ARCHITECTURAL INERTIA:

THE EVOLUTION OF MODULAR SYSTEMS

IN NETWORK MARKETS[1]

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ABSTRACT

What causes the transformation of technological systems from modular structures and open architectures to integrated and proprietary ones? This paper takes a multi-level approach to develop a model of the evolution of modular technological systems that exhibit positive network externalities. Changes in technological architectures are driven by the behavior of powerful manufacturers of core subsystems that bundle and integrate complementary components and make the system less modular and open. Proprietary technologies and integrated structures reduce a system's flexibility and ability to adapt to environmental changes thus increasing *architectural inertia*. Propositions are formulated and the model is supported with an analysis of the personal computer industry.

Evidence from personal computers, telecommunications systems, bicycles and even textbooks suggests that product architectures are dynamic and unstable as they continually migrate toward or away from increased modularity (Fine, 1998; Schilling, 2000). Given the coevolutionary nature of the relationships between technologies, firms, and industries (Nelson, 1998; Rosenkopf & Nerkar, 1999), changes in product architectures are both driven by and have significant repercussions on organizational and industry structures. The purpose of this paper is to examine the multi-level dynamics that drive technological systems that exhibit positive network externalities from modular and open architectures to proprietary and integrated ones, and the consequences of these shifts. Are these architectural transitions strictly the result of exogenous events and discontinuities (as prior research has assumed) or is there something inherent to the nature of these systems and the behavior of their actors that result in these changes?

The model presented in this paper explains the evolution of technological systems as a function of the rent-seeking behavior of dominant producers of core subsystems. When firms benefit from the positive feedback effects of network markets and become dominant suppliers of a core component, they seek to increase their market power and control over the architecture by bundling and integrating complementary components in order to extract more rents from the system. This closes and renders more proprietary the architecture, which in turn leads to a lack of flexibility and an increased vulnerability of the system to environmental disturbances that I refer to as *architectural inertia*. This process underscores how the short-run, rent-seeking behavior of dominant suppliers can threaten the long-run survival chances of the architecture as a whole. Propositions are formulated and the case of the personal computer (PC) industry is analyzed to test the model.

NETWORK EXTERNALITIES AND STANDARD ARCHITECTURES

Products for which the utility that a user derives from consumption increases with the number of other users consuming the same or compatible good are said to exhibit positive network externalities (Farrell & Saloner, 1986; Katz & Shapiro, 1985). The classic example is the telephone, whose value to a user increases as the number of other people that he can talk to (i.e. with compatible telephones) increases. The presence of positive network externalities can have important effects on industry and population dynamics (Barnett, 1990; Baum, Korn & Kotha, 1995). In particular, network externalities may lead to increasing returns to adoption (Arthur, 1989) and technological bandwagon effects (Wade, 1995).

These effects are triggered by the positive feedback generated when a large installed base of users increases the incentives for firms to develop complementary products and services, and access to complementary and compatible products creates in turn more incentives for new users to adopt the technology, and so on. However, the development of complementary products depends to a great extent on the existence of standard component interfaces. Therefore, before both users and producers start to benefit from the effects of the positive network externalities, a standard architecture must be specified in order to ensure technological compatibility and stimulate the development of complementary goods and services.

Technological standards can either be enforced by regulation (*de jure* standards) or emerge *de facto* – what Katz and Shapiro (1986) call 'standardization-by-sheer-force-of-numbers' – when no authoritative standards-setting body exists. In these cases, the chances of given technology emerging as the standard are a function of the level of organizational support that it attracts (Wade, 1995) and firms must develop strategies for promoting and sponsoring their technology. A typical strategy involves a sponsoring firm offering technology licenses at little or no cost in order to induce other firms to adopt its technology (Farrell and Gallini, 1988). Garud and Kumaraswamy (1993) show how Sun Microsystems was able to shape standards in the computer workstation market by freely licensing out its technology and sharing technical knowledge. Conversely, the case of Sony and the Betamax VCR (Rosenbloom and Cusumano, 1987) illustrates the potential dangers of keeping technology proprietary when in the midst of a standards war.

Nevertheless, the licensing and open source strategy leads to a crucial dilemma faced by technology sponsors in network industries: how to ensure the rapid adoption and proliferation of its technology as the dominant standard while still maintaining enough control over the product's design and architecture to capture positive rents? When technology is freely available, the sponsoring firm effectively loses its ability to control the flow of rents through the system. In the absence of traditional sources of isolating mechanisms (Rumelt, 1984) that are typical of proprietary systems, the key question arises of how to generate abnormal returns while freely licensing out a technology.

On the one hand, retaining exclusive rights over a technological standard ensures that the rents generated through the adoption of the standard will flow directly to the firm holding these rights. On the other hand, given that other firms are unable to capture any of the rents from the proprietary architecture, the technology is unlikely to generate sufficient support from suppliers of complementary goods and services, which is needed to stimulate the rapid adoption of the standard. As Arthur (1996) argues, the central player must be willing to cede some of the profits to the other firms in the network – "to feed the web" – in order to amplify the positive feedback to the base technology. The strategies of IBM and Apple in the early days of the PC industry exemplify the tradeoffs involved in this so-called 'dilemma of network markets'.

While IBM opted for an open platform strategy that ensured that the 'IBM PC', as it was initially called, became the dominant design for personal computers, it essentially ceded all the rents to be derived from the manufacture of computer hardware and software to clone manufacturers and assemblers such as Dell and Compaq, and to key component producers like Intel and Microsoft. Only by virtue of its size and its strong brand name was IBM able to survive and eventually thrive by shifting its focus to offering technical and professional services. In fact, the constant upheaval and struggle that characterized the PC industry for many years wiped out many smaller and less well-known computer manufacturers. By contrast, Apple Computer decided early on to keep its technology proprietary and has successfully captured all of the rents from an architecture that failed to become the dominant design and holds less than 10% of the market – despite what many argue is a “superior technology”. This example demonstrates how network markets involve a trade-off between capturing a small share of a large pie (i.e. IBM) or a large share of a small pie (i.e. Apple).

MODULAR DESIGNS AND NETWORK STRATEGIES

Complex technological systems consist of interdependent and hierarchically nested subsystems that can be successively decomposed into more subsystems at increasingly finer levels (Simon, 1962). Tushman and Rosenkopf (1992) propose a typology of technological products that distinguishes between non-assembled products, simple assembled products, and assembled systems. Assembled systems can be further divided into closed systems that are composed of an enclosed set of simple products and are produced by single organizations; and open systems that consist of multiple, interdependent closed systems and rely on distributed networks of organizations to produce the various subsystems and which are the most complex type of technological product. Given that they are composed of multiple subsystems produced by different organizations, open systems are by definition modular.

Modularity refers to the extent to which a system's components are structurally independent yet function together as a whole, or are functionally interdependent (Baldwin and Clark, 2000). Several researchers have proposed that product modularity is the key to resolving the ‘dilemma of network markets’ (e.g. Garud and Kumaraswamy, 1993; 1995; Schilling, 2000). In contrast to highly integrated architectures, modular systems provide many entry points for other firms to design complementary and compatible components. The opportunity to profit from the development of complementary products stimulates the entry of organizations that support and have a stake in the technological standard. This drives technology adoption and builds the installed base and modularity thus greatly increases the chances of a given architecture emerging as the standard. However, modular designs also allow the technological sponsor to retain a share of the rents without keeping the technology proprietary. Strategies for exploiting ‘transient monopolies’ (Garud, Jain and Phelps, 1998) or ‘component monopolies’ (Schilling, 2000) illustrate how modularity enables firms to capture monopoly rents in open systems and are described below.

Modular designs allow a firm to dramatically increase the pace of technical innovation and continually introduce new products to always stay a step ahead of competitors. Rapid technological advances allow the firm to capture ‘temporary’ monopoly rents while their rivals catch up. Modularity facilitates this because the organization can preserve valuable technical knowledge across successive generations of product designs in order to cope with (or trigger) very short product life cycles. Firms benefit from ‘economies of substitution’ in modular systems 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, 1995: 96). The other way in which a firm can capture monopoly rents through modularization is by “encapsulating proprietary technology within a component that conforms to an open-standards based architecture" (Schilling, 2000: 328) and becoming a component monopolist.

Modularity therefore provides a solution to the dilemma of network markets by allowing sponsoring firms to open the system to developers of complementary products in order to drive adoption of the standard while still capturing monopoly rents. The properties of modular systems also confer other advantages to organizations involved in their production and these are discussed at length in subsequent sections. We now examine the conditions under which dominant designs and standard architectures emerge within open and modular technological systems.

DOMINANT DESIGNS AND CONCEPTIONS OF CONTROL

Tushman and Rosenkopf (1992) argue that technological evolution is driven by a combination of technical, economic, social, political and organizational processes. While a technology may suggest a logical path, as systems become more complex, non-technical processes play a greater role in shaping technological evolution – in open systems, socio-political processes play a pervasive role. They propose a model of technological change driven by community factors where dominant designs do not emerge from technical logic but "from a negotiated logic enlivened by actors with interests in competing regimes" (1992: 322). However, the work of economists on network externalities and standards setting, invariably fails to discuss the socio-political processes that drive the adoption of a standard or dominant design. Wade (1995) suggests that although economic theories provide useful descriptions of the outcomes of technology adoption under increasing returns, they are deficient in two respects: they are "mathematically derived and have not been tested empirically… and the process by which a given design gains supporters is not specified, just its consequences" (1995: 112).

When discontinuities trigger an era of technological ferment (Anderson and Tushman, 1990), the product's critical dimensions of merit are highly uncertain and users are unable to choose between competing designs supported by the different communities of organizations. A dominant design then emerges from socio-political processes within and between these competing technical communities and when key stakeholders converge and support a single design. Organizations must develop not only technical competence, but also inter-organizational skills needed to forge alliances and shape critical dimensions of merit and solve industry problems. This view of technological evolution closely resembles Fligstein's (1996) account of how firms attempt to control competition in emergent markets. I therefore draw on concepts from his 'markets as politics' metaphor to describe how, in the presence of network externalities, open technological systems tend to stabilize through the adoption of a dominant design.

Eras of ferment are characterized by substantial product-class variation and high uncertainty. Positive network externalities increase the uncertainty given the race to establish a large installed base and the excess inertia of users from the previous technological regime. These eras are what Fligstein (1996) describes as ‘murky worlds’ where actors must construct accounts of the world in order to make sense of it and determine courses of action. The uncertainty ends with the emergence of a dominant design or technological standard that allows for the development of component interfaces, complementary products, and significantly reduces product class confusion allowing users to adopt confidently. Given the increasing returns to adoption and bandwagon effects, once in place, the standard proliferates at a very rapid pace. This means increased sales for the manufacturers of components that are part of the dominant design. Therefore, there are tremendous incentives for component manufacturers to aggressively promote their products and develop the alliances required to establish their technology as part of the dominant design.

Fligstein (1996) suggests that in emergent markets, the largest firms will attempt to stabilize the market by creating conceptions of control and political coalitions to control competition. In open technological systems, the standard architecture or dominant design is the conception of control that allows the environment to stabilize. Furthermore, the political coalition of organizations that is promoting the standard and controlling competition is made up of the manufacturers of the components of the dominant design. Therefore, in open systems, the standard component interfaces are determined through socio-political processes and they reflect the relationships between the organizations as well as the physical interactions between the different subsystems.

However, rather than the largest firms, in open systems, stable conceptions of control are created by the firms that manufacture the core subsystems of the architecture. Not all components in a system are of equal importance. Clark (1985) shows that both physical and functional interactions impose a hierarchical structure on technological designs. Core subsystems are more tightly connected to other subsystems through linking mechanisms while peripheral subsystems are more weakly coupled to others, so that changes to a core subsystem have greater systemwide repercussions than changes to a peripheral subsystem (Tushman and Murmann, 1998). In a technological architecture, control is more a function of centrality than size. Given that they have more and stronger links to the other components, the core components are critical to the overall performance of the system. Therefore, the manufacturers of core components have greater power and ability to lead political coalitions to control competition and are the technology sponsors that promote the adoption of a standard architecture. This process is explored in the context of the PC industry and formalized in Proposition 1.

A personal computer is a complex system consisting of various components linked together and produced by different organizations. Given the need for applications software, peripheral components such as disk drives and printers, as well as product-specific training and knowledge, the PC industry exhibits strong network externalities. As described above, IBM made the initial decision to develop a personal computer with a modular architecture by outsourcing production of most of the system's components to other firms. In a personal computer, the core subsystems are the central processing unit (CPU), which basically fulfills the computing function in the computer, and the operating system (OS), the master control program that runs the computer and sets the standards for the application programs that run in it. By outsourcing these core components, IBM essentially lost control of the architecture to their manufacturers, Intel and Microsoft, who then became the dominant coalition in the PC industry. In failing to recognize the power that the core component producers exert in a technological architecture subject to strong network externalities, IBM committed a strategic mistake of great proportions. The 'Wintel' architecture (as it eventually became known) now represents the stable conception of control created and enforced by the coalition of firms led by Intel and Microsoft. Although it has experienced successive generations of CPUs and OSs, the Wintel architecture has remained the dominant standard in the PC industry for the past 15 years. The main implication of this case is that organizations deciding to modularize a system in order to increase organizational support and stimulate adoption would be wise to relinquish control only over the peripheral components rather than the core components of the architecture.

> *Proposition 1: In open technological systems that exhibit positive network externalities, manufacturers of the core subsystems will create political coalitions in order to control competition through a standard architecture.*

CORE SUBSYSTEMS AND MARKET POWER

Once a dominant design is in place and the market stabilizes, core subsystem manufacturers become even more powerful. Given the externalities, these manufacturers quickly become dominant and command very large shares of the market. A dominant supplier will then have the opportunity to exert more control over the architecture by restricting access to technical knowledge in order to extract more value from the system. The firm can bundle complementary components into an integrated product and require customers to purchase the whole package. Strategies that leverage a firm's market power to integrate complementary components drive the system away from modularity and towards a closed and proprietary architecture (Schilling, 2000).

The core component producers are the ones that set the rules by which all the others must play given that they control the critical interfaces. Once dominant, they can take advantage of this and restrict access to key technical knowledge. They can make the architecture more proprietary and their rivals' products incompatible with the standard. The network externalities lead to high switching costs and transient incompatibility costs (Farrell and Saloner, 1986) and users are effectively locked into the dominant design. Therefore, holding technical knowledge proprietary provides dominant firms with competitive advantages that can become important sources of monopoly rents given the strong isolating mechanisms (Rumelt, 1984). Firms possessing unique assets (e.g. a large installed base that experiences high switching costs) or powerful market positions can create significant entry barriers by offering their core component only as part of a total product system. They will then gain even more market power and make the architecture more integrated and proprietary. Dominant firms can also control the evolution of the architecture and decide which products will be compatible with the standard by deliberately excluding certain vendors from accessing the full details of the interface.

Fine (1998) describes how different industries have evolved through cycles going from modular and open architectures with many component producers, to closed and proprietary architectures with vertically integrated manufacturers, then back to modular and so on. Although his analysis does not specifically address network industries, he points to similar factors that push an industry toward vertical integration and proprietary architectures. Technological innovations in one component can make it a more valuable part of the system and give market power to its producer. Market power in one component encourages bundling with other components to increase control and create more value, and also encourages integration with other components to develop proprietary solutions.

Economides (1998) explains the decision of firms to integrate in network industries by showing that the value that a firm can extract from selling a component in a system is positively related to the degree of competition in the markets for complementary components – 'the interdependence of value among markets for network components'. In other words, the value that a firm can extract from a system increases when the complementary markets in which it does not participate are more competitive. Furthermore, in a modular system, value cannot be extracted more than once, irrespective of the number of components the system is divided into. Therefore, even if a firm monopolizes a given component, it has no incentive to enter into complementary component markets that are perfectly competitive. On the other hand, entering an imperfectly competitive complementary component market, allows a firm to capture rents that it was losing in its original market. However, the winner-take-all nature of network markets virtually guarantees that they will not be perfectly competitive and that some component manufacturers will attempt to enter complementary markets. I refer again to the PC industry to test these arguments that are summarized in Proposition 2.

The legal challenges faced by Microsoft have centered on exactly these bundling and integration issues. Many features that users once purchased separately from an operating system now come bundled with the Windows OS. Microsoft had initially partnered with several vendors supplying the suite of software applications that was compatible with its DOS operating system: Lotus's 1-2-3 spreadsheet, MicroPro's WordStar and later WordPerfect's word processor, and Ashton Tate's dBase database management program. This was a wise strategy as Microsoft alone could not provide all the applications that were needed to stimulate adoption of the PC and make the Wintel architecture the dominant design. However, once firmly in place as the dominant OS supplier, Microsoft no longer had as much incentive to continue ceding profits to its partners. Therefore, Microsoft subsequently developed and bundled its own versions of these software programs (Excel, Word, and Access) along with presentation and e-mail software into its Office package, effectively eliminating the other vendors from the market and preventing others from entering. When Microsoft bundled Internet Explorer with Windows in order to attack and eliminate Netscape from the Internet browser market, the US Department of

Justice decided to sue the company for violating anti-trust regulations. Nonetheless, the speed at which Microsoft has become the dominant leader in the browser market, despite Netscape's early and commanding lead, attests to the power of core component manufacturers in network markets. A similar process is also taking place in the battle for control over the media player market currently dominated by RealNetworks as Microsoft has decided to bundle Windows Media Player 8 in the upcoming release of the Windows XP operating system.

Proposition 2: In open technological systems that exhibit positive network externalities, dominant manufacturers of core subsystems will enter imperfectly competitive complementary markets and bundle the complementary components or integrate them with the core component.

EVOLUTIONARY PROCESSES AND ARCHITECTURAL INERTIA

Technological change has been characterized as a socio-cultural evolutionary process of variation, selection and retention (Anderson and Tushman, 1990; Basalla, 1988) and evolutionary theorists have emphasized how selection processes in a technological system operate at nested levels that coevolve: technology, firms, industry structure, and institutions (Nelson, 1998); and products, firms, and systems (Rosenkopf and Nerkar, 1999). Therefore, modularity in technological architectures will have an impact on the nature and evolution of relationships at the intra-firm, inter-firm, and institutional level of a system. This is consistent with the hierarchical view of modularity articulated by various researchers. For example, Sanchez and Mahoney (1996) propose that organizations be structured in a way that reflects the level of modularity and the degree of coupling of the components in the technologies they produce. At the inter-firm level, Garud and Kumaraswamy (1995) argue that the relationships between the organizations manufacturing the different components of a product are analogous to the interactions between the components, and that at the institutional level, the environment within which the firms are embedded (i.e. the rules and procedures) mirrors the product's architecture.

We now examine the properties of modular architectures in order to assess their impact on the evolutionary processes operating at the inter-firm and industry level. In his seminal paper, Herbert Simon (1962) showed how evolution favors systems that are composed of stable sub-assemblies that can be discarded or modified (rather than the entire system) in response to environmental changes and shocks. Modularity thus increases a system’s ability to adapt to complex, changing environments while minimizing the degree of internal disruption or the probability of failure. More recent research on product modularity has focused on the benefits it provides firms with respect to increased flexibility in product design, in manufacturing, and in coping with technological change and uncertainty (Baldwin & Clark, 2000). Garud and Kumaraswamy (1995) and Sanchez (1995) argue that modular product designs provide firms with the flexibility to rapidly develop new products at low incremental costs. This is particularly desirable in highly uncertain environments where firms need to respond to rapidly changing markets and technologies. Therefore, from an evolutionary perspective, the flexible and adaptive features of modular technologies enhance their survival rates.

Moving up to the inter-firm and industry level of analysis, modularity also increases the amount of variation and heterogeneity in an environment by dramatically increasing the number of possible product configurations (Ulrich, 1995). Selection processes are then determined through the adoption of a dominant design whose components are subsequently retained by the producing firms in the next generation of product designs (Garud and Kumaraswamy, 1995). However, the adaptive benefits of industry-wide modularity will not persist when the core subsystem manufacturers seek to extract more value from the system by using their market power. By restricting the amount of variation on which selection processes operate through proprietary technology and incompatible standards, and making the components more tightly coupled through bundling and integration, core component producers compromise the whole architecture's ability to adapt and survive – a concept referred to as *architectural inertia*.

Open and modular systems enable new entrants to compete in relatively narrow niches by producing a specific component while obeying the design rules of the architecture. This increases the diversity in a technological system by providing new firms with more entry points. Increased specialization and horizontal competition in modular systems fosters innovation by increasing the number of firms searching for solutions to a given problem (Robertson and Langlois, 1995). Given that no one organization can develop a whole array of innovations by itself, this is critical to the system's evolution. Modularity therefore increases the survival chances of an architecture by allowing it to try out many alternatives simultaneously, leading to more rapid trial-and-error learning and greater adaptiveness. By contrast, in markets organized around proprietary technologies, there are numerous barriers to entry and therefore significantly less diversity. A lack of novel alternatives deprives a system of the ability to respond adequately to changes in its environment. Systems that are unable to generate sufficient variation will have lower survival rates than systems where greater diversity leads to increased chances of achieving an adequate level of fitness with a rapidly evolving environment.

A more integrated architecture also results in a tighter coupling between the system's components. Two components are tightly coupled if a change made to one component requires a change to the other in order for the overall product to work correctly (Ulrich, 1995). Therefore, tight coupling constrains the architecture's evolution and flexibility and makes it more inert and vulnerable to environmental disturbances. Any shock affecting one component will have a ripple effect on the other components that are tightly coupled to it and tighter coupling hinders the architecture's ability to integrate component innovations by requiring changes to be made to all the other components. On the other hand, in loosely coupled systems, environmental disturbances can be localized within specific modules and components innovations more easily integrated thereby increasing the overall system's adaptability (Orton and Weick, 1990). Faced with an environmental discontinuity of sufficiently large magnitude, an integrated architecture needs to be completely replaced as opposed to a modular architecture where some components can still be retained while integrating new components in order to adapt to the new environmental conditions. Proprietary technologies and integration thus decrease the architecture's flexibility and reduce the long-run survival chances of its members.

These evolutionary dynamics imply that the decisions of core component manufacturers involve a trade-off between increasing their own share of the rents in the short term and the longer-term survival of the architecture. In their analysis of governance structures, Robertson and Langlois refer to the trade-off "between the diversity of ideas that specialization and fragmentation may encourage, on the one hand, and the ease of implementation and internalization of returns permitted by vertical integration, on the other" (1995: 556). Schilling's description of firms increasing their control over the product's architecture suggests that certain strategies may be "at odds with the migration path suggested by the nature of the technology and its context" (2000: 330). Therefore, in order to enhance the long-run survival of the system as a whole, dominant manufacturers need to refrain from using of their market power to bundle and integrate complementary components.

In summary, dominant suppliers of core components enter into complementary component markets in order to appropriate a greater share of the rents. When these suppliers bundle and integrate components, they drive the system toward a closed and less modular architecture. This results in a lack of diversity given that other firms are denied the opportunity of contributing innovations to the system, and in a tighter coupling between the system's components. The lack of diversity and innovation makes the architecture more inert and at greater risk of being overthrown by an environmental discontinuity or shock. Similarly, tighter coupling makes the architecture more prone to collapse and less adaptive.

Proposition 3: In open technological systems that exhibit positive network externalities, dominant manufacturers of core components that bundle or integrate complementary components increase the architecture's inertia and risks of failure

ARCHITECTURAL TRANSFORMATION IN THE PC MARKET

We now pursue our analysis of the Microsoft case and the personal computer market to assess the validity of the model presented. Using its power as a dominant supplier of a core component, Microsoft has successfully integrated many complementary products from former partners and bundled them with its Windows operating system. However, in doing so, Microsoft has also increased the failure rate of the technology. A system is less prone to failure when there are stable intermediate modules that form the system's building blocks and are more resilient to shocks (Simon, 1962). This type of problem is precisely what critics of Microsoft's monopoly are quick to point out when they argue that the so-called 'feature creep' in Windows, where the operating system assumes the functionality of previously independent applications, has made the latest versions of Windows 'bloated', highly unstable, and more likely to crash.

Fligstein (1996) proposes that the transformation of markets results from three exogenous forces: invasion, economic crisis, or political intervention by states. Notwithstanding the current slowdown in the market for personal computers, the Wintel franchise currently faces two of these threats. The US Department of Justice has ordered Microsoft to break itself up into separate organizations for operating systems and software applications (political intervention) and; Linux is slowly making inroads into the operating system market and attempting to reorganize it around a new architecture and conception of control (invasion). According to Fligstein, the reorganization of a market usually resembles a social movement (1996: 668). The rise of the Linux operating system, which is a free and open source program first released on the Internet by a Finnish student, is as close as the PC industry has ever come to a social movement. As one of its central players, Microsoft can ensure the viability and survival of the Wintel architecture by continuing to specify standards while refraining from using that power to bundle and integrate other components and increase the system's inertia and chances of failure.

CONCLUSIONS

The propositions formulated in this paper form the basis of a theoretical model that explains the evolution of modular technological systems in the presence of network externalities. The case of the Microsoft in the personal computer market is analyzed and provides support for the model. Most of the empirical research having examined the population dynamics in network markets following technological discontinuities and the adoption of a dominant design attributes the failure of incumbent firms to these exogenous discontinuities (Anderson and Tushman, 1990; Barnett, 1990; Baum, Korn and Kotha, 1995). Although this relationship seems empirically robust, the model presented in this paper suggests that technological systems can buffer themselves from the deleterious effects of environmental discontinuities by retaining modular and flexible architectures. Loosely coupled, modular systems will lead to localized discontinuities rather than wholesale shifts to radically new dominant designs. However, remaining modular and open appears to conflict with firms' ability and desire to extract and appropriate more value from the system. Modularity is the right strategy when it allows the market to converge around a dominant design but once market power and architectural control can be increased, firms face significant pressures to integrate complementary components and increase their share of the rents. The long-term survival chances of the architecture are thus compromised by the short run, rent-seeking behavior of dominant firms. This paper therefore presents a different perspective than the existing literature and suggests that a multi-level approach can provide greater insight into the evolutionary dynamics of open technological systems.

Open systems are the most complex form of technological systems (Tushman and Rosenkopf, 1992) and understanding the evolutionary dynamics that characterize these systems requires an integrative framework that draws on very different streams of research and theoretical perspectives. First, economic theories on network externalities and increasing returns to adoption provide the necessary background for understanding why certain technological systems require the adoption of a standard architecture. Second, the process by which a dominant design emerges is best explained through the use of sociological and political approaches to markets. Finally, evolutionary and systems theory provide the lens through which architectural inertia and the failure of dominant designs are best understood. This paper thus integrates complementary theoretical perspectives in order to build a conceptual model of the multi-level dynamics in modular technological systems. More research is nonetheless required in order to provide a more comprehensive account of the evolution and failure of complex technological systems. What happens in cases where systems do not exhibit strong network externalities and in systems that are designed and built around closed and proprietary architectures that do not face pressures to modularize? In addition, although currently supported in a single case, the conceptual model developed can provide the basis for further exploration of the evolutionary dynamics of complex technological systems and for greater integration between different theories and research streams.

REFERENCES

Arthur, W.B, Competing Technologies and Lock-in by Historical Events: The Dynamics of Allocation Under Increasing returns. Economic Journal. 99, (1989), 116-131.

Arthur, W. B., Increasing Returns and the New World of Business. Harvard Business Review. (July-August, 1996), 101-109.

Anderson, P. and Tushman, M. L., Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. Administrative Science Quarterly. 35, (1990) 604-633.

Baldwin, C. Y. and Clark, K. B., Design Rules: The Power of Modularity. MIT Press. Cambridge, MA, 2000.

Barnett, William P., The Organizational Ecology of a Technological System. Administrative Science Quarterly. 35, (1990), 31-60.

Basalla, G., The Evolution of Technology. Cambridge University Press. Cambridge, UK, 1988.

Baum, J.A.C., Korn, H.J. and Kotha, S., Dominant Designs and Population Dynamics in Telecommunications Services: Founding and Failure of Facsimile Transmission Service Organizations, 1965-1992. Social Science Research. 24, (1995), 97-135.

Clark, K. B., The Interaction of Design Hierarchies and Market Concepts in Technological Evolution. Research Policy. 14, (1985), 235-251.

Economides, Nicholas, Competition and Vertical Integration in the Computing Industry. Working paper. Stern School of Business. New York, NY, 1998.

Farrel, J. and N. Gallini, Second Sourcing as Commitment. Quarterly Journal of Economics. 103, (1988), 673-694.

Farrel, J. and G. Saloner, Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation. American Economic Review. 76, (1986), 940-955.

Fine, Charles H., Clockspeed: Winning Industry Control in the Age of Temporary Advantage. Perseus Books. Reading, MA, 1998.

Fligstein, N., Markets as Politics: A Political-Cultural Approach to Market Institutions. American Sociological Review. 61, (1996), 656-673.

Garud, Raghu and Kumaraswamy, Arun, Changing Competitive Dynamics in Network Industries - An Exploration of Sun Microsystems' Open Systems Strategy. Strategic Management Journal.14, (1993), 351-369.

Garud, Raghu and Kumaraswamy, Arun, Technological and Organizational Designs for Realizing Economies of Substitution. Strategic Management Journal.16, (1995), 93-109.

Garud, Raghu, Sanjay Jain and Corey Phelps, Organizational Linkages and Product Transience: New Strategic Imperatives in Network Fields. Advances in Strategic Management.15, (1998), 205-267.

Katz, M. and Shapiro, C., Network Externalities, Competition, and Compatibility. American Economic Review. 75, (1985), 424-440.

Katz, M. and Shapiro, C., Technology Adoption in the Presence of Network Externalities. Journal of Political Economy. 94, (1986), 822-841.

Langlois, R. N. and Robertson, P. L., Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries. Research Policy. 21, (1992), 297-313.

Nelson, R.N., The Co-Evolution of Technology, Industrial Structure, and Supporting Institutions, in Dosi, G., Teece, D.J. and Chytry, J. (Eds.) Technology, Organization, and Competitiveness, Oxford University Press, 1998, 319-335.

Orton, J. D. and Weick, K.E., Loosely Coupled Systems: A Reconceptualization. Academy of Management Review. 15, (1990) 203-223.

Robertson, P. L. and Langlois, R. N., Innovation, Networks, and Vertical Integration Research Policy. 24, (1995), 543-562.

Rosenbloom R. and M. Cusumano, Technological Pioneering and Competitive Advantage: The Birth of the VCR Industry, *California Management Review*, (1987)

Rosenkopf, L. and Nerkar, A., On the Complexity of Technological Evolution, in Baum, J. A. C. and McKelvey, W. (Eds.) Variations in Organization Science, Thousand Oaks, CA. Sage, 1999, 169-183.

Rumelt, R. P., Toward a Strategic Theory of the Firm (1984) in N. J. Foss (Ed.) Resources, Firms and Strategies: A Reader in the Resource-Based Perspective. Oxford University Press, UK., 1997, 131-145.

Sanchez, R., Strategic Flexibility in Product Competition. Strategic Management Journal. 16, (1995), 135-159.

Sanchez, R. and Mahoney, J. T., Modularity, Flexibility, and Knowledge Management in Product and Organization Design. Strategic Management Journal.17, (1996), 63-76.

Schilling, M., Towards a General Modular Systems Theory and its Application to Inter-firm Product Modularity. Academy of Management Review. 25 (2000), 312-334.

Simon, H.A., The Architecture of Complexity. Proceedings of the 1962 American Philosophical Society. Vol. 106, 1962, 467-482.

Tushman, M.L. and Murmann, J. P, Dominant Designs, Technology Cycles, and Organizational Outcomes. Research in Organizational Behavior. 20 (1998), 231-266.

Tushman, M.L. and Rosenkopf, L., Organizational Determinants of Technological Change: Toward a Sociology of Technological Evolution. Research in Organizational Behavior. 14 (1992), 311-347.

Ulrich, K., The Role of Product Architecture in the Manufacturing Firm. Research Policy. 24 (1995), 419-440.

Wade, James, Dynamics of Organizational Communities and Technological Bandwagons: An Empirical Investigation of Community Evolution in the Microprocessor Market. Strategic Management Journal. 16, (1995), 111-133.