Networks of innovation and modularity: a dynamic perspective

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Abstract: The aim of this paper is to provide a comprehensive perspective for understanding the dynamics of modularity and the implications of those dynamics for innovation networks. The main contention of this paper is that the dynamics of technology development should reflect the dynamics of a firm network. During the early development of a technology, when the interactions among component types are unclear (in a state of flux) and, therefore, difficult to codify and freeze, organisations build connections with research centres and universities to explore alternative technological solutions. Once such interactions are better understood, codified, modularised and shared, then more exploitative networks (*e.g.*, with suppliers and customers) may be better suited to exploit the current technology. In the transition from the early development phase to the more mature phase, firms must build ties to startups and new entrants, because these firms experiment with alternative design configurations that exploit the underlying technology. In addition, during this transition stage, firms must connect to third-party firms, since the supporting investments made by these firms may determine which of the alternative configurations will become 'the standard'. During this stage, the relationships across firms are defined and governed by modular interfaces that are, in turn, dictated by product interfaces.

Keywords: development; development dynamics; innovation networks; modular architectures; modularity; organisational interfaces; technology.

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1 Introduction

Some of the recent theoretical and empirical work on modularity considers modularity as the natural end-result of a development process that starts with an initially poorly understood product architecture (Baldwin and Clark, 2000). Architecture interfaces are progressively clarified and refined, and the process of refinement leads towards product modularity, which in the end state embodies this increased understanding. Modular product interfaces then enable interfirm division of labour (Sanchez and Mahoney, 1996) in a pattern of organisational modularity. Firms may specialise in specific product modules, because coordination among modules is embedded in a modular product architecture.

Recent empirical studies in the engineering and economics of innovation suggest that this process need not come to a modular end, however (Brusoni *et al.*, 2001; Chesbrough, 2003a; Chesbrough and Kusunoki, 2001; MacCormack and Iansiti, 2002). Because the technological interfaces that define and enable the emergence of modularity in products also impose limits on the evolution and further advance of a product architecture, eventually a new architecture will arise to transcend the limits of the older modular architecture.

The aim of this paper is to provide a more comprehensive perspective for understanding the dynamics of modularity, and the implications of those dynamics for the innovation networks that firms use. The main contention of this paper is that the dynamics of technology development should be reflected in the dynamics of a firm's development network. During the early development of a technology, when the interactions between components in an emerging product design are unclear, in a state of flux, and therefore difficult to codify and freeze, organisations should build connections with research centres and universities to explore alternative technological solutions. Once technical interactions are better understood, codified, modularised, and shared, then more exploitative networks (*e.g.*, with suppliers and customers) may be better suited to exploit the current technology. Importantly, in the transition stage from the early phase to the more mature phase, firms should build ties to startups and new entrants, because these firms experiment with alternative design configurations that exploit the underlying technology. In addition, during this transition stage firms should connect to third party firms, since the supporting investments made by these firms may determine which of the alternative configurations will become 'the standard'. During this stage, the relationships across firms are defined and governed by organisational modular interfaces that reflect modular product interfaces.

As some engineering and innovation studies have suggested, however, modularity need not be the end state of a development process. When a new technology emerges, a different organisational set up may be required, and new network relationships need to be developed. More explorative approaches may be required before the old technology reaches its limits. Accordingly, firms should develop connections with universities and research centres through the modular phase so that they can sense through external sources the emergence of new technological solutions. In this regard, a firm's *degree of openness* to such inputs plays a fundamental role in shaping the competitiveness of a firm network (Chesbrough, 2003a).

We develop these arguments as follows. The next section briefly discusses the literature on innovation networks. Section 3 presents studies on dynamics cycle of modularity that characterises the evolution of a technology. Section 4 articulates normative propositions that emerge from joining these two streams of literature, particularly the alignment of network structures to the phase of the dynamic cycle of modularity. Section 5 presents the conclusions to the paper.

2 Networks of innovation: a literature review

Empirical research in the 1960s demonstrated the vital importance of the role of external sources of scientific, technical, and market information for successful innovating firms and networks. As Freeman (1991) noted, "Networking for innovation is an old phenomenon and networks of suppliers are as old as industrialized economies" (pp.510–511). Successful firms with their own internal R&D were found also to intensively use external sources of R&D. Such external sources were seen as an important ancillary and complementary source of scientific and technical information, rather than a substitute for a firm's own innovative activities (Freeman, 1991). More recently, Chesbrough (2003a) and others have argued that external sources of technology are an important additional source of innovation inputs. These sources of external technology are often referred to as an *innovation network*. There has been substantial academic interest in innovation networks, though these structures have varying labels, such as strategic alliances (Contractor and Lorange, 1988) and communities (Brown and Duguid, 2000; Grandori and Prencipe, 2004). Research on networks identified two main types of network benefits (Afuah, 2000). First, resource sharing enables firms to combine knowledge, skills, and physical assets. Second, access to information spillovers increases when network relationships act as information conduits through which news about discoveries and failed approaches are exchanged. Henderson and Cockburn (1996) found that pharmaceutical firms with a more open approach to innovation networks were more successful than others.[1]

Following March's (1991) distinction between exploration and exploitation, networks have been analysed for their ability to help firms explore new areas (Duysters and De Man, 2003) and to exploit existing areas (Krackhardt, 1992). Some studies of strategic technology alliances have begun to focus on the use of networks for exploitative or explorative learning and have argued that the structure of networks ought to vary by the objective they are intended to serve (Ahuja and Lampert, 2001; Hagedoorn and Duysters, 2002; Rowley *et al*., 2000).

Exploration strategies lead to lower-commitment R&D alliances in new technological capabilities, since the focus is on learning new ideas from new partners. Exploitation strategies, on the other hand, lead to high-commitment alliances within existing technological capabilities (Koza and Lewin, 1998). Recent empirical work provides evidence that the appropriateness of forming strong or weak ties depends on the type of learning to be undertaken and the external environment. Rowley *et al*. (2000) demonstrated that strong ties are particularly effective for exploitation purposes, but are less effective for exploration. In conditions of rapid technological change where the need for explorative learning is highest, Afuah (2000) has shown that firms need to rely primarily upon weak ties.

While many network researchers assess the strength of network ties through survey data from actors within the network, other proxy measures are also used to represent the strength or weakness of ties between actors in an innovation network. One such proxy is the presence or absence of equity linkages between parties within the network. Networks focused on exploitation will rely extensively upon equity ties (Pisano, 1990; Koza and Lewin, 1998). Joint ventures that create a new separate administrative entity also are indicative of strong ties. By contrast, joint development agreements, licensing arrangements, or joint research pacts may involve no new administrative entity or equity, and typically have exit clauses that impose little or no cost upon withdrawal. Such features would be associated with weak ties, and with explorative strategies.

Another way to categorise a network type is to examine the rate of turnover of participants within an innovation network. Exploration requires access to a diversity of knowledge, combined with a careful scanning of potential technological opportunities. As these opportunities often arise outside existing partners, partner turnover will be high. Exploitation requires intense collaboration that takes time to build up, and benefits accrue only after long-term collaboration. Specific investments may be required to achieve the economies of scale required to exploit an opportunity, for example, and these will often be safeguarded by stronger equity linkages (Williamson, 1991). Exploitation networks will therefore have a lower rate of turnover among its members, relative to the rate of turnover in exploration networks.

A more challenging characteristic to observe is the degree of overlap between the capabilities of the firm, relative to the capabilities of other firms within the innovation network. As Mowery *et al*. (1998) found using patent citation data, member companies in Sematech became more complementary and specialised in their patenting over time. In exploration networks, firms will look for partners with capabilities outside their existing business. In exploitation networks, firms will tend to look for companies with similar technological knowledge. Innovation networks with a high degree of similarity in capabilities are likely to be exploitative in their purpose, while explorative innovation networks will likely feature a far lower degree of overlap in capabilities among the members of the network.

3 The dynamics of modularity

Theory predicts, and longitudinal engineering studies have confirmed, that architectures have specific and intrinsic technological limits. The concept of *architectural yield* (Iansiti, 1997; MacCormack and Iansiti, 2002) has been introduced to denote the unexploited technological performance remaining within an architecture. After an extent of development, a product architecture can yield only incremental innovations that may no longer address or satisfy future customer demands. As an architecture reaches its theoretical limits, firms will increasingly be drawn toward another innovation process to establish a new architecture. A new architecture would require new capabilities, new systems knowledge to be introduced, and consequently new transactions to be organised.

The inherent limits of any architecture calls for a more dynamic perspective on modularity based on recognising two modes of technological advance affecting modular architectures: first, advance within an architecture; and second, advance from one architecture to another. Within an architecture, as the primary components within a system become well-understood, the interactions between them can be studied, codified, elaborated, and shared. As this knowledge becomes codified, an architecture's interfaces coordinate technical transactions within the architecture, and the price mechanism and market transactions can be used to exploit possible combinations of components from differing suppliers within a system.

When prices become sufficient statistics for exploiting an architecture, the coordination of technological development for the system shifts from inside the firm to outside. This enables greater experimentation within the architecture, as different companies vie for competitive advantage with incremental improvements and different configurations of components within the system. No architecture can advance indefinitely, however, and a technological ceiling will eventually be reached in any architecture, and another architecture will be required to supersede the current architecture's system constraints. New architectures, and their (different) underlying interfaces, build upon new systems knowledge (Henderson and Clark, 1990). In creating new architectures, the price system cannot coordinate transactions outside the firm: customers cannot fully specify their needs; suppliers cannot verify that they have met the customers' requirements; and the costs of switching suppliers are unclear or prohibitive.

A short example may be instructive. Consider the advance of microprocessor design over the past 20 years. The initial high volume processors were 8 bit designs, such as the Intel 8088 in the original IBM PC. As line widths in microprocessor design narrowed, the speed of 8 bit processors increased. Notwithstanding this improvement, every major manufacture has chosen to develop 16 bit microprocessors (*e.g.*, the Intel 80286), 32 bit microprocessors (*i.e.*, Intel's original Pentium processor), and now 64 bit processors (*e.g.*, Intel's Itanium processor). In each new architecture, *there were no pre-existing standards for the use of the additional bits*. When Intel moved from the 32 bit Pentium to the 64 bit word length Itanium, for example, there were no common standards governing bits 33 through 64.

The functions that these bits would manage, how they would connect to the overall system, and how the operating system would invoke them to run software – all had to be developed. The advance of microprocessor architectures from 8 to 16 to 32 to 64 bits required careful coordination in advance of any standards. To achieve these advances, substantial knowledge of each new system is again required, so that the next generation architecture can become feasible, effective, and likely to be adopted.

As it happens, the transition from the 32 bit microprocessor Pentium to the 64 bit Itanium has been anything but smooth for Intel. Its rival, AMD, developed a different approach to bits 33 through 64, and got many of the complementary developers who supported Intel's Pentium (such as Microsoft) to develop products that worked with AMD's approach. Others, such as enterprise database and Customer Relationship Management (CRM) suppliers, delayed committing to Itanium until market demand for the new version was evident to them.

Architectural transition is not limited to product-based industries, but is also important in services-based industries. Based on a longitudinal study of the US mortgage banking industry, Jacobides (2005) proposed that intermediate markets have emerged through a process of organisational unbundling. Such unbundling is driven by firm efforts to exploit gains from specialisation (of different intra-organisational units) and trade (with different external firms), which in turn leads to simplification of coordination and standardisation of information. Governmental entities also played a role in disintermediation of the mortgage market, through creating information standards (in the case of US mortgage banking, the FHA regulations for conforming loans). With more standardised information and credit scoring algorithms, out-of-area lenders are at less of an information disadvantage in lending in local markets. Following creation of this new information architecture for the mortgage market, local lending networks atrophied within their geographic locales, but out-of-area suppliers of financial capital strengthened substantially.

Though not explored by Jacobides (2005), there is a new development in financial services that is consistent with our story. Recently in the UK, there has been a new trend back towards re-integration of financial services, as banks have developed new financial products that combine personal savings and checking accounts with mortgages, credit cards, and personal lines of credit into a single unified financial product. Such a re-integration will re-architect this industry yet again into something approaching a risk management architecture. Better credit scoring will no longer suffice, as new systems knowledge about real estate markets and values, which are the single largest assets for most consumers, will become critical for successful risk management products. This shift in financial services architectures promises to shift the innovation network in new directions.

4 Normative propositions

4.1 Network evolution and the dynamics of modularity

Empirical and theoretical studies on networks suggest that firm networks progress through stages. Lorenzoni (1982) argued that networks evolve through three main stages, from a state of *reaction* (realised constellation) through *efficiency* (rationalised constellation) to *effectiveness* (planned constellation). The evolution of a network is a function of a number of dimensions, including the knowledge underlying a particular product or system. Hite and Hesterly (2001) and Oliver (2001) applied the life cycle approach to analyse the evolution of firm networks. According to the life cycle approach, each network stage represents a unique strategic context that influences the main dimensions of a firm network strategy and, particularly, the external resources a firm needs and its associated resource acquisition challenges. The evolution of a network is thus the process by which firms adapt and align their networks to access the resources they need to ensure continued growth.

Kogut (2000) argued that the structure of a network might depend on the specific characteristics of the industry technologies or on specific institutional factors at work in a particular context (*e.g.*, Italian industrial districts). Accordingly, science-driven industries lend themselves better to networking between firms and research centres, while mass-production production industries lend themselves better to networking between firms and the supplier base. This happens when a capable supplier base emerges – or in other words, when "markets learn" (Stigler, 1951). A firm network structure, therefore, changes according to structural industry contingencies and specificities.

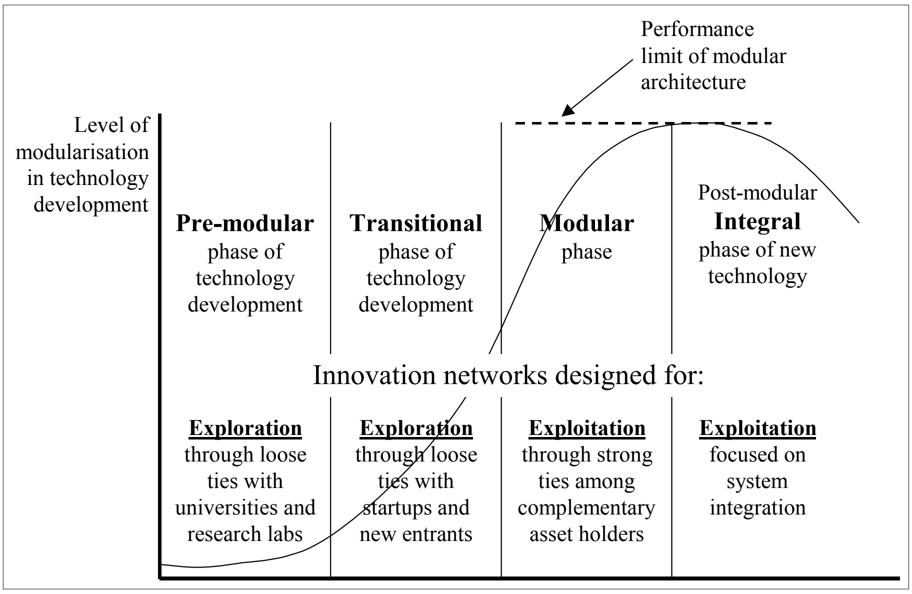
Burt (1992) argued that the configuration of relationships in a network has a strong impact on network efficiency and effectiveness. Indirect ties provide access to information held by a partner's partners (Gulati and Garguilo, 1999) and increase a firm's 'catchment area' of relevant information (information-screening) and of access to new sources (information-gathering) (Afuah, 2000). According to Burt (1992), the most efficient and effective network is one that (a) maximises disconnections (or structural holes) and (b) selects partners with many other partners. In other words, in a high-performing network with many indirect ties, partners have access to a large number of different information flows. Networks rich in structural holes enable access to new unconnected partners and to new information flows. Partners become sensing devices that enable lead firms to exploit the variety of such information flows.

Information and knowledge requirements also influence innovation network configurations in terms of number, intensity (weak or tight) of relationships, and partner selection. Firms may therefore seek to configure their networks in terms of specific contractual terms (formal, such as joint-ventures, alliances or informal) to be adopted for each of their network relationships.

As we mentioned above, some recent empirical studies have suggested that the degree of modularity of a technology evolves (increases) over time. Based on these results, we suggest that in order to accommodate the evolutionary dynamics of modularity, the typology and nature of innovation network relationships that a firm organises must also evolve accordingly. Following the Abernathy and Utterback (1978) model of innovation life cycle, we identify four main phases in the intertwined dynamics of modularisation in technological development and of innovation network evolution. In particular, we argue that organisations should focus their openness in specific directions at specific stages of technology development, as suggested in Figure 1.

During the early stage of technological development, which we label the *pre-modular phase*, information and knowledge requirements call for an explorative approach to networking. The innovation network structure must span multiple technical domains, utilise weak ties with its members, and be designed for flexibility. Innovation networks designed for exploration should be characterised by weak ties (Granovetter, 1973). When exploring a novel area of technology, firms need to search broadly (since they do not know where exactly a new useful technology may be found), and they need to engage with many actors, at least some of whom they may not know well at the outset. Relations with universities, research institutes, and corporate and government laboratories are likely to figure prominently in this phase. To achieve the requisite flexibility, firms should avoid entering into inflexible forms of alliances, because they do not know whether a specific technology will prove to be useful to them (Duysters and De Man, 2003).[2]

Figure 1 Four phases in the modularisation of technology



Proposition 1 *In the pre-modular phase of technological development, firm innovation networks should be oriented toward exploration.*

In the *transitional phase* from a pre-modular to a modular phase of technology, firm innovation networks need to pay particular attention to startup firms and new entrants. This helps define which business model will be effective in taking the technology to market, and identify the parties that need to be included in what will soon become a more exploitative innovation network. Complementary asset holders, in areas such as manufacturing, sales, or distribution become important resources to access to enable the business model (Teece, 1986; Chesbrough and Rosenbloom, 2002). Resources and attention begin to be shifted away from the university and other research sources within the innovation network.

Proposition 2 *In the transitional phase, firm innovation networks should develop stronger ties with startup firms and complementary asset holders to shape the successful business model.*

In the *modular phase*, when modularity has become established within a technology and its industry, firm innovation networks should change dramatically and become primarily exploitative. The innovation network structure must become denser, with stronger ties between primary actors with complementary assets, and be designed to support significant economies of scale in operations. Exploitation networks will be characterised by strong ties, with intimate and trustful relationships and intensive and recurring knowledge exchange (Krackhardt, 1992). Equity links often provide the enduring structures to support such exchange (Gerlach, 1992). Explorative networks must either be transformed or terminated.

Proposition 3 *In the modular phase, firm innovation networks should be oriented to the exploitation of existing relationships in order to reap economies of scale.*

When the modular phase has reached its performance limits, and a new, *integral phase* is in prospect, firm innovation networks must again reach out to a wide variety of innovation sources. By re-opening their transactions to research centres and universities, firms can build new momentum (both individual and organisational) and identify new technological and market opportunities. Firm behaviour in the initial phase of the cycle may constrain its ability to do this effectively this time, however. During the modular phase, firms broke their (weak) ties with diverse innovation sources, and established strong ties with fewer players. Some important sources of innovation that may have been abandoned at that time may be less willing to engage a second time around. Therefore, the memory of network actors regarding previous behaviour of the firm will constrain the firm's ability to enact purely exploratory or purely exploitative networks.

Hybrid forms of innovation network structure may be needed to enable movement from one phase of modularity and associated type of network to another, and later, back again. Empirical studies have emphasised the role and relevance of so-called *systems integrating firms* for the coordination of activities carried out by suppliers and other organisations around stable modular architectures, as well as the coordination of activities required to introduce new design rules and hence new architectures (Prencipe *et al.*, 2003). Systems integrating firms are the organisations that generate the set of rules that define technical and organisational interfaces linking the network of actors involved in the development of new product architectures. Systems integration is central to the capabilities sought in this hybrid form of innovation network (Menard, 1994).

Proposition 4 *In post-modular phases, firms should develop hybrid forms of innovation network in order to cope with the dynamics of technology modularity.*

5 Conclusions

The aim of this paper has been to discuss relationships between firm innovation networks and the evolutionary dynamics of technological modularity. The literature on modularity suggests that the process of refinement and clarification of product architecture interfaces leads towards product modularity (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996). Modular interfaces in a product architecture then embed technical coordination that enables firms to specialise in the design and production of specific product modules. In this way, product modularity enables organisational and institutional modularity.

Based on empirical studies on the dynamics of technological and organisational modularity (Brusoni and Prencipe, 2001; Chesbrough, 2003b), we have proposed a complementary, more articulated dynamic view of modularity in which we bring together the modularity literature and the innovation networks literature. We have argued that technological modularity follows a dynamic cycle. We identified four main phases of the modularity life cycle and discussed the ways in which each of these phases calls for specific information and knowledge requirements. We have argued that while modularity is a pervasive characteristic of industrial sectors, it does not inform the entire life cycle of their underlying technologies, and thus firm innovation networks should reflect identified phases in the dynamics of technology modularity. In other words, in order to cope with changes in the information and knowledge requirements that characterise the modularisation process of technologies, firms must change their innovation networks in terms of their search approach (explorative vs. exploitative), intensity of relationships (weak vs. strong times), and type and number of partners (*e.g.*, research centres, component suppliers). Based on this argument, we have developed four normative propositions for aligning innovation networks with phases of technological modularity.

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Notes

1 Henderson and Cockburn measure the degree of openness (though as measure of architectural capabilities) by counting the number of publications, patents, and presentations at conferences by firm scientists.

2 Note that these more recent scholars (*e.g.*, Duysters and De Man; Koza and Lewin; Oliver) have made a significant departure from much of Granovetter's (1973) argument of "embeddedness". Instead of an embedded view, which takes the network as an institutional fact beyond managerial volition, these more recent scholars implicitly assume that networks are instrumental, and can be altered by firms to serve their strategic objectives. It is far from clear that Granovetter would agree. For clarity of exposition of our argument, we will follow the more recent scholars, while acknowledging that the implicit assumption of instrumentality is not shared by all scholars of these relations.