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TECHNOLOGICAL AND ORGANIZATIONAL DESIGNS FOR REALIZING ECONOMIES OF SUBSTITUTION

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Today's industrial landscape is characterized by rapid change and systemic technologies. Rapid change results in ever shorter product life cycles that demand continual innovation from firms. The systemic nature of technologies makes it difficult, if not impossible, for any one firm to manufacture all components of a technological system. We propose that these challenges be met by designing technological systems that have the potential to yield economies of substitution. Additionally, we propose that these economies be realized by adopting the network mode of governance. We examine the network mode at three levels—intrafirm, interfirm, and institutional—to illuminate the inherent tension between cooperation and competition at each level, and to explore the implications of this tension for industrial dynamics.

The Schumpeterian era during which 'gales of creative destruction' brought about revolutionary changes over long periods of time (Schumpeter, 1942) is past. In recent times, we have entered a neo-Schumpeterian era where technological change appears to be ceaseless. To survive in this new era, firms have to innovate continually (Klein, 1977). Continual innovation, however, imposes limits on a firm's ability to realize scale economies. Moreover, rapid change dampens the diffusion of new technologies as customers postpone purchases due to fear of obsolescence (Rosenberg, 1982). Slower diffusion of technological changes creates problems for firms attempting to recoup investments made in technologies that change continually.

There is another facet to this new era that renders contemporary environments different from those prevalent during Schumpeter's time. Specifically, many of these technologies are 'systemic' in nature (Winter, 1987); i.e., they are embodied in multicomponent products that connect to each other. The development and production of such technological systems require significant investments in several complementary technologies (Hakansson, 1989; Powell and Brantley, 1992; Quinn, 1992; Teece, 1987). It is difficult for any one firm to invest in all complementary technologies because, after a point, bottlenecks arise in the form of overextended scientists, engineers, and manufacturing personnel (Penrose, 1959; Teece, 1980). Such congestion imposes limits on the firm's ability to realize scope economies.

How may firms deal with these challenges? We propose that firms take advantage of a different source of economies—economies of substitution—instead of relying exclusively on economies of scale and scope. We use the term 'substitution' to suggest that technological progress may be achieved by substituting certain components of a technological system while reusing others. The potential for such economies increases if technological systems are modularly upgradable. By designing modularly upgradable systems, firms can reduce product development time, leverage their past investments, and provide customers with continuity.

Key words: technological innovation; networks; reuse; modularity; upgradability; standards

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Additionally, we suggest that firms reorganize their internal and external relationships to reduce the costs of component reuse, while enhancing associated benefits. The network mode of governance, with its emphasis on knowledge sharing, adaptability, and continual innovation, appears to be best suited for this task (Powell, 1990). Indeed, networks form the basis for a variety of arrangements ranging from giant Japanese 'keiretsus' to small Italian firms linked by cooperative associations (see Best, 1990; Kenney and Florida, 1993; Nelson and Wright, 1992; Piore and Sabel, 1984; Porter, 1990; Quinn, 1992). Increasingly, these network forms are challenging traditional 'Fordist' organizations based on Taylor's scientific management principles.

Figure 1 summarizes our core thesis and depicts the organization of this paper. First, we discuss how technological systems are built of components that interact with one another under an overall system architecture. We identify three system-level attributes: integrity, modularity, and upgradability. All three attributes must be considered while designing technological systems for economies of substitution. We substantiate why technological systems must be modularly upgradable to yield economies of substitution. Then, we explore organizational issues that arise in realizing these economies of substitution. We emphasize the similarity between the design of technological systems and organizational systems for realizing substitution economies. Just as technological systems are composed of components interacting with one another within an overall architecture, these organizational systems are composed of individual firms interacting with each other within an overall institutional framework. We explore how modularly upgradable organizational systems may be created, and how modular upgradability gives rise to both cooperative and competitive dynamics. Finally, we discuss the implications of our thesis for firms operating in the neo-Schumpeterian era.

TECHNOLOGICAL SYSTEMS FOR ECONOMIES OF SUBSTITUTION

A technological system comprises a set of components that, together, provide utility to customers. System performance is dependent not only on the performance of individual components, but also on the extent to which they are compatible with one another (Gabel, 1987; Henderson and Clark, 1990; Tushman and Rosenkopf, 1992). Compatibility is a relational attribute that defines rules of fit and interaction between components across boundaries called interfaces. The overall set of rules that defines acceptable fit and interactions constitutes a system's architecture.

The degree of compatibility among components defines three important attributes of technological systems: integrity, modularity, and upgradability. *Integrity* represents 'the consistency between a product's function and its structure: the parts fit smoothly, components match and work well together, the layout maximizes available space' (Clark and Fujimoto, 1990: 108). Although individual system components may have been designed to yield high performance, a lack of compatibility among them results in suboptimal system performance. In other words, incompatibility between components comprises the integrity of a technological system.

Firms may ensure system integrity by custom-designing components and assembling them through an iterative process of rework to obtain requisite fit and interaction, as in craft production (Cox, 1986; Womack, Jones, and Roos, 1990). Firms may also ensure system integrity by designing and producing components to standard dimensional and interface specifications. Conformance to standard specifications enables the production of identical (and therefore interchangeable) components in large numbers, as in mass production (Marshall, 1961).

Production of components conforming to standard interface specifications also leads to modularity. *Modularity* allows components to be produced separately and used interchangeably in different configurations without compromising system integrity (Demsetz, 1993; Flamm, 1988; Garud and Kotha, 1994).[1] The degree of modularity of a technological system varies, depending

[1] Baldwin and Clark (1994) make a useful distinction among *modularity-in-design*, *modularity-in-production*, and *modularity-in-use*. In this paper, we make a general argument that encompasses all three types of modularity. Specifically, modularity-in-design creates a potential for the reuse of components and knowledge, modularity-in-production arises from the partitioning of production tasks, and modularity-in-use provides customers the benefits of speed and scope flexibility.

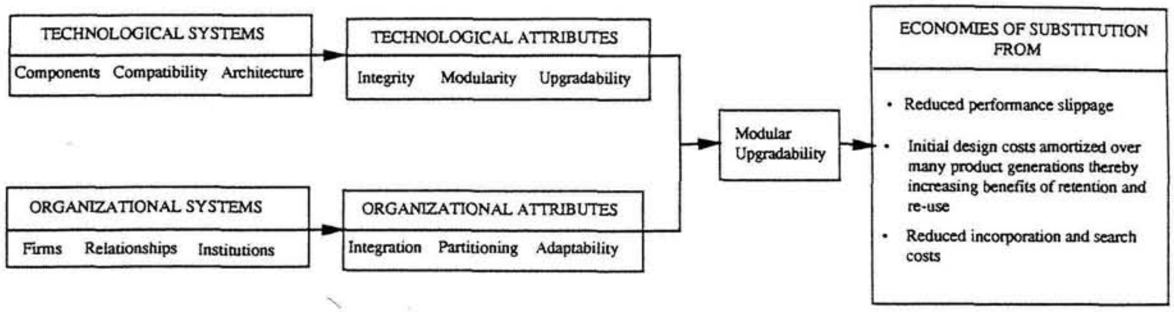

Figure 1. Technological and organizational designs for economies of substitution

on whether interfaces are standardized within only a single firm or throughout an industry. In the former case, components may be used interchangeably only within a firm's own product lines. In the latter case, components manufactured by different firms may be mixed and matched. This ability to mix and match allows firms to offer a variety of system configurations, and to economize on product development investments (Baldwin and Clark, 1994; Pine, 1993; Sanchez, this issue). At the same time, it offers customers the flexibility to buy components from different firms and create technological systems that are most appropriate for their requirements (Matutes and Regibeau, 1988).

In rapidly changing environments, a third system-level attribute—*upgradability*, or the ease with which system performance can be enhanced over time—also becomes important. If a system is not upgradable, performance improvements may involve its complete redesign. Such a process entails the destruction of existing knowledge and competence. Given the rapidity of technological change, the repetitive destruction and creation of knowledge and competencies for each new generation may increase firms' R&D investments to levels that cannot be recouped within ensuing short product life cycles. At the same time, customers will be wary of adopting new technologies that become obsolete rapidly, thereby decreasing the rate at which these technologies diffuse (Rosenberg, 1982).

To be upgradable, a technological system must possess degrees of freedom that enable improvements in existing capabilities and the addition of new capabilities.[2] To understand how degrees of freedom may be created, we have to appreciate the hierarchical organization of components within a technological system (Clark, 1985; Hughes, 1987; Simon, 1962). Component choices at any given level of the hierarchy outline operational boundaries for lower-order components. For instance, the performance capability of a computer is dependent on the speed of its microprocessor. Over time, technological advances in microprocessor design have led to significant increases in the speed of the entire computer. These innovations in microprocessor design represent a movement 'up the system hierarchy' and, typically, represent revolutionary changes where system foundations are built

[2] The design of cochlear implants provides an illustration of all three system-level attributes. Cochlear implants are biomedical devices that provide the profoundly deaf with a sensation of sound. For illustrative purposes, consider two parts of the implant: the electrode that is implanted within the cochlea, and the processor that is worn outside the body. Here, system integrity represents how well the processor works with the electrodes to create a sensation of sound. Modularity refers to the decoupling of the electrode from the processor. Recipients may disconnect the processor when desired, even though they are compelled to wear the electrode in the cochlea. Moreover, modularity provides the recipient with the flexibility to use different types of processors. The type of electrode implanted (single-channel or multichannel), however, limits the benefits that a recipient may derive from processor improvements. It is here that the notion of upgradability is best illustrated. A multichannel electrode possesses greater technological degrees of freedom. Therefore, it allows recipients to benefit from the development of new processing schemes that utilize more than one channel in the implanted electrode. In contrast, a single-channel electrode has fewer degrees of freedom, thereby limiting its upgradability (see Garud and Rappa, 1994, for more details). Moreover, in attempting to migrate from a single-channel device to a multichannel device, designers have not been able to retain either the electrode or the processing scheme associated with the single-channel device. This is because it is difficult to create a multichannel device by replacing only one or the other subsystem of the single-channel device. Both subsystems need to be replaced, thereby entailing a complete redesign of the device.

afresh (Clark, 1985): Movement up the system hierarchy makes it more difficult to maintain compatibility between product generations because core components are replaced.

Firms, however, may design higher-order components with performance capabilities that are not fully exploited at early design stages. These unutilized degrees of freedom in higher-order components can be exploited progressively through innovations in lower-order components. Clark (1985) labels such innovations as a movement 'down the system hierarchy.' Specifically, movement down the hierarchy represents incremental change where core components are preserved even as innovations occur in lower-order components. In this case, it is easier to maintain compatibility between product generations because innovations occur only in lower-order components.

In sum, firms may impart upgradability to technological systems by designing unutilized degrees of freedom into higher-order components. These unutilized degrees of freedom enable designers to enhance system performance by substituting only those lower-order components whose potentials have been exhausted. However, the benefits of upgradability and associated retention of components must be weighed against the costs of component reuse. We now explore these benefits and costs in greater detail, and suggest how to design technological systems that yield economies of substitution.

Economies of substitution

Economies of substitution exist when the cost of designing a higher-performance system through the partial retention of existing components is lower than the cost of designing the system afresh (Garud and Kumaraswamy, 1993). Component retention yields several benefits. The most obvious benefit is the reutilization of the existing base of knowledge associated with the retained components. Other benefits include savings in testing and production costs. Savings in testing costs arise when test programs developed for retained components are reused. This benefit is especially valuable in cases where test program development takes as much time as the actual design of the system itself. For instance, Texas Instruments (TI) cites such savings in testing costs as one of the main benefits that it expects to receive from its new PRISM methodology. TI's PRISM methodology allows circuit modules to be combined in different configurations to create new chips (*Texas Instruments*, September 1992). Additionally, the reuse of circuit modules enables TI to standardize chip fabrication processes, thereby yielding significant savings in production costs. In general, savings in production costs accrue from the reutilization of capital equipment and production routines associated with reused components.

Yet, these benefits have to be balanced against performance slippage and several costs incurred in reusing components. *Performance slippage* may occur when designers try to incorporate newly developed components into a technological system. This is because newly developed components may not fit or interact well with existing components, thereby compromising system integrity.

Designers can minimize performance slippage by using gateway technologies, such as adapters and converters, that enable the coexistence of incompatible components within a technological system (David and Bunn, 1990). Gateway technologies, however, imply higher costs because they involve the development and usage of additional components. Moreover, gateway technologies seldom restore system integrity completely. Therefore, they may not provide the best way for firms to realize economies of substitution.[3]

A better way for firms to realize economies of substitution is by designing modularity into technological systems. Modularity minimizes performance slippage arising from incompatibility between the newly designed and reused components. Additionally, modularity makes it easier for designers to integrate newly developed components into the existing system; that is, modularity reduces *incorporation costs* for both designers and customers. Incorporation costs in a modular system are limited to eliminating incompatibilities that were not anticipated while designing standard interfaces.

Therefore, modularity and upgradability are

[3] However, for systems that were originally designed for obsolescence, gateway technologies remain the only way to retain or reuse existing components. See Toffler (1971) for reasons why systems were designed for obsolescence in earlier periods.

both important system attributes for realizing economies of substitution. Modularity increases the ease with which system designers can substitute certain system components while retaining all others. Upgradability provides designers with the opportunity to work on an already-established technological platform thereby preserving their core knowledge base (Wheelwright and Clark, 1992). In this manner, modular upgradability simplifies the task of coping with very short life cycles.

Besides enabling the preservation of knowledge over successive generations, modular upgradability creates new knowledge that enhances, rather than destroys, existing knowledge. This competency-enhancing knowledge (Tushman and Anderson, 1986) is derived from experience as designers gain a deeper appreciation of (1) which aspects of the platform will lead to future improvements, (2) which aspects of the platform will lead to dead ends, and (3) how new lower-order components fit in with the base platform.

Modular upgradability leads to economies of substitution in another way. Modular upgradability allows firms to listen to customer feedback and modify their systems accordingly by substituting some components while retaining the others. Rosenberg (1982) points out that such learning by using is essential for the evolution of complex multicomponent systems whose optimization only occurs through large-scale customer trials. Insofar as the system design incorporates modular upgradability, designers will find it easy and economical to carry out modifications. Wheelwright and Clark (1992) call this process 'rapid prototyping.'

Increasingly, firms competing in neo-Schumpetarian environments are designing modularly upgradable systems to enable component reuse. In computer hardware, for instance, Sun Microsystems had created the modularly upgradable Sparcstation10 family of computer workstations (see Garud and Kumaraswamy, 1993, for more details). In computer software development, object-oriented programming (OOP), a technique that allows reuse of program modules and easy upgradability, has gained in popularity and usage by firms. By using OOP techniques, Brooklyn Union Gas Company created 20 percent more functionality (over the previous nonobject-oriented system) with 40 percent fewer lines of code; Shearson Lehman, Inc. reduced development costs by 30 percent through reuse of objects (*Business Week*, 30 September 1991); and the U.S. Marine Corps reduced prototype time from the normal 6 to 8 weeks to just 2 weeks. In general, OOP users report two- to five-fold increases in programmer productivity (*Financial Executive*, July/August 1991).[4]

Firms in the automobile industry, too, have designed models that allow for the sharing and reuse of key components. For instance, Honda developed a single basic 1994 Accord model and customized it later for different markets. Honda held its total development costs down by reusing components from other models. All versions of the 1994 Accord had at least 50 percent common components (*Business Week*, 21 December 1992). Additionally, Honda reduced retooling and procurement costs by (1) reusing components, (2) designing new components so that these could be manufactured using existing equipment in its Japanese and U.S. plants, and (3) delegating design of certain components entirely to its suppliers (*Wall Street Journal*, 1 September 1993).

However, modularly upgradable technological designs alone are inadequate for firms to realize economies of substitution. This is because several costs are implicit in the design of modularly upgradable systems: initial design costs, testing costs, and search costs. *Initial design costs* refer to the additional costs that designers incur in creating components for reuse over and above those incurred in designing components for one-time use. These additional costs are incurred up-front to impart additional degrees of freedom to a system, such as standardized interfaces or the design of higher-order components with unutilized capabilities. For instance, analysts of OOP estimate that initial design costs of reusable objects may be as high as three to ten times the costs incurred in building an object for one-time use (Balda and Gustafson, 1990; Kain, 1994).

[4] Several researchers have studied and catalogued the actual costs and benefits of employing OOP techniques. Based on these studies, several simulation models that perform cost–benefit analysis for OOP and predict productivity increases and returns on investment have been generated (e.g., Banker, Kaufman, and Zweig, 1993; Gaffney and Durek, 1989; Graham, 1994, 1995; Henderson-Sellers, 1993; Pfleeger, 1991). As data on the costs and benefits of employing OOP have accumulated, these simulations are yielding more accurate estimations of productivity and return on investment.

Baldwin and Clark (1994) highlight that *testing costs* constitute a high proportion of product innovation costs. They suggest that the ability to perform tests at the component level (rather than at the system level) is essential for reducing testing costs. Although testing at the component level and the reuse of testing programs reduce costs, overall testing costs increase cumulatively with the number of modular components to be tested. Additionally, as Baldwin and Clark point out, designers of different components must strike prior agreements on the interface specifications and the encompassing system architecture to develop testing programs. This increases initial design costs.

Finally, designers incur *search costs* to locate reusable components. Typically, search costs increase with the proliferation of modular, reusable components. For instance, in OOP, Banker *et al.* (1993) found that reuse percentage decreased with an increase in the number of reuse candidates. They cite the case of Carter Hawley Hale Information Services where reuse dropped by more than 15 percent when the number of reusable objects in the firm's repository grew by four times. In these cases, even libraries that allowed searches by key words did not promote reuse.

To realize economies of substitution, then, initial design costs and testing costs need to be amortized over a number of reuses, and search costs need to be minimized. These demands raise issues concerning the design of appropriate organizational systems. For instance, consider a firm that does not consciously encourage component reuse. In such a firm, the extra costs associated with the creation of modularly upgradable components may not be amortized fully. Consequently, the firm will not realize economies of substitution. Or consider a firm that does not institute effective mechanisms to search for reusable components. In such a firm, high search costs may prevent reuse altogether; or even if reuse occurs, costs may outweigh benefits. Again, the firm will not realize economies of substitution.

ORGANIZATIONAL SYSTEMS FOR ECONOMIES OF SUBSTITUTION

Technological systems consist of components that together provide utility to users. Similarly, firms that manufacture the components of a technological system together comprise an organizational system for that technology. Relationships between these firms are analogous to interactions between components of the technological system. The mosaic of rules, procedures, and norms that comprise the institutional environment of this organizational system parallels the architecture of a technological system.

A key challenge in realizing economies of substitution is the design of organizational systems that enhance component retention or reuse while reducing associated costs. We suggest that this challenge be met by designing organizational systems to be 'modularly upgradable.' A modularly upgradable organizational system allows constituent members to work independently and in unison, even as they evolve over time.[5]

Intrafirm issues

Realization of economies of substitution requires knowledge sharing and the reuse of components. Traditional hierarchical and SBU structures, however, inhibit realization of these economies. Specifically, these traditional structures result in 'knowledge hoarding' by independently functioning units. To encourage 'knowledge sharing,' Prahalad and Hamel (1990) propose that firms organize themselves around core competencies. Garud and Nayyar (1994) recommend that firms enhance knowledge sharing and reuse by cataloguing, updating, and distributing lists of available 'shelved projects' (see also Kogut and Zander, 1992). Kotha (this issue) reports how the National Bicycle Company rotates personnel between its plants, thereby creating a mechanism for the sharing of tacit knowledge (see also Nonaka, 1994). Indeed, Hill, Hitt, and Hoskisson (1992) report that related-diversified firms that install mechanisms to promote cooperation and knowledge sharing between constituent units tend to perform well.

Cusumano (1991) illustrates how a knowledge-sharing organization might look in his description of Toshiba's software production facilities. Tosh-

[5] Following Weick (1976) and Granovetter (1985), we must design various elements of an organizational system such that they are coupled neither too tightly nor too loosely. Very tight coupling between elements will constrain the evolution of the system. Very loose coupling, on the other hand, will undermine the coordination required for system elements to function in an integrated manner.

iba has instituted elaborate procedures to evaluate, catalogue, store, and disseminate reusable software throughout the company, thereby reducing search costs. Toshiba has also created special 'committees,' 'departments,' and 'centers' to ensure that designers create reusable software and reduce incorporation costs by conforming to company-wide standards. Additionally, committees help overcome the short-term concerns that may arise with knowledge sharing and reuse.

There are yet other challenges involved in designing reusable components, and in reusing components designed by others. As Mary Wells, erstwhile training program manager at Tektronix Inc., asserted: 'There will always be tension between those pushing for a library and reuse, and those trying to get a job done. People focusing on reuse want to make (objects) as general as possible, while the application developers want things as specific as possible' (*Datamation*, 15 November 1989: 90). In a similar vein, Graham (1994) states: 'We are used to rewarding analysts and programmers according to the amount of code they produce rather than the amount of other people's code they reuse .... Furthermore, project managers are paid to make projects come in on time and not to write code for the benefit of subsequent projects' (also see Banker *et al.*, 1993; Cusumano 1991). Therefore, firms need to realign their incentives to encourage reuse.

Cusumano (1991) describes Toshiba's integrated set of incentives and controls associated with knowledge sharing and reuse. At the beginning of each project, managers at Toshiba agree to productivity targets that can be met only if a certain percentage of software specifications, designs, or code is reused. Design review meetings held at the end of each phase in the development cycle monitor progress against reuse targets. Moreover, when building new software, management requires project members to register a certain number of components in data bases for reuse in later projects. Personnel receive awards for registering particularly valuable or frequently reused modules, and their formal evaluations from superiors report on whether they have met their reuse targets. An overall committee, meanwhile, monitors reuse levels at Toshiba as well as deviations from targets both at the project and individual levels, and provides regular reports to managers.

Although reuse and knowledge sharing lead to economies of substitution, they have the potential to trap firms within the confines of old knowledge. To overcome this eventuality, Garud and Nayyar (1994) suggest that firms must continually create new knowledge through a combination of the old. (See also Jelinek and Schoonhoven, 1990.) Moreover, Hamel and Prahalad (1994) note that firms must upgrade their core competencies over time, partially by continually retraining employees. Lei, Hitt, and Bettis (1995) provide a more complete thesis on how firms can update core competencies through a meta-learning process that consists of information transfer, continuous improvement based on experimentation, and the development of firm-specific skills based on dynamic routines

These arguments, and the Toshiba example in particular, establish a firm's capabilities to reorganize its structure, routines, and incentives to encourage reuse and realize economies of substitution. However, there are limits to the number of activities any one firm can perform within the purview of its administrative structure. To appreciate these limits, we have to compare the costs of internalizing activities within the firm with the costs of sharing some of these activities with other firms.

Internalizing activities within a firm involves two costs: managerial and production costs. *Managerial costs* increase with the number of components produced in-house (lateral integration) and with the number of stages required to produce a given component (vertical integration). First, as the extent of vertical and lateral integration increases, managerial costs of coordinating different activities increases disproportionately (Demsetz, 1993; Piore, 1992). These coordination costs will increase further if congestion occurs in the deployment of scarce resources among competing activities (Teece, 1980). Second, cognitive complexity faced by managers also increases. This is particularly true in neo-Schumpeterian environments where each change brings with it disproportionate cognitive demands. As cognitive complexity increases, at some point, it becomes more costly for a firm to undertake any more activities in-house than it is to delegate them to other firms.

Additionally, in-house *production costs* will increase if the demand experienced by a firm is low or uncertain. In such circumstances, the firm cannot justify production facilities that operate at a minimum efficient scale for each component.[6] However, a specialized firm that consolidates demand for a particular component can justify building a minimum efficient scale plant, thereby realizing scale economies.[7]

Thus, in neo-Schumpeterian environments, increases in managerial and production costs are key forces for the disaggregation of activities. To understand fully why disaggregation is occurring, however, we must trade off the benefits of depending upon external component manufacturers with increases in transactions costs (Langlois and Robertson, 1992). Transactions costs arise from asset specificity under uncertainty, and from the potential for opportunistic behavior under conditions of information asymmetry and bounded rationality (Williamson, 1985). However, the advent of information technologies (such as electronic data interchange) allows firms to coordinate activities more closely (Manzi, 1994), thereby reducing information asymmetry and opportunism. Furthermore, a steady movement in many systemic industries toward industry-wide standards has reduced asset specificity and small numbers bargaining. Consequently, transactions costs are progressively decreasing (Malone, Yates, and Benjamin, 1987; Quinn, 1992). With decreases in transactions costs and increases in managerial and production costs, firms are focusing on a set of conceptually related activities and outsourcing the rest (Demsetz, 1993; Langlois, 1992; Piore, 1992; Piore and Sabel, 1984; Richardson, 1972).[8]

Interfirm issues

As firms manufacture only some components and outsource others, they implicitly 'partition' the technological system.[9] Partitioning a technological system can create an organizational system whose organizational modules (firms) can engage and disengage in response to market and technological changes (also see Miles and Snow, 1986; Sanchez and Mahoney, 1994). However, to accomplish such 'flexible specialization' (Piore and Sable, 1984), it is important that these organizational modules coordinate among themselves to design and produce compatible components. Otherwise, performance slippage and the costs associated with integrating the various components into a technological system will become prohibitively high.

A key question is whether such integration should be left to markets, or whether some other governance mode is required. If we were dealing with a static technological system, perhaps markets could serve as a forum for integration. However, when technological systems are changing rapidly, the cost of creating and maintaining interface standards within a market mode of governance will be prohibitively high. Standardization requires much closer coordination among firms than markets can offer.

Coordination between vertically interdependent firms requires an approach to contracting that emphasizes long-term relationships based on trust and reputation (Macneil, 1980; Powell, 1990).[10] Analogous to the notion of unutilized degrees of freedom in technological systems, relationships between firms are defined broadly, allowing enough latitude for evolution over time. Once relationships are established, continual interactions (including the exchange of strategic information, personnel and knowledge) among collaborating firms create an environment that

[6] A firm could establish minimum efficient scale plants and sell excess production to other system manufacturers. But, as the number of system components manufactured in-house increases, the firm will encounter greater cognitive complexity and higher coordination costs in dealing with multiple activities in several different markets.

[7] Even with the usage of flexible manufacturing technologies, eventually cognitive complexity will set in as the variety of product configurations increases.

[8] For several illustrations, see a recent *Fortune* (14 December 1994) article which provides the benefits of outsourcing and examples of firms that benefited from outsourcing.

[9] von Hippel (1994) offers the notion of sticky data to explain why such a task partitioning is important. Data are sticky when there are costs associated with replicating and diffusing location-specific information. Consequently, if different components of a technological system require conceptually different kinds of knowledge, it makes sense to partition the system into modules that different members can manufacture in a distributed manner.

[10] Relational contracting is an important characteristic of the Japanese Keiretsu system (Abegglen and Stalk, 1985; Aoki, 1990; Piore and Sable, 1984; Womack *et al.*, 1990). Keiretsus are characterized by a governance mode that possesses features of both markets and vertically integrated hierarchies while being neither. Reflecting on the benefits of such a 'quasi-integrated' system, Aoki (1990: 3) states: 'A key to an understanding of Japan's industrial performance can be found in the ability of firms in certain industries to coordinate their operating activities flexibly and quickly in response to changing market conditions and to changes in other factors in the industrial environment, as well as to emergent technical and technological exigencies'.

engenders trust and mutual accommodation. That is, the relationships between firms become 'upgradable.' Indeed, as Morgan (1986) points out, the broadest agreement would be one in which only those eventualities that definitely must be avoided (noxiants) are specified.

The classical approach to contingent claims contracting reduces such upgradability. This is because contingent claims contracts create a rigid framework for relationships by attempting to prespecify performance under all likely contingencies (Macneil, 1980). However, when technology is evolving rapidly and it is difficult to foresee the future, the very notion of a contingent claims contract becomes questionable.[11]

Furthermore, a zero-sum mentality which prescribes that firms should view buyer–supplier relationships as a source of competition also inhibits upgradability (Garud, 1994). For instance, Porter (1980) has suggested that firms should develop 'bargaining advantage' over suppliers to 'squeeze out the best deal.' Such a zero-sum mentality engenders distrust (Kelley and Stahelski, 1970; Weick, 1979) and leads to conflict in a self-fulfilling way. Eventually, such a mentality destroys the coordination required to realize economies of substitution.

There are indications that some firms in the U.S.A. are increasing their emphasis on upgradable relational contracts. For instance, vertically related firms are focusing on the practical aspects of building relationships and trust among themselves. In particular, some firms are reducing the number of suppliers and focusing their energies on building long-term relationships with this core group.[12] Such long-term relationships seek to ensure that '. . [e]ach player's destiny will be joined with that of the other. And mutual dependence will characterize the relationships' (Davidow and Malone, 1993: 142).

The advent of new information-mediated technologies (Zuboff, 1984) makes coordination between firms all the more possible (Fombrun and Astley, 1982). If we view firms as modules of knowledge, mechanisms such as electronic data interchange (Malone *et al.*, 1987) enable connections between these modules and promote interfirm coordination. These information technologies reduce transactions costs, thereby improving the management of disaggregated systems (Quinn, 1992).

A neo-Schumpeterian industrial landscape requires cooperation between horizontally interdependent firms as well. As technologies change, firms may find that they do not have all the required competencies to create a viable technological system. These competencies may be resident in their rivals. Given the difficult task of creating new competencies rapidly as and when they are required, firms may be compelled to forge hybrid arrangements with rivals.[13] Taligent is one such hybrid arrangement. IBM and Apple, two direct competitors, created the Taligent collaborative venture and gave it wide latitude to create a common object-oriented operating system.

Another form of cooperation between horizontally interdependent firms is knowledge sharing without the formation of a formal alliance such as a joint venture (Langlois and Robertson, 1992). Knowledge sharing between rivals is desirable to the extent that it increases the density of firms manufacturing technological systems that conform to a common standard. As the density of firms manufacturing systems to a common standard increases, so do the benefits to customers who get a wider choice of complementary products from which to create their preferred system configurations (see Wade, 1994). The larger customer base, in turn, provides

[11] This line of reasoning has led many researchers to suggest that these types of transactions be internalized within firms. However, as we have noted earlier, there are limits to the different kinds and number of activities that can be internalized.

[12] A recent *Fortune* (21 February 1994) article describes these emerging practices in the U.S.A. For instance, AMP, a manufacturer of electronic connectors, supplied Silicon Graphics, a workstations manufacturer, with an order over the weekend to replace defective connectors (supplied by a competitor) on the basis of just a phone call. Similarly, Donnelley Corporation built a new plant to manufacture exterior mirrors for Honda based on a verbal agreement to initiate a new partnership. From Honda's point of view too, this agreement involved a lot of trust because Donnelley neither had prior experience in making exterior mirrors nor did it have the requisite production facilities.

[13] In dynamic environments, in-house development of components as and when they are required is prohibitively expensive because of time compression diseconomies (Dierickx and Cool, 1989). Time compression diseconomies arise when an attempt is made to reduce the time taken to accomplish a set of activities by allocating additional resources. The diseconomies result because the resources additionally required are disproportionately more than the benefits that accrue from time compression.

incentives to manufacturers of complementary components to invest in innovation.

In their study of the music and computer industries, for instance, Langlois and Robertson (1992) note that a firm can earn higher profits by sharing knowledge with rivals than by attempting to appropriate all the benefits itself. They add that 'when a component maker is unable to offer customers enough variety to justify the purchase of associated components in a modular system, the most successful firms will be those that abandon a proprietary strategy in favor of membership in a network of competitors employing a common standard of compatibility' (Langlois and Robertson, 1992: 301).

Eventually, distinctions between horizontal and vertical interdependence become blurred. As vertically interdependent firms learn from one another, they may become horizontally interdependent over time (Hamel, Doz, and Prahalad, 1989). For instance, Donnelley Corporation, a supplier of glass for making mirrors, became a rival to its own buyers when it built a plant to supply Honda with exterior mirrors (*Fortune*, 21 February 1994). As winners and losers arise in a technological race, firms that were horizontally interdependent may become vertically interdependent over time. For instance, Next Corporation, an erstwhile rival to workstation manufacturers like Hewlett Packard and Sun Microsystems, exited the workstation hardware market and currently supplies its object-oriented tools and operating system software to these companies. Moreover, two firms that are vertically interdependent in one organizational system may become horizontally interdependent in another organizational system. In the telecommunications industry, for instance, AT&T supplies wireless communications equipment to the Baby Bells. However, with its recent acquisition of McCaw, AT&T will compete with the Baby Bells in the cellular services market.

In summary, the partitioning of the technological system among specialized manufacturers confers modularity on the organizational system. The coordination of specialized firms manufacturing components of the partitioned technological system occurs under a governance mode that is neither a hierarchy nor a market (Best, 1990; Powell, 1990; Richardson, 1972). This governance mode is characterized by a 'lattice type' network of relationships (Powell and Brantley, 1992) wherein the distinction between horizontal and vertical relationships becomes blurred. This network structure must be generally, rather than specifically, defined to allow enough latitude for interfirm relationships within the organizational systems to evolve with time. The result is a modularly upgradable organizational system.

Piore and Sabel (1984) note that the partitioning of tasks in the production process need not map neatly on to customers' preferred system configurations. In this regard, intermediary firms, commonly known as value-added resellers or system integrators, play an important role. Such firms perform two functions. First, they provide customized solutions to meet specific customer needs. In doing so, they reduce the cognitive complexity customers confront in mixing and matching the components manufactured by different firms. Second, when performance slippage occurs due to incompatibilities created by technological change, these firms ensure that the integrity of the technological system is maintained. To this extent, the role of system integrators in an organizational system is analogous to the role of gateway technologies in a technological system.[14]

Whereas system integrators reduce cognitive complexity, their presence increases transactions costs. These costs can be minimized to the extent that members of an organizational system subscribe to a common set of standards. According to Astley and Brahm (1989: 258), for 'the functional integration of modules as part of a coherent system, an overarching "framework" of planning and coordination would be necessary' (see also Toffler, 1985). Indeed, we are now witnessing a growing movement toward 'open standards' in the institutional environment of standards. Open standards act as mechanisms for coordinating the emerging network mode by reducing transaction costs. We now direct our attention to the institutional aspects of open standards creation.

[14] For instance, in OOP, several firms, including Visual Edge Software Ltd., Iona Technologies Inc., and Digital Equipment Corporation, have created products to bridge various systems based on incompatible object models from Object Management Group (OMG) and Microsoft Corporation (*Computerworld*, 3 October 1994, p. 8.). Recently, however, Microsoft and OMG have agreed to make their object models compatible with each other (*Computerworld*, 5 September 1994, p. 1).

Institutional issues

Langlois and Robertson (1992) distinguish between two types of networks: 'centralized' and 'decentralized.' They suggest that a centralized network is one in which network members are tied to a 'lead' firm, as in the Japanese automobile industry. A decentralized network is one in which no one firm exercises exclusive control over common standards; moreover, any firm that tries to dictate standards in a decentralized network risks being isolated if network members and customers do not follow its lead.

Increasingly, we are witnessing the growth of such decentralized networks in rapidly changing systemic environments, because of network externalities (Rotemberg and Saloner, 1991). Network externalities arise when the benefits a user derives from a product increase from current levels as others use compatible products (e.g., Farrell and Saloner, 1986; Katz and Shapiro, 1985).[15] In the presence of network externalities, the larger the network, the greater is its attraction. In such a situation, firms are finding it in their best interests to adhere to industry-wide standards and promote compatibility, thereby increasing network benefits.[16] Even the largest of firms have been forced to participate in the joint setting of industry-wide standards. For instance, in the computer industry, dominant computer manufacturers (e.g., IBM in the U.S.A. and NEC in Japan) were reluctant to adopt open standards, fearing loss of market control. However, over time, customers have compelled even these firms to offer systems based on open standards.[17]

Although the impetus for open standards stems from market demands for compatibility, the actual process of standard-setting is political— one that unfolds in the institutional environment of standards-setting bodies. The political process manifests itself in the form of broad agreements on system architecture, rather than in the form of precise definitions of standards. Indeed, only such broad agreements provide organizational and technological systems with the degrees of freedom required for future evolution. Recognizing the importance of this upgradability, Graham (1994) suggests that open standards must be specified at a high level of abstraction to allow greater degrees of freedom. At the same time, if standards are specified too loosely, they may result in the creation of incompatible components.

Working with open standards leads to decentralized innovation wherein individual firms can autonomously create differentiated components. At an extreme, a proliferation of components occurs, thereby increasing the costs involved in identifying and selecting appropriate components (both for system manufacturers and users). Under these circumstances, specialized information brokers arise to reduce these search costs. For instance, in the case of OOP, the Object Management Group has created an information brokerage that provides information as well as a market for component software. Participating firms list their products with the brokerage, along with descriptive information and product specifications (Object Management Group, 25 July 1994: 1).

Thus, open standards reduce asset specificity and information asymmetry between interdependent firms manufacturing complementary components of a larger system. Moreover, with open standards, the negative consequences of opportunistic behavior are mitigated because no one firm can change industry-wide standards on its own. No firm is held hostage by others because open standards create second sources for the supply of components. Therefore, as more firms embrace open standards, transaction costs decline. In turn, a reduction in transactions costs makes it possible for firms to form dynamic networks (Miles and Snow, 1986). In these dynamic networks, coordination occurs through institutional mechanisms that comprise both the standard-setting bodies and the open standards they foster. While modularity in the organiza-

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[15] The importance of compatibility in OOP is captured by Graham (1994: 5), who states: 'Object technology can only succeed against the inertia of existing practice if users can achieve the confidence in moving to it that they require from a move to open systems. If object-oriented applications are all mutually incompatible, if object-oriented databases cannot interwork with each other and with relational databases and if there are no standard notations and terms for object-oriented analysis there is little hope of this (success).'

[16] See Arthur (1988), David (1993), and Garud and Kumaraswamy (1993) for a deeper appreciation of why the presence of network externalities is leading to the creation of open standards in contemporary environments.

[17] For instance, the Network Applications Consortium, a group of 25 large users with annual revenues of almost $200 billion, hopes to use its buying capacity to exert pressure on hardware and software vendors to conform to standards, so that applications, operating systems, and network services from various vendors can work smoothly together (*Computerworld*, 12 September 1994).

tional system makes it highly adaptive to external contingencies, the overarching institutional umbrella of standards maintains overall consistency of action.

In sum, just as relational contracting imparts hierarchy-like characteristics to the network organizational system, the institutional environment of open standards imparts market-like characteristics to it. Reliance on open standards allows firms to 'trade' knowledge encapsulated in reusable components. Just as markets comprise regulatory bodies and institutional arrangements to guarantee efficiency, the organizational system comprises autonomous bodies to maintain and guarantee conformance to open standards. In markets, changes in customer demand result in resource reallocation between competing activities. In organizational systems too, customers play an important role in providing incentives for firms to conform to a common set of standards. Specifically, customers are the arbiters of whether or not a technological system has greater network benefits, and firms that offer 'incompatible' systems pay a price. At the same time, institutionalized standards endow memory on the organizational system—a feature missing in traditional atomistic markets. Thus, open standards create a unique institutional environment that coordinates activities of the organizational system.

COOPERATIVE AND COMPETITIVE DYNAMICS IN A MODULARLY UPGRADABLE WORLD

We have introduced three levels of analysis—intrafirm, interfirm, and institutional—to explain how organizational systems may be designed to realize economies of substitution. A fundamental attribute of these emerging organizational systems is the presence of both cooperation and competition at each of the three levels. Within the firm, for instance, competition for a limited pool of resources between individuals creates incentives for increasing current performance even at the expense of future performance. Contributions to current performance provide instant recognition and rewards, whereas contributions to future performance (through the design of reusable components) may yield little recognition or rewards. Moreover, creators of reusable components may have to face an additional burden when problems arise with their reusable components. Consequently, there will be a tendency to avoid or postpone the creation of reusable components. In addition, there may be a reluctance to reuse components designed by others (even if created). Clearly, cooperation is required to create and reuse such components. Firms need to balance the tension between cooperation and competition by instituting appropriate systems, structures, and incentives to encourage the creation of resuable components.

This tension between cooperation and competition is manifest at the interfirm level as well. Firms confronting a rapidly changing technological system will have to rely on others for complementary components even as they focus on the creation of core components. Indeed, firms will have to share knowledge with one another to ensure that the components they manufacture are compatible. Knowledge sharing, in turn, increases competitive pressures on firms.[18] In such a situation, firms have to innovate continually, destroying some core competencies and enhacning others to suit current requirements (see Lei *et al.*, 1995, for a detailed discussion of how core competencies can be changed over time).

As Powell and Brantley (1992) and Mowery and Rosenberg (1989) suggest, these efforts to extend and adapt core competencies essentially serve as a 'ticket of admission' into the wider organizational network to which they belong. Indeed, from this perspective, the main question is not whether to 'make or buy.' Rather, it is 'What competencies are complementary to our own?' so that access to these may be secured through appropriate realignment of relationships within organizational networks (Quinn, 1992; see also Black and Boal, 1994). Depending on how firms answer this question, they may terminate some relationships and forge new ones to create a dynamic learning environment that enables them to adapt to the demands of an evolving technological system.

The tension between cooperation and competition pervades the institutional level as well.

[18] For instance, Motorola, Apple, and IBM have had to share technical knowledge with one another in order to create the Power PC microprocessor; this effort eventually will increase competitive pressures on each firm to innovate (*Fortune*, 14 December 1994).

Because of network benefits, firms will try to create or join as large a network as possible. As we saw earlier, this implies the creation of, or conformance to, open standards. To this extent, cooperation is required. However, confronting the prospect of subscribing to common standards, firms would want to be proactive in shaping these standards to suit their competencies better. Specifically, each firm would want its own component specifications built directly into emerging standards. To this extent, firms compete to define standards that favor their own conceptualization of the technological system.

Thus, firms operating in a neo-Schumpeterian world of rapidly changing systemic technologies have to focus their attention on some core components while depending upon others for complementary ones. To ensure compatibility between these components, firms have to share their knowledge with others and subscribe to open standards. Such cooperation leads to competition as firms differentiate their activities through innovation and attempt to shape their institutional environment of standards. In this way, the tension between cooperation and competition is manifest between levels of the organizational systems.

CONCLUSION

Kenney and Florida (1993) state that the 'challenge facing American industry is similar to that faced by Britain at the turn of the century—the need to restructure according to the organizational principles of a new production paradigm in the face of social inertia resulting from the legacy of a past industrial order.' These authors caution that American industry may lose its global leadership role if contemporary industrial challenges are not articulated in appropriate technological and organizational terms.

This paper is an attempt to pose these challenges in appropriate technological and organizational terms. Specifically, firms are operating in a neo-Schumpeterian environment where systemic technologies are changing rapidly. In such an environment, firms have to design technological systems to yield economies of substitution, and at the same time, design organizational systems to exploit these economies.

Implicit in the design of technological and organizational systems for economies of tution is an ability to manage what we considered to be mutually exclusive con incremental vs. radical technological markets vs. hierarchies, cooperation vs. tition, and craft vs. mass production. A we can see a trend toward the coexist these mutually exclusive concepts as ev by the prevalence of terms such as 'n upgradability' (*New York Times*, June 2 'networks' (Powell, 1990), 'co-opetitior Sam Albert in *Fortune*, 14 December 19 'mass customization' (Pine, 1993). Clea need new theoretical frames to underst basis for these concepts.

Our paper provides a basis for unders how these new terms are the order of t industrial landscape. For instance, consi dichotomy between radical and increment nological change. As our paper suggests, logical change need not be radical breakt that destroy previous knowledge.[19] Inn from scratch each time is difficult, impossible, given the systemic nature of t ogies and the rapidity of change. At th time, reliance on incremental change ma technological progress and lead to stag Instead, firms may create higher-perf systems by reusing some components and tuting others, thereby building on existing edge and reaping economies of subst Thus, the technological change proces not be either incremental or radical, b incorporate aspects of both.

Similarly, consider the traditional dic between markets and hierarchies. As ou suggests, the network mode of gov integrates both the decentralization of governance and the coordination of hier governance. Moreover, we argue that the n mode requires reconceptualization of practices at the intrafirm, interfirm, an tutional levels. For instance, at the in level, we need to design systems, incentiv

[19] We are not alone in suggesting this. Usher (19 the thesis of cumulative synthesis where inventio through accumulation of incremental progress in s unconnected areas until such time the stage is set f of insight (the actual invention) to take place. Dougherty (1992) suggests that product innovation occur in a vacuum, but typically build upon knowledge.

structures that promote knowledge sharing rather than knowledge hoarding. At the interfirm level, we need to conceptualize alliances and relationships in fluid terms calling into attention relational aspects of contracting. At the institutional level, we need to explore the sociopolitical processes involved in the creation and evolution of self-regulatory mechanisms such as open standards. Emphasizing the unique status of networks, Powell (1990: 299) declared that they are 'neither fish nor fowl, nor some mongrel hybrid, but a distinctly different form.' Indeed, Powell argues that network governance is the most appropriate mode for organizing complex and idiosyncratic exchanges (such as knowledge) under dynamic conditions.

Next, consider the dichotomy between cooperation and competition. As our paper suggests, firms need to cooperate and compete with one another simultaneously. Firms need to cooperate with suppliers and even rivals to secure complementary resources, skills, or components. At the same time, they may have to compete with their collaborators in the product markets. For instance, standards creation requires cooperation among firms; at the same time, these firms compete with one another to ensure that their own technical specifications are included in the evolving standards.

Together, the technological and organizational designs that we have described in this paper address another dichotomy—the trade-off between craft and mass production. Specifically, modular upgradability makes it possible for customers to mix and match components to create customized solutions to their technological needs. At the same time, modular upgradability allows firms to realize scale and scope economies. For instance, firms realize scale economies when they partition the system and specialize in mass producing specific components (an aspect that Baldwin and Clark, 1994, term as modularity-in-production). Firms realize scope economies by reusing components across different product lines (Goldhar and Jelinek, 1983). Thus, modular upgradability leads to mass customization (Pine, 1993).

Although our paper provides a framework with which to view these emerging phenomena, it is but a first step. As is the case with most new frameworks, ours raises as many questions for future research as it attempts to answer. For instance, what are the limits to economies of substitution? Clearly, after a poin results in too many options, there cognitive complexity and search cos ers, manufacturers, and customers. too has its limits; the degrees of f into a system will be exhausted eve can firms anticipate these limits an to sustain continual innovation?

Consider another issue. How can organizational systems that balanc demands created by the coe cooperation and competition? We description of a network form that is industries characterized by network and built around technological sys have reported network forms in indu from biotechnology to textiles (Kenney and Florida, 1993; Nelson 1992; Piore and Sabel, 1984; P Powell, 1990; Quinn, 1992). Wl idiosyncratic features of these net These are but illustrative question researchers and practitioners need Indeed, our ability to raise the questions and address them is cri continued success of American f emerging industrial order.

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