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MANAGING KNOWLEDGE IN LOOSELY COUPLED NETWORKS: EXPLORING THE LINKS BETWEEN PRODUCT AND KNOWLEDGE DYNAMICS*

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ABSTRACT

The contemporary literature concentrates on 'make or buy' decisions in design and production activities, assuming that decisions about the underlying fields of technological knowledge will automatically be the same. Building on previous research on multitechnology firms and products, this paper argues that firms know more about technology than they apply in their own production. We propose two major dimensions according to which firms should adjust their knowledge and production boundaries, namely systemic interdependencies across components and uneven rate of change across components' underlying knowledge bases. We analyse the implications of this less-than-perfect overlap between knowledge and production boundaries for the management of firms' external relationships.

INTRODUCTION

The current interest in knowledge management has focused the debate on important dimensions of knowledge that have emerged from earlier research traditions: the distinctions and interactions between information and knowledge, codified and tacit knowledge, and individual and group knowledge. One other feature deserves special attention, namely, specialization. Since the industrial revolution, and as was foreseen by Adam Smith, the production of useful knowledge has become increasingly specialized and professionalized, with the continuous emergence of new and useful disciplines and sub-disciplines (Coombs and Metcalfe, 2000; Pavitt, 1998). This trend has been most pronounced in the natural sciences and engineering, but can also be observed in the social sciences, including the management sciences. The continuous increase in specialization in corporate knowledge production lies at the root of a number of fields of current research, including networks of professionals that transcend firms' boundaries (Hicks, 1995; von Hippel, 1987); processes of horizontal co-ordination and integration (Burns and Stalker, 1961;

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Lawrence and Lorsch, 1967); conflicts between professional and functional groups (Leonard-Barton, 1992); criticisms of notions of 'information asymmetry' (Loasby, 1999); and the nature of group knowledge (Wegner et al., 1991).

Inside the firm, the R&D function devoted to the systematic production of scientific and engineering knowledge has emerged over the past 100 years as part of a more general process of functional specialization. With the continuous emergence of promising new fields of knowledge, one of the major management tasks is to define the knowledge boundaries of the firm. What fields of knowledge should firms develop in-house (make)? What fields of knowledge should they outsource (buy)? We argue that 'make or buy' decisions about knowledge are not the same as those about products. Recent empirical research on the world's largest, technologically active firms, reveals the importance of distinguishing products from the bodies of technological knowledge on which they are based (Granstrand et al., 1997; Patel and Pavitt, 1997). Although the two obviously are linked, they have different dynamics and require different management prescriptions. Specifically, products and the firms that develop and make them are increasingly 'multitechnology'. Large firms do not concentrate their technological capabilities in a narrow range of fields. They are active over a wider number of technological fields than those in which they actually produce, and this number is increasing over time.

This paper aims to analyse the implications of this less-then-perfect overlap of knowledge and production boundaries for the management of firms' external relationships. It does so by focusing on the evolution of the network of firms that interact to design, manufacture and market a final product. Building on previous research on multitechnology firms and products, we propose two major dimensions according to which firms should adjust their knowledge and production boundaries, namely systemic interdependencies across components and uneven rate of change across components' underlying knowledge bases. We argue that the interaction of these two dimensions helps to explain the emergence of different organizational network arrangements.

This paper is organized as follows. The second section discusses the current literature on organizational arrangements for innovation and its treatment (and lack thereof) of the distinction between technological knowledge and products. In the third section we build on the earlier research of Loasby (1999) and of Orton and Weick (1990) to explore the notion of 'loosely coupled systems' and suggest how it can help explain some neglected aspects of knowledge management in a multitechnology environment. In the fourth section we argue that loosely coupled systems, based on a strong systems integration capability, are long established, pervasive and likely to grow in importance in future. Our conclusions are presented in the final section.

ORGANIZING FOR INNOVATION

Drawing on the current management literature, this section explores the relations between knowledge, the organization of innovation and production, and the evolution of networks. In reviewing the existing literature, we propose a working definition of organization. Given the paramount importance of ability to manage external relationships (Coombs and Metcalfe, 2000; Miller et al., 1995), we argue that the relevant unit of analysis is not the single firm, but the network of firms that underpin the design, development, and manufacturing of products. By organization we mean therefore the structure of the network of firms. The notion that networks of firms are a useful category of analysis is definitely not new. We argue, however, that different types of networks are more, or less, appropriate for the management of the innovation process according to their reliance on market-based vs. hierarchical co-ordination mechanisms.

As the number of independent sources of technologies outside the firm increases, product and knowledge dynamics need to be studied with reference to the dense network of external relationships into which firms are embedded. Innovative firms collaborate with users, suppliers and other non-business organizations (e.g. universities, regulatory agencies and so forth) to gather, develop and maintain useful information and knowledge. Moreover, innovative processes build upon an increasing number of technological fields, and innovations need to be integrated into wider technological systems. Thus, modern approaches to technological and organizational change need to cope with two fundamental attributes of innovative processes: (1) their embeddedness in a dense network of external relationships; and (2) their combinatorial nature (in terms of the number of technological fields and components to integrate).

Autonomous Versus Modular Innovations

The notion that different types of innovation call for different organizational arrangements is well known at least since the seminal contribution of Henderson and Clark (1990). Henderson and Clark made the important distinction between architectural and modular innovations. Architectural innovations change how components interact within a product, while leaving untouched their inner functions. Modular innovations instead are changes to components' inner functionings that leave their linkages with other components unaltered. Focusing on intra-firm managerial processes, Henderson and Clark argued that firms are built around stable product architectures, since the latter defines key functional relationships, information processing capabilities, communication channels, and information filters. For this reason, the introduction of architectural innovations is always risky for incumbent firms.

Chesbrough and Teece (1996) extended this line of enquiry and shifted the focus on the characteristics of organizational arrangements for innovating by taking into account the reliance of firms on internal as well as external sources of technological knowledge. They identified two main types of organizational arrangements, i.e. integrated and virtual corporations, each of them characterized by a different 'mix' of internal and external sources of technological knowledge. Integrated corporations maintain a large set of in-house capabilities spanning R&D, design and manufacturing, whereas virtual corporations by using market-based mechanisms rely to a greater extent on external sources of technologies. Chesbrough and Teece (1996) maintained that the appropriateness of a firm's organizational arrangement is defined by the interplay of two sets of factors, namely the number of external sources of knowledge, and the types of technological innovation.

In relation to the former, Chesbrough and Teece argued that when the number of external sources of knowledge (e.g. suppliers) is low, firms should adopt integrated arrangements to face the likely opportunistic behaviour of suppliers, and vice versa. In relation to the latter, they identify two main types of innovation, autonomous and systemic. Autonomous innovations can be pursued independently from other innovations because they are characterized by standarized interfaces with existing component technologies that are often codified in industry standards. Systemic innovations can be realized only in combination with complementary innovations. The management of this system of innovations requires the continuous exchange and sharing of information and knowledge across units of production since systemic innovations redefine the interfaces 'throughout an entire product system' (p. 68).

Chesbrough and Teece (1996) argued that these different features of innovation call for distinct organizational designs. Autonomous innovations can easily be co-ordinated via market mechanisms, since their integration with existing technologies rests on well-defined interfaces. In this case firms can adopt virtual structures that are more responsive than integrated ones, since they can use market-based incentives to access quickly and economically the technological resources they need. Likewise, they can easily form alliances with other firms deemed relevant for the commercialization of the autonomous innovation. Large integrated firms are unable to duplicate such a responsive mode. Systemic innovations are best managed instead within the same firm. When innovations are systemic, virtual corporations become vulnerable due to their inability to co-ordinate the required exchanges of knowledge and information through the market mechanism, and to settle conflicts between firms over integration. According to Chesbrough and Teece, integrated firms can therefore take advantage of their scale and their complementary assets when systemic innovations are introduced.

Technology Phase-Shift: From Modular to Integral and Vice Versa

Building upon the dichotomy between autonomous and systemic innovations, Chesbrough and Kusunoki (1999) introduced a dynamic element into the analysis of organizational arrangements for innovation. Using empirical evidence from the hard disk drive industry, they argued that technologies follow a dynamic cycle that goes from integral to modular. In the integral phase, usually the first stage of technological development, the interactions between systems elements are fast changing and poorly understood. The integral phase calls for tight co-ordination mechanisms typical of the centralized organization. Such interactions eventually become articulated and codified as industry standards. In the modular phase, when sub-systems and components and their interactions are better understood and modularized, co-ordination is better achieved through decentralized or virtual arrangements of organization.

Accordingly, firms should align their organizational arrangements to the phase of the technology. Firms that do not adapt their organizational arrangements fall into what Chesbrough and Kusunoki defined as 'traps'. A 'modularity trap' emerges when the technology shifts from the modular to the integral phase but firms maintain a decentralized organizational arrangement. Virtual organizational arrangements lack the systems knowledge required to co-ordinate integral technologies. An 'integrality trap' emerges when an integral technology becomes modular and firms retain a centralized organization. In other words, when component interactions are well articulated and codified and innovation activities can be organized via arms' length market relationships, centralized organizations become cumbersome arrangements of co-ordination.

The research reviewed above has extended the analysis of the relationships between innovation and organizational arrangements. An important question remains unanswered, however. How do firms manage the transition from an integral to a modular phase, or vice versa? What types of capabilities are required to go through such a transition? And where would these capabilities reside? Are they part of each firm's reservoir of skills? Could they be bought on the market (from, for instance, consultancy services) when needed?

An important clue to the answers to these questions is provided by Chesbrough and Kusunoki. In discussing the shift from a modular to an integral architecture, they present the case of Fujitsu. Fujitsu was the firm that proved the most successful in the shift from the modular to the integral phase in the hard disk drive industry. Unlike other firms that fell into the 'modularity trap', its systems knowledge facilitated the mastery of the new integral technology (i.e. the magneto-resistive head). In their own words, this success 'was due to its [Fujitsu's] continued investments in systems knowledge and materials and component technology in its R&D labs' (Chesbrough and Kusunoki, 1999, p. 13). Chesbrough and Kusunoki also argued that in a possible reverse shift from the integral to the modular phase, Fujitsu may have taken the appropriate strategic steps in relation to technological investments and organizational set-ups with other firms, in order to align its organizational arrangement with the technological shift.

While Chesbrough and Kusunoki's prescriptions about organizational arrangements are confined to the two classical ones, namely virtual or integrated, we want here to stress the analytical importance of the finding that the success of Fujitsu during a shift from a modular to an integral phase rested on its systems knowledge. In the modular phase Fujitsu, like its competitors, relied extensively on external suppliers (i.e. it became 'virtual'). Unlike its competitors, however, Fujitsu did not entirely outsource the technological capabilities underlying the components whose design and production it had outsourced. By maintaining knowledge about the whole system, Fujitsu was capable of anticipating and exploiting the technological shift. Fujitsu's case shows clearly that product and knowledge dynamics are related, yet different.

Knowledge Versus Product: Between Integration and Specialization

In order to identify circumstances in which the product and knowledge dynamics follow similar, or dissimilar, trajectories in the presence of technological change, we rely on the work of Granstrand et al. (1997). Building on Chesbrough and Teece (1996) and Prencipe (1997), they identified four intermediate corporate positions between full integration and full disintegration (integrated corporations and virtual corporations, respectively, à la Chesbrough and Teece), namely exploratory research capability, applied research capability, systems integration capability, and full design capability. In particular, they distinguished two sets of factors that affect corporate outsourcing decisions: (a) the degree to which the innovation is autonomous or systemic, and (b) the number of independent sources of technologies outside the firm. On these grounds, they proposed a two-by-two matrix that identifies four cells. Each cell is associated with a different case calling for a particular degree of internal technological capabilities.

For instance, when the number of external sources is low and the innovation is systemic, firms should maintain a wide range of in-house capabilities, from exploratory and applied research down to production engineering. Granstrand et al. enriched the framework proposed by Chesbrough and Teece (1996). By identifying the above-mentioned intermediate stages between integrated and virtual systems, they contended (and argued empirically) that decisions related to products are distinct from those concerning their underlying capabilities (e.g. technological). In other words, outsourcing the production of components does not necessarily entail outsourcing the sets of knowledge employed to specify, design, integrate, manufacture, test and assemble them. In fact, they argued that 'whatever the type of innovation and the number of external sources, firms should maintain capabilities in exploratory and applied research in order to have the capability to monitor and integrate external knowledge and production inputs' (p. 20).

These results are at odds with the stream of research that focused on the managerial implications of modularity for the design of organizational networks for knowledge production and products design (Arora et al., 1998; Sanchez and Mahoney, 1996). Modularity was first proposed as a product design strategy aimed at defining stable interfaces among components (modules) composing a product. Accordingly, each module can be improved (via changes in design or the introduction of new materials) within a predefined range of variation and an intended period without impacting on the design of the other modules (Ulrich, 1995). Arora et al. (1998) and Sanchez and Mahoney (1996) claim that modularity not only is a characteristic of product design, but also a characteristic of the knowledge underlying the products and of the organizations designing and producing them.

In particular, Sanchez and Mahoney (1996) emphasized that modularity is a powerful design paradigm, both for products and organization arrangements. They argued that due to advanced knowledge about component interactions, components' interfaces can be fully specified and standardized. These interfaces define an architecture that must stay unchanged over an 'intended period' of time, so that the processes for developing the single modules can be de-coupled and carried out independently. Firms, therefore, can choose to develop the product architecture or specific component modules, and the corresponding organizational set-up will reflect this modular structure.

Arora et al. (1998) argued that not only can the production of new artefacts be conceived in terms of production and combination of modules, but also that the knowledge underlying such artefacts is a matter of 'mixing and matching' of specific modules. Once knowledge is codified into 'general' and 'abstract' modules with clearly defined property rights attached to them, these knowledge modules become readily available to firms (which can 'buy' them on spot markets). Thus, firms can concentrate either on the production of new modules or on a combination of them according to their proximity to the final customer. Some firms, therefore, will focus on specific components or activities within a given architecture. Other firms will specialize in the 'mixing and matching' of these components (i.e. the product architecture). In short, the key implication of Grandstrand et al. (1997), i.e. that outsourcing the production of components does not necessarily entail outsourcing the underlying knowledge, would be a special situation characterized by ill-defined property rights. If property rights on knowledge are not well-defined, then the rents from innovation could be appropriated through secrecy, and not only the relevant capabilities but also the actual activities from which they stem should be kept in-house.

Current Analysis: A Critique

The foregoing discussion has reviewed some interpretative schemes on the relationships among products, organizations, and knowledge. We argue that, with the exception of Granstrand et al., the research discussed above fails to recognize that knowledge, products, and organizations may follow different dynamics. Two main positions have emerged that reach the same conclusions. The first does not explicitly distinguish the knowledge and product dimensions. The corollary of this position is that these two dimensions are conflated together, so that modular or integral products are characterized respectively by modular or integral knowledge (Chesbrough and Kunusoki, 1999; Chesbrough and Teece, 1996; Sanchez and Mahoney, 1996). The second position explicitly distinguishes between knowledge and products, but it contends that they are informed by the same principles, e.g. modularity (Arora et al., 1998).

Moreover, all the frameworks reviewed pay inadequate attention to the rates of improvement in performance, enabled by changes in the bodies of knowledge (i.e. technologies) underlying products and their components. Consider, for example, the sweeping changes in microelectronics and material technologies that have enabled such an impressive growth in the performance of microprocessors, with the somewhat more stubborn limitations of energy-storage technologies. Thus, despite having in our laptops enough computational power to send a manned shuttle to the moon and back, we can barely keep them switched on for the time that it takes to fly across the Atlantic.

Indeed, knowledge specialization increases the likelihood that firms need to accommodate technologies that change at uneven rates. Such changes are not necessarily accommodated in modular product architecture. Uneven rates of technological change can create performance imbalances amongst components and subsystems that may require co-ordination in their design and development.[1] This may well require intermediate stages of integration, in contrast to the traditional distinction between the pure 'make' or the pure 'buy' arrangements. These uneven rates of change, therefore, do and should inform firms' outsourcing and partnering decisions, especially in those industrial sectors characterized by multicomponent, multitechnology products.

Furthermore, although the process dimension of innovation and its managerial implications have been stressed by Freeman (1982), most of the literature reviewed above does not focus on the specific characteristics of the innovation process that lead to a given innovative output. Rather, it focuses on the organizational implications of different 'types' of innovation. Innovation 'types' are characterized in terms of the degree of novelty they achieve (i.e. radical vs. incremental innovations); the scope of their impact on existing products and processes (i.e. modular vs. architectural innovations); and the physical entity they impact upon (i.e. product vs. process innovation). These distinctions are very useful, but are focused on the ex-post consequences of innovative processes whose outcome, in terms of novelty or scope, can hardly be predicted ex-ante. Following Freeman (1982), we propose that the choice of alternative organizational settings for innovation, particularly from a knowledge management perspective, should be more closely related to the characteristics of the process that firms are managing as well as to its outcome.

While some works discussed above do take into account the role and importance of external sources of technologies (e.g. suppliers, universities, or research centres), there is no explicit emphasis on the management of such inter-firm relationships. Following Coombs and Metcalfe (2000), we argue that firms compete also on their capabilities of managing external relationships.

A DIALECTIC APPROACH TO ORGANIZATIONAL DESIGN FOR KNOWLEDGE MANAGEMENT: THE IMPORTANCE OF 'LOOSE COUPLING'

This section aims to elaborate a simple model that will link knowledge and product dynamics to generate alternative organizational settings. It builds upon four specific points highlighted above: (1) the differences between product and technological (i.e. knowledge) dynamics; (2) the uneven rates of change of components' technologies; (3) the importance of the management of the innovation process as well as its outcome; hence, (4) the relevance of firms' external relationships. Relying on these and using the concept of 'loose coupling', we develop a simple taxonomy of organizational arrangements that link product and knowledge dynamics. Contrary to much of current research, we argue that organizations do not swing between purely integral or modular architectures following changes in the architecture of the product. Rather, integral and modular features coexist at all times. The coexistence of these features is enabled by the increasing reliance of firms on a variety of inter-organizational arrangements 'which firms can use to co-ordinate their respective contributions to a multi-firm innovation process' (Coombs and Metcalfe, 2000).

Defining 'Loose Coupling'

Following Loasby (1999), we maintain that the aim of innovating organizations is twofold: (a) they generate variety in order to foster the process of discovery of novel solutions by developing specialized bodies of knowledge; (b) they co-ordinate dispersed learning processes that rely on different bodies of knowledge. We argue that the generation of variety calls for some degree of distinctiveness among organizational sub-units. We define distinctiveness in terms of the different scientific and technological disciplines they master. The achievement of co-ordination requires some degree of responsiveness among organizational sub-units. We define responsiveness in terms of the understanding and active management of organizational interfaces. The interaction of these two dimensions (distinctiveness and responsiveness) determines the knowledge boundaries of the firm as distinct from its production boundaries.

As regards the definition of effective organizational arrangements, we adopt the original, dialectic interpretation of loosely coupled systems proposed by Orton and Weick (1990). According to them, the extent of coupling across organizational subunits is determined by their degree of responsiveness and distinctiveness:

> If there is neither responsiveness nor distinctiveness, the system is not really a system and it can be defined as a noncoupled system. If there is responsiveness without distinctiveness, the system is tightly coupled. If there is distinctiveness without responsiveness, the system is decoupled. If there is both distinctiveness and responsiveness, the system is loosely coupled. (Orton and Weick, 1990, p. 205)

The usefulness of the concept of 'loose coupling' lies in its capacity to frame within a unified analytical setting the study of contradictory aspects of organizational behaviour. In particular, 'loose coupling allows organisational analysts to explain the simultaneous existence of rationality and indeterminacy without specialising these two logics in distinct locations' (Orton and Weick, 1990, p. 204). In terms of the discussion above, loose coupling will allow us to explain the coexistence of both 'integral' and 'modular' features in the organizational settings we study.

Social scientists have approached the problem of the 'duality' of organizations from different viewpoints. Burns and Stalker (1961) identified the two dimensions of connectedness and autonomy to distinguish between mechanistic and organic organizations. Lawrence and Lorsch (1967) tried to reconcile this dichotomy by analysing the emergence of integrating mechanisms (e.g. cross-functional teams). March (1991) expressed this problem by juxtaposing the different logics of exploitation and exploration. Iansiti (1998) analysed the organizational processes through which firms achieve technological co-ordination by integrating the work of specialist units. In terms of the discussion on systemic and autonomous innovation, loosely coupled systems would allow for the co-existence of integral as well as modular patterns of organization. Integral patterns would rely on the responsiveness between loosely coupled units. Modular patterns would follow from the distinctiveness these units are enabled to maintain.

Despite its rather common use in organization theory, the concept of loose coupling often has been applied to 'simpler organizational puzzles than originally intended' (Orton and Weick, 1990, p. 204). In particular, most authors have used this concept in a rather static sense, as a point along the loosely coupled–tightly coupled continuum. The quotation from Orton and Weick cited above should make it clear that such a continuum is a misconception. Loose coupling is a situation whereby organizations exhibit properties of both decoupled and tightly coupled systems, which are the real extremes of the organizational continuum. Relying on the correct dialectic definition, this paper aims at identifying the conditions under which 'looseness contributes to successful change' (Weick, 1982, p. 378). In particular, we argue that the notion of loose coupling allows for the joint analysis of processes of specialization, in terms of the activities firms do (or do not) carry out in-house, and processes of integration, in terms of the bases of technological knowledge firms continue to maintain in-house despite having outsourced the related activities. Also, we put forward the idea that maintaining capabilities wider than the range of activities actually performed in-house is, under some circumstances, a necessary condition to effectively manage external relationships in the presence of technological change.

Causes of Loose Coupling

The organizational literature reports a huge number of factors to explain the emergence of loosely coupled systems. We argue that some of these factors also apply to multitechnology firms and, therefore, it makes sense to analyse them in terms of loose coupling. Broadly speaking, these factors can be lumped into two sub-groups: those related to cognitive processes embedded in the organization, and those related to the external environment that embeds the organization. The former are related to the traditional concepts of bounded rationality (Glassman, 1973), uncertainty (Weick, 1976) and ambiguity (March, 1987). Clark (1983), studying university structures, identified another possible source of loose coupling that is most pertinent to this paper: knowledge. As quoted in Orton and Weick (1990, p. 206):

> [A]n academic system works with materials that are increasingly specialised and numerous, knowledge-intensive and knowledge-extensive, with a momentum of

> autonomy. This characterisation applies most strongly to advanced systems, but even the most retarded systems will be based on a half-dozen or more distinct bundles of knowledge that have their own internal logics and an inherent bent toward autonomy. (Clark, 1983, p. 16)

Originally designed for universities, this description perfectly fits the situation faced by multitechnology firms studied by Granstrand et al. (1997). The increasing number of relevant bodies of knowledge stretches the possibilities of traditional co-ordination processes. Management is caught between the need to monitor potentially useful bodies of knowledge, and the necessity to maintain some control over increasingly and necessarily fragmented learning processes.

This point leads to the second set of causal factors, i.e. those related to the external environment. In particular, as firms need to interact with a widening range of actors to gather and develop information and knowledge, they increase the dispersion and heterogeneity of the stimuli they receive and interpret (Manning, 1982). This sort of fragmentation can also lead to the necessity to face up to the incompatible expectations of different actors in the network (Meyer and Rowan, 1977). These findings (usually stemming from studies of non-business organizations, such as prisons, the police, or hospitals) capture some of the problems that multitechnology firms have to cope with when dealing with small, specialized and science intensive firms as shown in Orsenigo et al. (2001) in the case of pharmaceuticals.

Purpose of Loose Coupling

Loose coupling allows firms specialized in different bodies of knowledge, design steps, manufacturing processes to follow their idiosyncratic learning processes while retaining some degree of responsiveness. Firms that lead these networks can manage the network in such a way as to increase or decrease the degree of responsiveness. Consistent with our previous research on complex products and systems, we call these firms 'systems integrators' (Brusoni and Prencipe, 2001). The different forms of co-operative agreements that are available (market-based, joint ventures, strategic alliances and so forth), demand that firms (and systems integrators in particular) establish criteria to assess the extent of responsiveness needed to co-ordinate and integrate dispersed learning processes.[2]

Loose coupling has been studied by adopting various units of analysis: individuals, sub-units, organizations and hierarchical levels, ideas, activities, intentions and actions (Orton and Weick, 1990, p. 208). We use the concept of loose coupling to study the interactions between organizations embedded in a hierarchical network. The development of new products requires the combination of the capabilities of several firms. As stressed by Coombs and Metcalfe (2000), 'the necessity to govern extra-firm relationships adds new layers of complexity to intra-firm governance, and indeed to our understanding of the boundaries of the firm itself' (p. 210). The analysis of distributed learning processes extends the explanatory power of accounts that link innovation to intra-firm variables only. Loose coupling enables us to study organizational arrangements as structures of networks of firms that underpin the design, development and manufacturing of products.

A FRAMEWORK TO INTERPRET ORGANIZATIONAL ARRANGEMENTS FOR INNOVATION

In this section, we identify the key variables that systems integrators must consider when assessing the benefits of different degrees of responsiveness and distinctiveness. Building upon Rosenberg (1976), we argue that the notion of 'imbalance' is vital to characterize alternative innovation processes and understand how they are organized. Rosenberg argued that in multicomponent products different modules might change at different rates, thus providing internal pressures that focus the innovative efforts of an organization. While he focused on imbalances among physical components, we argue that the distinction between technologies and products put forward in the above discussion identifies a second source of imbalances.

In particular, we argue that the appropriate organizational network (in terms of the proper degree of organizational coupling) is influenced by the interaction of two dimensions, namely product-level imbalances à la Rosenberg and knowledge-level imbalances. The interaction of product- and technology-level imbalances is more or less complex according to two key variables: the degree of predictability of interdependencies across components, and the rate of change of the underlying scientific and technological disciplines. For instance, irrespective of the degree of novelty sought, the presence of unpredictable interdependencies among physical components causes the complexity of the innovation process to increase. Any change in one component entails a series of controls as to its consistency with the functions performed by other components. In so doing, it raises the need to increase responsiveness among the organizational units (within and across firms) involved in the process itself. Market-based co-ordination mechanisms must then be complemented (if not replaced altogether) with tighter hierarchy-based mechanisms.

Figure 1 summarises our view. It proposes a two-by-two matrix that identifies four quadrants, which in turn, distinguish three types of networks, decoupled, tightly coupled, and loosely coupled (1) and (2). Each network is characterized by a different degree of organizational coupling and, therefore, inter-firm relationships (market-based relationships, hierarchy-based relationships, or a mix of the two) which are discussed below.

Market-based Relationships

Stable bodies of knowledge embodied within products with predictable interdependencies would be manageable via de-coupled systems. A decoupled system is a network without systems integrator, whereby the final producer, who relies on a relatively stable product architecture, can assemble product components by merely mixing and matching individual units. This is the case with the PC as described by Langlois (1997) or any other modular product which relies on a stable body of knowledge such as, for example, trolleys (Ulrich, 1995). In this case, market-based co-ordination is achieved due to the standardized interfaces of the modular architecture. Flows of knowledge and/or physical components can be arranged relying on market transactions. Coombs and Metcalfe (2000) provide a few examples of this type of transaction mechanism such as 'the use of consultancy services; the hiring of key individuals or teams from other firms; the pur-

Rate of change of component technology	Systemic interdependencies: Predictable	Systemic interdependencies: Unpredictable
Low	De-coupled network (market-based)	Loosely coupled network (1) (authority and problem-solving)
High	Loosely coupled network (2) (authority and problem-solving)	Tightly coupled network (hierarchy-based)

Figure 1. Determinants of organizational coupling

chase of licenses; the use of contract R&D services; and the special case of purchasing firms solely in order to acquire their specific technologies'. Although these mechanisms may entail substantial 'transaction costs', the stability of the knowledge base and the flexibility of a modular architecture give firms time to acquire the relevant information, either by paying a fee of some sort, or by buying the physical component that embodies the relevant information.

Hierarchy-based Relationships

Fast growing bodies of knowledge embodied into systems with a high degree of unpredictable interdependencies would require a tightly coupled system. Tight coupling guarantees fast adaptation to exploit fast changing trajectories. Vertically integrated firms in the mobile phone systems industry (Davies, 1999) are a case in point. Here, vertical integration offers the advantage of providing clear, univocal rules of technological and organizational co-ordination under conditions of high uncertainty and complexity. The complexity of the system and the fast rates of change of component technologies favour firms that can deliver a 'total solution' tailored to the needs of specific customers. In this case, the network of relationships on which producers rely is very tight. Although the 'perfect case' of vertical integration is rather extreme, it is likely that producers of these types of systems will manage rather tight, long-term, exclusive relationships with suppliers of components, sub-systems and specialized knowledge (Coombs and Metcalfe, 2000).

Loosely-coupled Relationships

Loosely coupled systems would provide firms with the degree of freedom necessary to manage the other two quadrants in figure 1. We argue that loose coupling as originally understood by Orton and Weick (1990) as a 'dialectic' organizational structure enables firms to react to changing knowledge bases or to innovations with unpredictable systemic effects. As for the characteristics of loose coupling, we focus on what we consider the most pertinent to our analysis of multitechnology, multiproduct firms, that is to say, the necessity to cope with the well known exploration vs. exploitation trade-off. Weick (1982) argues that loose coupling facilitates adaptability and thus the exploration of novel solutions. Loose coupling facilitates adaptability by providing firms with an effective 'sensing system'. Loosely coupled systems 'understand' their environment better than tightly coupled systems, as they maintain a higher and more diversified number of nearly autonomous sensors (i.e. other firms in the network).

Research on multitechnology products suggests that loosely coupled networks rely on a combination of market based and hierarchical relationships (Brusoni and Prencipe, 2001; Prencipe, 2000). In particular, it is argued that loosely coupled networks are led by so-called systems integrators, i.e. firms that, while being specialized in terms of activities performed in-house, maintain wide portfolios of technological capabilities, and adopt the same terminology to distinguish these firms from the others in the network. Prencipe (2000) suggested that systems integration should be understood as a *synchronic* as well as a *diachronic* capability. By *synchronic* we mean that systems integrators should be capable of co-ordinating from a technological and organizational viewpoint the work of several firms within a given architecture. By *diachronic* we mean that systems integrators must be capable of envisaging different and alternative paths of product architecture to respond to evolving opportunities and requirements.

Synchronic systems integration hints at adaptation/exploitation issues. *Diachronic* systems integration refers to adaptability/exploration problems. Although these two kinds of systems integration are obviously different, systems integrators in loosely coupled networks are characterized by both at all times. Thus, loose coupling is an organizational result that likely allows systems integrators to rely on the advantages of distinctiveness, while maintaining the responsiveness to implement systemic innovations.

Systems integrators benefit from the sensors provided by the network by relying on their wide, in-house portfolio of technological and organizational capabilities. This situation emerges when bodies of knowledge change fast, as in the case of pharmaceuticals, discussed below. The 'sensing system' of the loosely coupled network led by a systems integrator allows it to monitor developments in a variety of fast moving, specialized fields. This system is maintained by relying on various types of relationships which, following Coombs and Metcalfe (2000) may include: multi-firm collaborations to produce generic knowledge (e.g. industrial research associations, R&D consortia); application-oriented collaborations (which aim at progressing the joint work beyond the R&D phase to get close to a marketable product); and joint venture firms that 'combine existing capabilities from participating firms and to develop new capabilities across the board' (Coombs and Metcalfe, 2000).

A case of this type of linkages can be seen in recent developments in the pharmaceutical industry. Orsenigo et al. (2001) studied the relationship between small firms specialized in biotechnologies and large pharmaceutical firms. Biotech firms become increasingly specialized as we move down the hierarchy defined by the R&D joint ventures studied, with each branch representing a (increasingly specific) scientific hypothesis. In the overwhelming majority of cases, large pharmaceutical firms lead these R&D networks (with only a few first-generation biotech firms challenging their position of systems integrators). What happens once the 'sensing phase' is over? The data that Orsenigo et al. analysed do not tell precisely. What we would expect is that, once a set of promising solutions has emerged (e.g. new compounds that may cure a specific disease), the systems integrator, relying on its own in-house integrative capabilities, will adopt a more pro-active management style, cutting off unpromising branches, focusing on others, opening up new avenues of research, and so forth. In short, responsiveness would be increased at the expense of distinctiveness.

Loose coupling also allows for the management of businesses that rely on more stable bodies of knowledge, e.g. the automobile industry. Carmakers increasingly rely on suppliers for the development and design of components. Within a given product family, suppliers are allowed (and encouraged) to introduce improvements at component level. Distinctiveness pays a premium, while responsiveness is achieved by respecting the limits set by the existing product architecture. Carmakers, however, do maintain in-house capabilities on all those components whose production they have fully outsourced. As argued by Sako and Murray (1999), car manufacturers develop and maintain in-house a deep understanding of the linkages between externally designed and produced components.

> Although the basic architecture of an automobile is fairly stable, it is said that there are many aspects of the linkages within the electro-mechanical architecture that are not yet fully understood. For example, to achieve a particular noise/vibration/harshness (NVH) level at different maximum speeds, engineers need a deeper understanding of the subtle linkage between the body, chassis, engine, and drive-train. This means that without the integration capability of vehicle manufacturers, the body, chassis, engine, and drive-train produced by separate suppliers each with their own specialised systems knowledge may not, upon assembly, lead to a workable automobile. (Sako and Murray, 1999, p. 4)

In our terms, the system remains loosely coupled. Indeed, only carmakers have the capabilities to design and develop a new product family. When that occurs, carmakers (i.e. systems integrators) have to step in and reorganize the network (or establish a completely new one) around the new product. Loose-coupling, as we define it, can cover a larger number of products and services and the corresponding knowledge and organizational strategies pursued by the firms offering them.

The wide capabilities that systems integrators maintain in-house allow them to increase responsiveness among firms via two main mechanisms: authority and problem-solving. These two mechanisms are linked and mutually reinforcing. As stressed by Loasby (1999, p. 100), authority is not necessarily associated with formal hierarchies but rather with the willingness of the recipient to consider a specific ‘communication’ as ‘authoritative’. In turn, this willingness derives from the acceptance of ‘zones of indifference’ whereby recipients reckon they have to rely on the capabilities of somebody else, somebody to whom they delegate ‘authority’. Systems integrators can work as ‘problem solvers of last resort’ precisely because they know much more than any of the organizations involved in the design and engineering of a plant. More specialized members of the network, therefore, appear to be willing to accept systems integrators ‘authority’ whenever their capabilities do not allow them to solve a specific problem.

The notion of loose coupling is interesting also because it highlights one of the dangers implicit in the recent trend towards corporate downsizing. In particular, Brusoni and Prencipe (2001) and Brusoni (2001) argued that systems integrators that have downsized too much in response to short-term cost pressures have lost the capabilities to define the general problem (in engineering and business terms) to be solved in co-operation with their specialized suppliers. In so doing, they have lost the 'authority' to call for an increase in responsiveness, as suppliers are no longer willing to assume that operators 'know what they are doing'.

CONCLUSIONS

This paper has proposed an interpretative framework to understand the relations between technology, product, and organization. It has argued that in complex multitechnology products, characterized by close systemic interdependencies across components and uneven rate of technological change across the relevant underlying knowledge fields, firms must adopt a loosely coupled network structure. Loosely coupled networks enable firms to manage knowledge across different technological fields and institutions and to adjust to the differing organizational requirements of innovations. A central characteristic of loosely coupled networks is an in-house capability for systems integration. Loosely coupled systems can be observed in the pharmaceutical industry, where large firms link up with biotechnology firms (Orsenigo et al., 2001), and in the automobile industry, where car manufacturers are linked with their suppliers (Sako and Murray, 1999). More generally, both historical evidence and the contemporary analysis of patenting data show that, in production machinery and instrumentation, both users and suppliers make significant contributions to technological improvements, which is what we would expect in loosely coupled systems (Rosenberg, 1976; Patel and Pavitt, 1994). In other words, loosely coupled systems are pervasive and have existed for a long time. We would speculate that they will become even more important in future, as the continuing growth and specialization of knowledge production will make firms' external knowledge relations even more important.

NOTES

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[1] See Rosenberg (1976) and Constant (1980) on how such systemic interdependencies have been important inducement mechanisms and focusing devices for technological change.

[2] In this way, our analysis squares with Tsoukas (1996), where organizations are understood as distributed knowledge systems.

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