from a source domain and fitted to the constraints of a new, less understood target domain (Nersessian, 1992). Two main theories of analogy, both originating from the 1980s, are Gentner's structure-mapping theory and Holyoak and Thagard's more pragmatic multi-constraint theory (for comparison between these views, see e.g. Holland, Holyoak, et al., 1986, pp. 300-304; Spellman & Holyoak, 1996; Kurtz, Gentner, et al., 1999, pp. 176-177). For our purposes, it will suffice to be able to extract the generally accepted understanding of how analogies are processed. First, one or more potentially useful analogs have to be accessed either by retrieval from memory, by compilation, or construction. This source analog is then mapped to the target analog in order to identify relevant, systematic correspondences. In particular, instead of surface similarities, common systems of relations between objects are searched. Mapping also allows the generation of further inferences about the target in order to fill gaps in understanding. The analogy and its inferences are evaluated and possibly adapted to take into account unique aspects of the target. Finally, as a result of learning from the success or failure of the analogy, new categories and schemas may be abstracted that can be used for later retrievals (Holland, et al., pp. 292-295; Gentner, 1998; Holyoak & Thagard, 1999, p. 15; Holyoak, Gentner, et al., 2001).

Analogy unavoidably connects us to its close relative, metaphor. Analogy can even be seen as a special case of metaphor, since, whereas metaphor spans the range from attributional, expressive-affective comparisons to relational, explanatory-predictive ones, analogy is a purely relational match and is used only in explanatory-predictive contexts (Gentner & Jeziorski, 1993; Gentner & Wolff, 2000). Most relational metaphors can be analyzed in the same way as analogies (Holyoak & Thagard, 1999, pp. 217-223; Gentner & Wolff); an analogy in a way operationalizes a metaphor (Tsoukas, 1991). As is noted below, some scholars use the term analogy, while others use metaphor, when analyzing science from a cognitive perspective. From our point of view, however, they are discussing basically the same phenomena. Thus, for simplicity, we treat them equally and mix them. Whether a metaphor refers to a strictly structural analogy in a problem-solving context, or to a looser analogy behind a worldview, or paradigm, should be clear from the context.

Analogy is a central component of human cognition. According to Gentner (1998), analogy contributes to learning by transferring knowledge and inferences across different concepts, situations and domains; analogies are used in problem solving and reasoning; analogies can serve as mental models in understanding a new domain; analogy is central in creativity; it is used in communication and persuasion; and analogy also underlies many other cognitive processes, such as categorization, reasoning and making conceptual metaphors. Analogy is, in fact, no less than a primary means for transferring knowledge from one domain to another (Nersessian, 1992).

Examples of Analogy and Metaphor in Science

Analogy also abounds in science. It has been found to play a significant role in scientific problem solving and reasoning; scientific discovery; hypothesis posing, testing and evaluation; model building and theory formulation; conceptual change; scientific communication and exposition of ideas; and the teaching and learning of science (e.g. Nersessian, 1992; Dunbar, 1995; Gentner, Brem, et al., 1997; Holyoak & Thagard, 1999; Gentner & Wolff, 2000; Duit, Roth, et al., 2001; Thagard, 2003). There are myriad instances of the use of analogy and metaphor in science; we only present a few diverse but otherwise rather random examples. Holyoak and Thagard (1999) list several famous examples of scientific analogies that have contributed to a major theoretical advance: sound/water waves, earth/small magnet (Gilbert), earth/moon (Galileo), light/sound (Huygens, Young & Fresnel), planet/projectile (Newton), lightning/electricity (Franklin), respiration/combustion (Lavoisier), heat/water (Carnot), animal and plant competition/human population growth (Darwin), natural selection/artificial selection (Darwin), electromagnetic forces/continuum mechanics (Maxwell), benzene/snake (Kekulé), chromosome/beaded string (Morgan), bacterial mutation/slot machine (Luria), and mind/computer (Turing). Dunbar (2001) mentions the discovery of Upsilon Andromedae with its three planets as a more recent example. Scientists had long been searching for a multiple-planet solar system analogous to ours, and after the discovery, they started mapping features of our solar system to the unknown one. To mention just a few more examples from the natural sciences, Dunbar (1995) reports frequent use of analogies in molecular biology laboratories, and Shelley (1999) demonstrates the vital role of (visual) analogical reasoning in evolutionary biology, in which the idea of extinct animals can only be understood by comparison with living ones.

Cognitive psychologists have made analyses of metaphors and analogies in their own field. Gentner and Grudin (1985) analyzed the metaphors for mental phenomena that were used in *Psychological Review,* from 1894 to 1975, in order to trace changes in psychologists' models of the mind. They found changes both in the frequency and in the categories of the metaphoric source domains used over time. Spatial and animate-being metaphors dominated in the early samples, and systems metaphors – mechanical, physical science, mathematical, symbol and computer systems – especially computer system metaphors, in later samples. They proposed that metaphoric language might be indicative of the underlying conceptual paradigms of scientists (Gentner & Grudin). Fernandez-Duque and Johnson (1999) demonstrate the constitutive role of conceptual metaphors in psychologists' understanding and reasoning about attention and therefore also in the formation of scientific theory and in research on attention. Fernandez-Duque and Johnson rely on the "conceptual metaphor theory" in which the human conceptual system is seen as inherently metaphorical. Other proponents of this view argue that the most fundamental concepts and operations of such formal sciences as mathematics are defined by metaphors (Lakoff & Nunez, 2001).

Sociologists and political scientists have employed analogies between society and organism and between state and machine, or family, and historians have drawn on comparisons between similar situations (Holyoak & Thagard, 1999, p. 197). Many concepts of economics, such as "elasticity," "depression," "equilibrium," "competition," or money's "velocity," are dead metaphors from non-economic spheres. Speaking of an invisible hand is clearly metaphorical, as it is to say that markets can be represented by supply and demand curves (McCloskey, 1983). Knudsen (2003) calls these kinds of dead metaphors closed metaphors. After a metaphorically structured hypothesis has been introduced, it is tested and accepted, or rejected, just as any scientific hypothesis would be. An established, or closed, metaphor – such as Knudsen's examples of the genetic code, messenger RNA, and translation – that has been included in the dominant scientific mental model is treated like any other scientific concept and is no longer considered metaphorical (Knudsen).

In his studies of biological scientists, Dunbar (1995) commented on the nature of analogical sources. According to his online observations in molecular biology laboratories, most of the analogies drawn were either local or regional – e.g., between very similar experiments on the same or same type of organism. Remote, long-distance analogies were rare and mostly used in teaching new researchers, or for clarifying a point for other members in a meeting. Distant analogies are, however, frequent in historical documents of scientific discoveries. Gentner, Brem, et al. (1997) propose the explanation that local analogies are available and useful for filling in an established framework (i.e., exploitation, in our terms), whereas more distant analogies may be the only possibility in creating a new framework (i.e., exploration, in our terms). Kepler, for instance, used many rather close analogies – such as sun and planets/earth and moon – but also many distant analogies when he was forming the new science of astrophysics (Gentner, et al.).

The role of analogy and metaphor in advanced knowledge production has changed over time. Gentner and Jeziorski (1993) illustrate a significant difference in the ways that medieval alchemists and modern scientists used similarity in their reasoning about the natural world. The alchemists' unconstrained use of all kinds of metaphorical similarities – including structurally inconsistent mappings and emphasis on surface similarity and symbolic reference – was rejected in favor of structurally consistent, one-to-one mapping analogs by more modern scientists such as Boyle, Carnot and Kepler. The authors suggest that the shift was partly due to a change in tacit cultural understanding of when and how to use analogy and other forms of similarity in justifying scientific theories and beliefs (Gentner & Jeziorski).

The debates on the proper use and role of analogy and metaphor in science have not ceased, however. Metaphors and analogies can indeed lead to erroneous or incomplete inferences if the analogist relies on plausible mappings and inferences without properly testing, evaluating and adapting them to the target (Holyoak & Thagard, 1999, p. 131), or if one is satisfied with drawing from examples worked out in the past, and avoiding hard thinking (Gentner, Brem, et al., 1997). As a cautionary example, Holyoak and Thagard (pp. 197-198) refer to Nancy Leys Stepan's analysis of the seriously erroneous analogy between race and gender and its occupation of a strategic place in scientific theorizing about human variation, for example, by linking intellectual inferiority with low brain weights of women and "lower" races.

In organization theory, Gareth Morgan's (1980) influential claims about the metaphorical nature of organization theory and more practical suggestions about using metaphors to diagnose and solve problems in organizations (Morgan, 1986) have aroused a lot of criticism. The most severe critics have warned about the detrimental effect of figurative language for the progress of organization theory (e.g., Pinder & Bourgeois, 1982), while others have made suggestions about how the initial metaphorical insights could be transformed to yield explicit literal knowledge in the form of scientific models (e.g., Tsoukas, 1991; 1993). Questions concerning metaphors and analogies have quite naturally been under discussion in such new research fields as industrial ecology, which has itself been founded on a metaphor (e.g., Bey, 2001; Salmi, 2001). Industrial ecology draws heavily on natural ecosystem metaphors and biological analogies in order to design more ecologically benign industrial systems. Isenmann (2003), in a recent paper, warns about the potential "philosophical pitfalls, ethical shortcomings and epistemological fallacy" in relying on metaphor and analogy in justifying the tenets of industrial ecology. Also Johansson (2001) warns of the danger that vague emotionally charged environmental metaphors – for instance, eco-efficiency, eco-design, eco-industry – can be taken as formally valid and start to live a life of their own in science and politics.

Several scholars stress the importance of being aware of the metaphors that implicitly guide scientific thinking and theorizing, whether the subject of study is world history (Cummings, 2000), psychological processes of the human mind (Ambrose, 1996; Fernandez-Duque & Johnson, 1999), the economy (McCloskey, 1983), or organizations (Morgan, 1980). It seems indeed to be warranted advice, if it is true, at least, that no science is free from metaphors, no matter how mature it is (Fernandez-Duque & Johnson, 1999).

Analogical Thinking and Conceptual Change in Science

We now shift our focus more closely to the mechanisms through which analogies can induce changes in knowledge. Explaining how conceptual change works is important for understanding the nature, growth and development of scientific knowledge (Nersessian, 1998; Thagard, 2003). The term "conceptual" change may refer either to a change in concepts or more generally to any change in the conceptual structure, including the levels of theory change and belief change (Gentner, Brem, et al., 1997). Most conceptual change in science relates to introduction and modification of concepts within existing conceptual schemes and theories (i.e. exploitation) instead of large-scale transformations of conceptual systems (Thagard). However, researchers have paid most attention to radical conceptual change (i.e. exploration). Scientific revolutions typically involve the introduction of: completely new concepts, such as gravitational force, spin, natural selection, continental drift; reclassification, in which a concept changes its place in the hierarchy, such as when Earth is classified as a planet, humans as a kind of animal, or thinking as a kind of computing; changing principles of classification, e.g. organizing species on the basis of evolutionary history instead of similarity; or disappearance of existing concepts, such as phlogiston from chemistry. Some concepts in new structures can be seen as descendants of existing ones – such as mass and field in relativity theory – or as absorbing significant aspects of disappearing concepts – such as the former ether vs. the later field and space-time (Nersessian, 1992; Thagard). One example of the most radical conceptual changes in the history of science is the so-called chemical revolution, i.e. the development of the oxygen theory of combustion and calcination by Lavoisier in the late eighteenth century. It required the replacement of the whole conceptual structure with different concepts of substance and element and new concepts of oxygen and caloric, and the removal of the concept of phlogiston – sulfurous earth with negative weight – from the lexicon (Nersessian, 1998).

How are these kinds of changes arrived at? The most important cognitive mechanisms of conceptual change are conceptual combination and analogy (Holland, Holyoak, et al., 1986; Thagard, 2003). Conceptual combination is frequent in the context of analogical problem solving (Holland, et al., p. 338; but see Keane & Costello, 2001, for an argument for the separateness of analogy and conceptual combination). Conceptual combination forms new concepts by combining two existing ones. Sound wave, light wave, natural selection and gastric bacteria are examples of such concepts in science. These kinds of concepts may not simply be the sum of the original ones; instead the internal structure of the original concepts makes the combination more complex with emergent properties (Holland, et al., pp. 338-339; Thagard, 1998). Analogy is the other major mechanism of conceptual change in science, affecting both concepts and theories. Scholars have used slightly varying vocabulary when analyzing the role of analogy in conceptual change, but processes like analogical problem-solving and reasoning, abduction, analogical schema formation, imagistic reasoning and thought experiments, or simulative modeling, have been mentioned (Holland, et al.; Gentner, Brem, et al., 1997; Nersessian, 1998; 1992; 2002).

Analogy and metaphor change knowledge by adding new concepts, connections, or perspectives to the underlying representations by highlighting and projecting inferences; by re-representing old concepts; and even by restructuring the conceptual systems (Gentner, Brem, et al., 1997; Gentner & Wolff, 2000). Mental models are central in analogical thinking. People reason about unfamiliar domains by constructing a mental model that can generate inferences in the target domain. Mental models are psychological representations constructed by analogy. They are structural analogs of real-world, or imaginary, situations, events, or processes, thus representing the salient relations and structures of the depicted thing. Mental models can be mentally “run” or manipulated during analogical reasoning and thought experiments (Holland, Holyoak, et al., 1986; Collins & Gentner, 1987; Nersessian, 1992; 1999). Even understanding and using scientific concepts and theories involve interpretation through building a mental model of their contents. In constructing scientific theories, models are first-stage abstractions of the phenomena being studied before further abstractions in the form of formal expressions in language, formulas, or axioms, take place (Nersessian, 1992; 1999).

Analogical reasoning and problem solving typically proceed in an abductive manner. A potential explanation for a puzzling phenomenon is sought by generating a hypothesis based on already understood ideas, transportable concepts, or problem-solving techniques, from known areas. This process may lead to scientific discovery and conceptual change, if the explanatory hypothesis, which can be compiled of several analogical sources, is evaluated as giving an acceptable explanation for the problem (Holland, Holyoak, et al., 1986). The observation that scientists create new representations from existing ones through processes like analogy and abduction helps us understand how scientists build on existing structures while creating genuine novelty. It also explains the continuous, but non-cumulative, nature of conceptual change in science (Nersessian, 1992).

Holland, Holyoak, et al. (1986) discuss analogical schema formation as a distinct mechanism of conceptual change alongside with abduction and conceptual combination. Analogical mapping may induce a schema that represents an abstract category of which the specific analogies are instances. The schema renders explicit the common identities found useful in a successful mapping while effectively hiding the differences. It is then ready to be used for further problem solving in other similar instances (Holland, et al., pp. 294-295). A popular example of this sort of schematization, as a result of perceived relational similarities across several analogical experiences, is the wave schema. It has developed from a specific analogy, originally tied to water waves, to an abstract category applicable in a vast range of situations involving rhythmic propagation of patterns, such as sound and light waves. In these new applications, the wave schema has fruitfully formed a bridge between remote, previously unconnected problem domains (Holland, et al., pp. 339-342; Holyoak & Thagard, 1999, p. 12).

Nersessian (1992; 1999) pays attention to imagistic reasoning as another "abstraction technique" in problem solving. She refers to the numerous instances where scientists have used visual representations in conjunction with analogical reasoning. External pictorial representations are helpful in organizing cognitive activity during reasoning by abstracting specific salient aspects and relations of a phenomenon and thus supporting immediate perceptual inferences. Visual representations may be more effective than text and formulae in communicating new representations and facilitate the construction of shared mental models in a scientific community and outside the local milieu of the model's construction. A well-known example of generative use of visual representation in reasoning is Faraday's construction of the field concept by drawing the "lines of force" surrounding a magnetic bar. Maxwell in turn was able to grasp the quantitative mathematical structures inherent in Faraday's qualitative drawing (Nersessian, 1992; 1999).

Thought experiments are still another important heuristic for creating conceptual change in science. Nersessian (1992; 1999) analyzes thought experiments as simulative model-based reasoning in which a mental model is constructed and "run" in order to draw inferences about the modeled real-world system in different states. People make frequent use of thought experiments in mundane and scientific reasoning. Although thought experiments may be reconstructed as arguments, their modeling function cannot be replaced with a propositional representation. Nersessian presents a few of the impressive thought experiments of Galileo and Einstein that have been traced from historical narratives. She states that the empirical power of thought experiments is inherited from their being abstracted from our activities and experiences in the world and our knowledge, conceptualizations and assumptions of the world (Nersessian, 1992; 1999).

Analogy and Metaphor in Collaborative and Interdisciplinary Research

Analogical thinking is by definition a means for finding similarities and establishing connections between separate domains of knowledge. The focus, however, of cognitive studies of science has largely been on major historical discoveries and the minds of individual scientific geniuses. Scholars in the cognitive studies of science have only recently begun to pay attention to the day-to-day scientific activities of normal scientists and to the fact that scientific knowledge production increasingly takes place in collaborative and interdisciplinary contexts. One of the pioneers in this area is Kevin Dunbar, who has conducted in-depth observational studies of the thinking processes of contemporary scientists in the world's leading molecular biology laboratories. He noticed that if an individual scientist, when outside of a group context, encounters evidence that is inconsistent with the present hypothesis, she or he usually attributes the evidence to error, avoiding the need to drastically change the hypothesis. However, when the same researcher presents the results in a laboratory meeting, the other scientists tend to focus on the inconsistency and suggest alternative hypotheses, or force the scientist to think of a new hypothesis. Analogy is frequently used in these reasoning situations when there is no apparent answer to the problem. Members of the group may first draw analogies to very similar experiments with the same organism, but in the case of persistent inconsistencies, references are made to findings with other organisms in their own or in others' laboratories, or even to more general knowledge of the domain (Dunbar, 1995; 1999). Dunbar (1999) calls this kind of collective reasoning by a group of scientists "distributed reasoning." Expert scientists typically make both more analogies and more productive analogies than novices. They have more knowledge and it is organized in a way that makes it easier for them to notice deep structural similarities (Dunbar, 1995).

Interestingly, Dunbar (1995) reports that he noticed that one of the laboratories studied did not engage in analogical reasoning, nor was it making any appreciable advance in its scientific work. The scientists used a different strategy when encountering problems in their experiments. Instead of finding local or regional analogies to solve the problem, as was done in the other laboratories, these scientists simply manipulated experimental variables to make things work. However, the problems often remained unsolved for months or longer. Dunbar found the reason for the absence of analogies in the social structure of the laboratory. While the members in the other laboratories had highly variable backgrounds, all members in this one came from similar backgrounds, and therefore had similar knowledge bases (Dunbar). Dunbar concluded that in order to make fruitful analogies and generate multiple hypotheses, a group of individual scientists working towards a common goal must have differing – but partly overlapping – backgrounds and pools of knowledge to draw from (Dunbar, 1995; 1999). Shelley (1999) also notes that all relevant source analogies that biologists need in constructing evolutionary scenarios cannot be well known to each scientist; instead they are distributed throughout the scientific community. He mentions disanalogy – disputing the analogies used in competing theories – and extension – finding further analogies from the basis of one holding analogy – as two particular processes in the social distribution of analogy-formation (Shelley).

Ambrose (1996) addresses the dual role of metaphors in both inhibiting and enhancing the integration of different perspectives in interdisciplinary theory formation. Predominant research paradigms that adhere to the root-metaphorical worldviews may be highly resilient, and if researchers are not aware of this shaping influence of metaphor, they may not realize that their perspective is only one of many, and may entrench themselves in dogmatic insularity. Ambrose has studied the endeavors to formulate interdisciplinary theory by researchers of creativity in a conference context. He sees metaphors as a necessary part of such theory integration processes.

Besides being an integral part of paradigms and theories, metaphors can be deliberately used to bridge the cognitive gaps between them (Ambrose). On the other hand, a final integration of perspectives, theories and concepts may not always be necessary, possible, or even desirable. As Bromme (2000) proposes, metaphors or metonymies can serve as tools for "linguistic division of labor." Participants in an interdisciplinary group may attach several meanings to the jointly used metaphor, and these perspectives need not be dissolved during cooperation. Metaphors may thus function as kinds of boundary objects that allow for a certain flexibility of interpretation, while offering a sufficient common ground for different perspectives to cooperate (Bromme).

Despite having been critical of the "anticognitive" sociological studies of science, several proponents of the cognitive perspective have strongly emphasized that not even the cognitive explanation is exhaustive, and have expressed a need for integrating the different approaches (e.g., Holland, Holyoak, et al., 1986, pp. 320-321; Giere, 1992; Thagard, 1993; 1994; Dunbar, 1995; Holyoak & Thagard, 1999, p. 265; Nersessian, 2004). The cognitive processes of a single creative mind are crucial, but so are the social structure and cultural context of research. Scholars on the cognitive side have even made several initiatives and proposals towards a synthesis of the cognitive and the socio-cultural. Thagard (1993) models scientific communities from the perspective of distributed artificial intelligence. He combines cognitive with historical, physical/methodological and social perspectives in his more recent study of the formulation and acceptance of the bacterial theory of ulcers (i.e., that peptic ulcers can be caused by Helicobacter pylori and thus cured with antibiotics) (Thagard, 1998a; 1998b). Nersessian (2004) discusses the possibilities of overcoming the divide between cognitive and socio-cultural reductionism in science studies. She sees a promising path to this kind of integration in the emerging "environmental perspectives" that attempt to account for the role of the social, cultural, and material environment in participating in and shaping cognition. These perspectives cultivate such notions as "embodied cognition," "embedded cognition," "distributed cognition and reasoning," "enculturated cognition," "situated cognition," "cognitive artifacts" and "cognitive system." The complex relationship with the material environment, the highly distributed nature of reasoning, the extensive use of external representations in reasoning and communication, and other practices of science are thus seen as inseparable from cognition (Nersessian, 2004).

5. Conclusion

In this paper, we review three academic discourses on the topic of knowledge production in contemporary society: the discourses on the social shaping of science (SSS), knowledge in innovation (KNOWINN) and analogy in science (ANALOG). The SSS discourse focuses on the institutional formation of scientific knowledge regimes and on the collaboration across them; the KNOWINN discourse attends to the production of knowledge within firms and to the role of knowledge for competitiveness; and the ANALOG discourse identifies its research object at the level of human cognition, and poses questions about how analogies are used and why they are so crucial for both exploitative and explorative thinking.

Despite a lack of communication among the three discourses, we suggest that they are complementary and should be interconnected. All three perspectives have strengths and weaknesses. Together they form a rich basis for a more comprehensive theoretical framework for the study of the epistemic texture of knowledge society. The SSS discourse goes the furthest in analyzing the socio-cognitive structure of knowledge production. It shows that epistemic perspectives do not necessarily coincide with established and formalized institutional units, such as the discipline, and that the local research site and emerging research programs are strong, often interdisciplinary, forces in shaping science. The SSS discourse also deals with the mechanisms for explorative communication and integration through notions such as standardization, boundary object and standardized package. Standardization builds communicative and practical bridges between distinct knowledge frameworks, while boundary objects facilitate collaboration by creating links without a demand for complete integration. Standardized packages have a similar function as boundary objects, but imply a homogenization of thinking, materials, instruments and practices at a larger scale, thus creating continuity across local research sites. Such continuity seems to be a prerequisite for the stabilization of research programs. A third strength of the SSS discourse is its awareness of the many dimensions of knowledge production, which can be seen in, for instance, its extensive list of barriers for scientific collaboration across epistemic and disciplinary boundaries.

With a few notable exceptions, the KNOWINN discourse is much more superficial on the issues mentioned above. Its strength is not in the micro-level analysis of knowledge production, but rather in its organizational and economic approach. Scholars of innovation are interested in how organizations, such as firms, organize and manage their own knowledge production, and how these solutions affect competitiveness. The approach introduces at least three new aspects to knowledge production that are generally ignored in the SSS discourse. First, the production of knowledge is often such a complex process, that it should be seen as an organizational rather than individual achievement. This understanding has resulted in a set of conceptual tools that have no equivalent in the SSS discourse. Second, it asserts that the production of knowledge should be related to measures of performance. This is often lacking in the SSS literature on science, which, whenever dealing with performance requirements, tends to view them as objects for analysis – as phenomena that should be explained – rather than as tools for doing a study. We think that a more performance-oriented approach is an important supplement to the SSS studies that are reviewed in this article. Thirdly, innovation research broadens our understanding of the heterogeneity of knowledge production contexts in contemporary society. Knowledge is produced not only in university departments or laboratories, but also in various non-academic organizations and their sub-units. The latter are often shaped through their function in the organization, which means that the disciplinary framework of science is paralleled by a functional framework in innovation. This leads us to an important question concerning the institutional texture of knowledge society: What happens when the two modes for organizing knowledge production – disciplinary and functional – are mixed, as they increasingly are, both in universities and in firms?

The SSS and KNOWINN discourses share an institutional approach to knowledge. They have less interest in the cognitive aspects of knowledge production, except as background information that legitimizes certain assumptions about the role of institutions. In the ANALOG discourse, this order of interest is reversed. Human cognition is at the forefront, while the institutional context is, generally, treated as a background constant. It should be noted that the analogy focus is just one of several possible foci in the study of human cognition and reasoning, and that others could have been included in this review as well. We are convinced, however, that the understanding of analogical thinking must be one of the key components in any attempt to build a more comprehensive framework for the study of knowledge production.

As shown above, analogies constitute important tools for building bridges between different knowledge domains. Their capacity to link novelty with what is already familiar, and thereby create conceptual spaces with multiple levels, makes them an ideal tool for explorative thinking. Analogies also function as conceptual boundary objects in the collaboration between people with different competencies. The existing research on the use of analogies in science provides us with several general hypotheses about the nature of knowledge production: that the transition from exploration to exploitation often involves a sedimentation (death) of analogies, or metaphors; that exploration may involve a change in prevailing root metaphors, and, as a result, that knowledge sometimes develops in a non-cumulative manner; that the degree to which human thinking is embedded in root metaphors explains at least a part of the difficulty of exploration and the common tendency to resist it; that a culture of distributed, analogical thinking improves the creative performance of knowledge producers; and that the expansion of analogies across larger cognitive distance is a potentially successful strategy in exploration.

Each of the hypotheses presented above has implications for how we understand the formation of knowledge regimes, the capabilities of groups and organizations, and many other issues raised by the SSS and the KNOWINN discourses. It is therefore crucial that the cognitive focus in the research on analogy is linked with the institutional approach of the other two discourses reviewed here. The same is as true for the ANALOG discourse as it is for the SSS and KNOWINN discourses; its contribution to a general theory of knowledge society is fully appreciated only when it is contextualized by the other two discourses. There is a need for exploration and integration.

An Illustrative Case: Making PCR

To demonstrate what integration implies, we briefly present an analysis of a concrete, empirical case that draws on the conceptual frameworks developed within each of the three discourses. The purpose of this presentation is to convince the reader that all three perspectives are necessary for a thorough analysis of the case. We have chosen the invention of the polymerase chain reaction (PCR) as our example, and use Paul Rabinow's (1997) *Making PCR*, his book about that process, as our empirical source. PCR is a technique for copying genetic material. The technique is crucial for modern biological research and analysis and for that its inventor, Kary Mullis, was awarded the Nobel Prize for chemistry in 1993. The key property of PCR is that it allows researchers to amplify small DNA fragments into a large quantity of copies of the same fragment, the implication being that researchers get more DNA material to work on. In theory, research procedures such as DNA sequencing, expression analysis, or genetic screening, could be made with just a single copy of the DNA fragment that is investigated. In practice, however, all available techniques require more material, and unless more copies can be produced in an efficient way, the research cannot be carried out. Today PCR is a commonly used technique and most laboratories have one or more PCR instruments as part of their standard equipment.

Rabinow distinguishes between two aspects of the PCR innovation process: the invention of PCR as a concept, and the development of PCR into a working experimental system. The concept of PCR is as follows: DNA fragments (templates) are multiplied through an iterative process of, first, synthesizing DNA copies on the templates (this is called polymerization) and then, second, a separation of the copies from the templates. As a result, the amount of templates for the next cycle doubles (the old templates plus the copies), which means that the amount of templates and new copies grows exponentially with each cycle. Kary Mullis, then employed by the well-known California biotech company, Cetus Corporation, invented the PCR concept almost accidentally in 1983, when he was working on quite a different problem. At the time, considerable effort was being expended at Cetus to develop a generalized diagnostic procedure by using the company's own sickle-cell test as a model system. A new procedure, the oligomer restriction (OR) assay, had already been developed. It showed some promising results, but the sensitivity of the test was unsatisfactory: there was too much background noise. Attempts by other scientists at Cetus to increase the sensitivity of the test had thus far failed. One of Mullis' own thought experiments on this problem led him to the idea of amplifying the amount of target DNA (the DNA to be identified by the test) instead of improving the specificity of the test. He realized that such amplification would reduce the need for sensitivity. At Cetus, the new concept was initially met by disbelief. Experimental work successively showed that the method had potential, however, and a PCR group was formed. The road from the concept to a working system was nevertheless long, involving several technicians who sorted through the many variables that affected outcomes of the various attempts. In 1987, Cetus used a joint venture agreement between itself and Perkin-Elmer Corporation to develop the PCR machine that was to become a commercial success. Again, the hard work of technicians – involving, among other things, the identification, purification and introduction of a new enzyme (polymerase) for copying the DNA (polymerization) – was needed. The first commercial PCR products were on the market in 1988 (Rabinow, 1997).

The PCR story contains elements of all the three discourses reviewed in this paper. Cetus had attracted researchers by being less hierarchical and more interdisciplinary than either academic institutions or large corporations tended to be in the 1980s. Work at Cetus was problem-driven, and there was relatively high flexibility in the projects. Explorative research (e.g., the OR assay) and pioneer knowledge networking was encouraged, while a collective awareness of new trends and ideas was created in regular meetings that were open to people from different projects. Cetus operated in a highly volatile knowledge environment and, therefore, had an urgent need to maintain and develop its absorptive capacity. At the same time, though, there were also mechanisms for initiating exploitation, such as, in the PCR story, modularization of knowledge production through the PCR group and the agreement with Perkin-Elmer, as soon as the potential of the idea had been recognized. The organizational capabilities of Cetus included both creative and imaginative scientists, highly skilled technicians, and collaboration with other companies. These components – combined, of course, with a whole set of other ones that cannot be discussed here – were necessary for both the scientific and the commercial success of PCR (Rabinow, 1997).

What about analogies in the PCR process, then? Analogies played a key role in the invention of the concept. Mullis himself had been trained in chemical engineering and biochemistry, but had a broad interest in computers and mathematics. He was particularly interested in the phenomenon of fractals – patterns generated by iteration of simple mathematical equations – and had explored such loops in the design of computer programs. Loops were easy to use in computers that could repeat operations over and over again at little cost, and were therefore well known to computer programmers. For biochemists, in contrast, iteration generally implied laborious and boring work in the lab, and was therefore to be avoided if possible. Mullis' invention of the PCR concept was at least partly based on exporting the idea of iteration from the more familiar source domains of fractals and loops to the new target domain of diagnostic systems. In Rabinow's (1997) words, "Mullis made the connection between the two realms and saw that the doubling process was a huge advantage because it was exponential."

At first, Cetus met the PCR concept with skepticism. The analogy that it was based on was too abstract and too structural to trigger an immediate positive response, even in a company such as Cetus, which seemed, on the basis of Rabinow's description, to have a culture of analogical and explorative reasoning. Several barriers – epistemic, cultural, communicative and psychological – had to be overcome in order to convince the other scientists at Cetus of the potential value of the concept. Some barriers were simply too rigid, and Mullis had serious quarrels with his colleagues, leading to mutual accusations of being a bad scientist. He left the company a few years before the first PCR products were commercialized (Rabinow, 1997).

Combining the Discourses

The PCR example illustrates the complementary nature of the three discourses reviewed here (SSS, KNOWINN, ANALOG). This concluding sub-section discusses some of the things that could be done with those complementarities. In the introduction, we argued that a more comprehensive approach to knowledge production in science and innovation could be achieved by combining the discourses. But what does such a combination imply, and why would it be valuable? We propose that combination could be fruitful at three levels: the levels of a) conceptual framework, b) research questions and hypothesis formation, and c) ontology.

At the first level, that of conceptual framework, a combination of the three perspectives on knowledge production simply means that we have a larger conceptual apparatus for describing processes of science and innovation. The description of the PCR case, in the previous subsection, is a good example. The enlarged conceptual framework led to a more comprehensive set of questions concerning the innovation process, with a focus *not* on epistemic-institutional boundaries *or* organizational capabilities *or* the use of analogical thinking, but on *all* of them. Expanded conceptual frameworks allow richer descriptions, and consequently a fuller understanding of the complexity of the phenomenon being studied. Yet, most of the literature that we reviewed for the present paper restricts itself to one of these perspectives. Historical accounts, such as that of Rabinow, tend to be more comprehensive, but are instead conceptually weak: they do not apply the arsenal of analytical concepts that scholars in other disciplines have developed. We are not advocating “a-theoretical” descriptions of single cases, but the combination of conceptual frameworks for richer “theory-based” descriptions. This does not mean that historical accounts would be of little interest. On the contrary, they can provide important material for the kind of conceptual analysis that is being promoted here, as in, for instance, the PCR-case discussed above.

At a more specific level, the level of research question and hypothesis formation, the knowledge that has been developed within the three discourses of this paper can be juxtaposed in order to develop new questions and hypotheses about the relations between various phenomena. We believe that there is much opportunity in developing such transepistemic strategies for defining research questions. This would be a form of exploration, and, as in all exploration, outcomes cannot be predicted with any certainty. What we can do, however, is to present some examples of what such transepistemic questions and hypotheses could look like, and trust that analogical inference will help the reader to develop new ones that we would never have thought of.

First, the KNOWINN discourse has developed the notion of absorptive capacity for describing the capacity an organization has to adopt new ideas and lines of thinking and operation. The question, then, is: What affects absorptive capacity? The KNOWINN literature tends to focus on economic investments in knowledge production (e.g., R&D) and organizational renewal. Combining these ideas with the ANALOG discourse, however, allows us to ask questions about the potential role of the culture of reasoning in the organization. It could even be hypothesized that organizations with a culture of distributed, analogical thinking (ANALOG) will be more successful in absorbing new knowledge (KNOWINN) than organizations that lack such a culture. A juxtaposition with the SSS discourse, at the same time, might suggest that organizations that develop a standardized package (SSS) of interlinked strategies, theories, practices, instruments, materials, etc., will be more successful in exploiting new knowledge (KNOWINN) than organizations that do not develop such a package. We present these hypotheses only as an illustration of the way one could benefit at the level of research question and hypothesis formation from juxtaposing the three discourses, and cannot in this context go into more detailed questions about how one would go about testing the hypotheses.

Juxtaposition does not necessarily mean *combination* or *integration*. In some cases, the perspectives cultivated within the distinct discourses predict different things about the world. As an example, the SSS discourse emphasizes the role of socialization and enculturation in the learning histories of people. According to this view, most students, or at least research students, acquire a disciplinary identity and buy into a relatively homogeneous body of knowledge as a part of their education and professional development as researchers. Specialization and exploitation imply an ever more narrowing of the scope of knowledge. The ANALOG discourse, on the other hand, has found that *experts* tend to use more structural analogies in their reasoning than *novices*. This means that in contrast to novices, who rely on surface similarities in closely related knowledge domains, experts develop a capability to analogically interconnect knowledge domains that are far away from each other. That is why experts are good at not only solving old and well-known problems, but also at solving completely new problems within their field of expertise. This is somewhat surprising from the SSS-perspective, since expertise was supposed to be about specializing the knowledge base. It also raises interesting questions about the relation between exploitation and exploration in science: Activities that normally might appear to be exploitation, that is, specialists pursuing their science, might turn out to be much more explorative than a first look would suggest. In sum, then, the ANALOG and SSS discourses seem to predict different and possibly contradictive properties in expert thinking. Such contradictions are fruitful sources for new research questions, in either field.

Finally, the combination of discourses can also be fruitful at the level of ontology. In contrast to the more general enlargement of conceptual frameworks that was discussed above, combination at the level of ontology is about identifying new phenomena in the world by the creation of completely new, hybrid concepts that combine features from the worlds of the three discourses. Again, it is impossible to predict what creative minds could come up with, but, as a model for analogical inference and as a kind of teaser, we mention a few suggestions for such hybrid concepts, the exact definition of which we leave to the reader. Here they are:

the analogical firm;

the absorptive capacity of disciplines;

the boundary analogy

Who knows what realities these concepts, and other similar ones, will capture in the future? The three discourses can be used as source domains for the creation of new, hybrid (from the perspective of present boundaries) ontologies. This is the most explorative level of discourse juxtaposition, and therefore also the least predictable in terms of fruitfulness. But it would certainly be a most interesting path to walk.

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Notes

[1] By "academic world," we refer to departments, faculties, tenure and promotion committees, reward systems, national and international scientific societies, specialized scientific journals, specialized funding agencies or departments within larger funding agencies, standardized educational curricula, etc.

[2] This happens through connecting the discipline-in-the-making with various societal functions, for instance, through the education of professionals, experts, counsellors and advisers. Thus, in the case of some disciplines, their formation has presupposed the establishment of an appropriate extra-academic clientele, such as hospitals, various sectors within public administration and industry (Lenoir, 1997).

[3] In the sense of organizational politics.

[4] The phage research programme contributed to the establishment of molecular biology as a discipline (Mullins, 1972).

[5] Indiscriminate interdisciplinarity, pseudo-interdisciplinarity, auxiliary interdisciplinarity, composite interdisciplinarity, supplementary interdisciplinarity and unifying interdisciplinarity.

[6] Multidisciplinary education, pluridisciplinary work, interdisciplinary work, cross-disciplinary work, transdisciplinary work.

[7] Encyclopaedic interdisciplinarity, contextualizing interdisciplinarity, shared interdisciplinarity, co-operative interdisciplinarity, generalizing interdisciplinarity, integrated interdisciplinarity.

[8] Some parts of this section have previously been published in the working paper: Bruun, H., Langlais, R. & Janasik, N. (2002). Transepistemic communication and innovation: A conceptual platform. *Technology, Society, Environment 3,* 7-52. Helsinki University of Technology Laboratory of Environmental Protection. Published here with the permission of the authors.

[9] There is, however, no direct relation between novelty and profit. There is no guarantee that novel products, or products based on novel manufacturing processes, will be adopted by consumers.

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