Digitalization and Innovation

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Digitalization and Innovations

Abstract

Developments in digital technology offer new opportunities to design new products and services. However, creating such *digitalized* products and services often creates new problems and challenges to firms that are trying to innovate. In this essay, we analyze the impact of digitalization of products and services on innovations. In particular, we argue that digitalization of products will lead to an emergence of new layered product architecture. The layered architecture is characterized by its generative design rules that connect loosely coupled heterogeneous layers. It is pregnant with the potential of unbounded innovations. The new product architecture will require organizations to adopt a new organizing logic of innovation that we dubbed as doubly distributed innovation network. Based on this analysis, we propose five key issues that future researchers need to explore.

Keywords: digitalization, innovation, product architecture, design rules

Digitalization and Market Innovations

Introduction

Since introduced by Apple in January 2007, iPhone has fundamentally changed the way consumers and mobile operators think about mobile phones. Not only iPhone offered users a novel way to interact with the sleek hardware with a striking user interface of a multi-touch screen, it completely re-invented what users could do with a mobile phone. By using over 200,000 different small application programs (called apps), iPhone users can do anything from making phone calls, listening music, watching movies, and reading books, to things like remotely controlling TVs and other home appliances, playing music ensemble (using an app called Ocarina), and even starting cars remotely. According to a recent study by the CTIA, the amount of non-voice data surpassed the amount of voice data in mobile phone networks in the United States for the first time in 2009 (Wortham 2010). According to an analysis by AdMob Mobile, more than 50% of non-voice mobile data are generated by iPhone users. Responding to iPhone's phenomenal success, companies like Google, Nokia, Samsung and Microsoft have introduced their own "smart phones". An important feature of these smart phones is that they are equiped with their own operating systems (such as Google's Android, Nokia's Symbian, Samsung's Bada, and Microsoft's Windows 7 Mobile) that allow users to install a wide variety of apps that are available on on-line stores for these apps. Unlike in the traditional model of mobile services where mobile operators used to exercise a virtually complete control over design, delivery and payment for services, the role of mobile operators are radically marginalized with the growing popularity of these smart phones. At the same time, "phone" function has become just one of many apps on these smart phones, and users often have alternative apps that provide cheaper, if not free, mobile voice services. Smart phone operating systems such as iPhone and Android have inspired diverse firms and individual entrepreneurs who are trying to develop the next killer app.

The innovation story of the iPhone offers us a striking example of how digitalization can bring heterogeneous resources together, blur market boundaries, and create new meaning out of familiar products. After all, a phone is no longer just a phone. The design and implementation of iPhone apps are done with distributed individuals and firms coming from many different backgrounds including software developers, network operators, publishers, broadcasting firms, all sorts of manufacturers, educational institutions, non-for-profit organizations, artists and musicians, and so on. These individuals' collective design actions together build a wholly new set of services in re-designing the idea of a "mobile phone". Conventional organizing logic that supported large vertically integrated enterprises are not likely lead to innovations like iPhone. Instead, Apple revisited a taken-for-granted product and its components as well as the larger systems in which they were embedded, in order to explore opportunities afforded by digital information and communication technologies, instigating “wakes of innovations” (Boland et al. 2007). The story of iPhone shows how digitally inspired redesign of the familiar can trigger a complex process of knowledge transfers and discoveries that ultimately result in a cascade of innovations.

From Apple’s iPhone, to Amazon’s Kindle, and to Google TV, digital technology is rapidly and pervasively re-making many of the products that we have taken for granted for decades, if not centuries, at a dazzling pace. Digital technology makes it possible to “reinvent the wheel”, and to radically reconfigure the design and production of nearly all products and services. Embedding of digital technology in physical infrastructure like roads, bridges, power grid, rail systems, and buildings change how individuals relate to others and their surrounding environments (McCullough 2004; Mitchell 2003; Yoo 2010). Advances in digital technology have de-coupled the media and contents in the music and movie industries, creating opportunities for products like Napster or Apple’s iPod. Digitalization has also brought together previously unrelated markets – like the new service created by connecting Nike’s running shoes and Apple’s iPod. Just as steam engines and railroad radically changed how organizations innovate in early19th century, shifting production from craftsmanship to mass scale (Chandler 1977), digital technology has now become a main engine for market innovation. Along with other forces that challenge many of the conventional assumptions of current organization theories (Andriani and McKelvey 2009; Powell 2001; Walsh et al. 2006), we believe that digitalization of products will accelerate the fundamental changes that we are seeing in contemporary organizations.

Organization and information system research have increased our understanding of the impacts of digital technologies in organizations over the last two decades (Fulk and

DeSanctis 1995; Zammuto et al. 2007). Most of these studies, however, focused on the uses of information technology within the confines of inter- or intra-organizational processes and structures – e.g. teams, knowledge sharing and supply chains. Also, recently, marketing literature has focused on the use of information technology to create e-commerce and new way to build customer relationship (Ba and Pavlou 2002; Kozinets et al. 2010; Winer 2001). Now, we are witnessing the emergence of a new breed of digitally fostered innovations that involve the pervasive penetration of digital technology in all spheres of life (Yoo 2010). The emergence of new products that interact with global digital infrastructures such as the Internet and global wireless network challenges us to re-think the scope of our theories and empirical analyses. Digitalized products continues to evolve through recombination with different digital artifacts and data in a similar way that a strain of virus mutates (Arthur 2009), often bringing in fundamental changes in the product is perceived and used in the market. As such, one must take the very nature of digital technology seriously into consideration when studying the nature of digital innovations. Marketing scholars have a unique opportunity to extend their received theories by analyzing the broader and more pervasive impacts of information technologies on patterns and practices of innovating. In this essay, we address one piece of this challenge and consider how the "new materiality" afforded by digital technologies affects organizational capabilities to innovate while exploring market innovation opportunities.

Our aim is to address the broad question: what are the broad implications of ongoing and pervasive digitalization on innovations? Specifically, we ask what are the impacts of ongoing digitalization of products on the way that organizations configure and participate in innovation processes. Drawing on product architecture literature (Baldwin and Clark 2000; Clark 1985; Ulrich 1995), we explore how digitalization change the product architecture of previously non-digital product. In particular, we propose a *layered product architecture* as a natural consequence of digitalization of a product. We suggest digital innovation as a series of generative recombinations of digitalized components connected through a set of organic design rules. Such a view challenges the conventional view of a market being given and stable that can be *discovered*. Instead, with an unceasing wave of digitalization, a market is something to be created and destroyed only with temporary period with a fixed and stable condition. Finally, drawing on actor network theory (Boland et al. 2007; Latour 2005), we further explore how the new product architecture of digitalized products influence the organizing logic of innovation. We conceptualize the processes of innovation as sets of heterogeneous activities that involve flows of knowledge, representations and materials among multiple actors who use different tools. In this view, no innovation is borne from a single idea of a single innovator, which will gradually diffuse to a market. In contrast, we see innovations emerging from the ebb and flow of knowledge transfers and "trades" among heterogeneous and distributed actors and their tools in a complex socio-technical network (Boland et al. 2007). We dub such networks *doubly distributed networks.* In a doubly distributed network, there are a series of fragile and uncertain negotiations among conflicting ideas, representations and material artifacts that are dynamically assembled by multiple, diverse actors. Further, we explore the unique challenges posed by the digitization of complex products in doubly distributed networks. The story of iPhone discussed above is one example of such networks. We argue that future innovation networks will become increasingly heterogeneous, volatile and distributed both socially and technically and that doubly distributed forms will become more commonplace.

Digital Innovation

Following Schumpeter (1934) who defined innovation is "a new combination of production factors", we refer to *digital innovation* as (1) a new combination of production factors that introduce discontinuity to product, technology, organizing principle, market, or set of behaviors *and* (2) made possible by digital technologies. This definition emphasize discontinuity, by noting that only those combinations that have never been tried before can be classified as innovation. A necessary but insufficient condition for such innovation is *digitization*, i.e., the encoding of analog information into digital formats.

The rapid miniaturization of computer and communication hardware, combined with their ever increasing processing power, storage capacity, communication bandwidth and more effective power management have made it possible to increasingly and pervasively digitize previously non-digital artifacts (Kurzweil 2006). According to Hagel et al (2009), a microprocessor that cost over $222 in 1992 cost only $0.27 in 2008. Similarly, one gigabyte of storage that cost $569 in 1992 cost only $0.13 in 2008; and the cost of communication with the bandwidth of 1 gigabits per second dropped 10 times from $1,197 to $130 from 1999 to 2008. These smaller, yet increasingly potent digital components are becoming a part of previously non-digital products such as book, cars, furniture and buildings, radically altering the price-performance ration and opening up new innovation opportunities for both incumbents and new entrants alike.

Digitization adds new capabilities to non-digital artifacts by making them programmable, addressable, sensible, communicable, memorable, traceable, and associable (Yoo 2010). When digitization leads to a reconfiguration of underlying socio-technical relationship between produces and users, we call it *digitalization*. And, when digitalization reshapes the underlying value propositions, we refer to it digital innovation. An example of digitization is when the telecom industry installed digital switching in the 1970’s, which did not change the socio-technical context of the production and consumption of the product. To the contrary, today's disruptive transformations in telecommunication, mobile media, broadcasting, and publications caused by iPhone and Google's Android are examples of digitalization. In these examples, broader socio-technical reordering of organizing logics are taking place among heterogeneous firms.

Despite these transformative potentials of digital innovation, management scholars paid little attention to it. A few studies in organization science have explored digital innovation in publishing (Tripsas 1997), photography (Benner 2010; Tripsas 2009), and telecommunications (Benner 2010). These studies, however, treat digital technology as an example of exogenous disruptive technology (Anderson and Tushman 1990). As a result, they fail to fully recognize the unique and distinct characteristics of digital innovation and their formative and transformative effects on the new industrial logics. While digital technology shares many common characteristics with its non-digital counterparts, we argue in this paper that it has distinctive characteristics that make digital innovation in fundamental ways different.

IS researchers, on the other hand, started paying an increasing attention to the nature of the IT artifact (Orlikowski and Scott 2008; Orlikowski and Iacono 2001). However, they have remained silent of the nature and the impact of digitalization of products, as most of them focus on the role of IT as a supporting tool to implement a firm's strategy and improve its processes (Fichman 2004; Sambamurthy et al. 2003; Sambamurthy and Zmud 2000). Therefore, despite of the growing presence of digitalized products and their transformative impacts, there is no systematic research on the nature and the consequences of digital innovation. In this study, we attempt to close this gap in the literature by first exploring the unique characteristics of digital technology.

What is unique about digital technology?

In order to understand what makes these new forms of innovation possible, we need to discern essential characteristics of digitalization that make digital innovation process a generative (Zittrain 2006) and unbounded (Harty 2005) without falling prey to simplistic versions of technology determinism. Our point of departure is the observation that ongoing digitization in our physical world adds new material properties to previously non-digital, industrial age products and processes (Arthur 2009; Yoo 2010). Among others, in this paper, we focus on three specific characteristics of digital technology that play pivotal roles in facilitating digital innovations.

First, based on the Von Neumann's Architecture, modern digital computers use a stored-program concept, where both data and instructions (program) are temporarily stored in the memory, instead of hardwired into the processing unit (Langlois 2007). Therefore, modern digital computers shift between handling bits (a contraction of binary digits) as data and as the instructions for manipulating that data. This basic architecture provides an inherent flexibility to perform many different functions (like clocks, calculators, word processors, or web browsers) all with the same physical device. Digitization of previously non-digital artifacts, therefore, means embedding microprocessors and software that follows Von Neumann Architecture into the physical artifacts. This digitization leads to the separation between the semiotic functional logic of a program and the physical hardware that performs it. Unlike other non-digital devices where the physical hardware and the function are tightly coupled to meet specific and fixed needs, digitized artifacts can be flexibly programmed and re-programmed.

Second, unlike an analog signal, which maps changes in one continuously varying quantity on changes in another continuously changing quantity, a digital signal represents analog signals into numbers and ultimately bits (Tilson et al. 2010). Since analog signals are stored using physical characterization of storage device (such as the pattern of a groove of an LP or magnetic variations on a tape) and transmitted through cables and air space, there is an inseparable tight coupling between analog data and analog devices, such as VHS tapes, vinyl records, books, and newspapers. However, through digitization of analog data, any type of content (audio, video, text and image) now can be stored and transmitted using the media. Therefore, the digitization of data leads to another form of separation between the contents and the media.

Third, digital innovation requires digital technology. This self-reflexive nature of digital innovation means that ubiquitous access to digital tools, such as inexpensive PCs as a design platform and the Internet as a distribution network, radically lowered the entry barrier for small firms and independent entrepreneurs to enter into the competition. Ubiquitous access of digital tools further accelerates the diffusion of digital innovations by creating network effects. As the price-performance and performance-size ratios of digital tools continue to improve over time, connecting them in a global data network (the Internet) creates a powerful feedback condition that irrevocably accelerated the creation and diffusion of digital innovations. By the late 1990's, PCs and the Internet became accessible to unprecedented number of users, who could experiment with different forms of digital innovations. Unlike other physical resources that require extensive capital to acquire, users could more readily participate innovation activities. This in turn opened a floodgate of new types and forms of innovation (Tuomi 2002; von Hippel 2005).

These three design characteristics – *programmable digital computing* *architecture, homogenization of digital data*, and *self-reflexive nature of digital technologies* – form a powerful set of reciprocal and mutually re-enforcing forces that have created a new product architecture and underlying unique socio-technical dynamics of digital innovations.

Technology Change and Product Architectures

Product architecture refers to "the scheme by which the function of a product is allocated to ... components" (Ulrich 1995, p. 419). A product architecture involves functional elements, physical components and the interfaces between physical modules (Baldwin and Clark 2000; Ulrich 1995). As technology develops, organizations mobilize different product architectures, which in turn influence the organizing logic of innovation space.

Integral Product Architecture

Much of the last century was dominated by large vertically integrated firms that produced physical products (Chandler 1962; Chandler 1977). These early physical products were often based on an integral product architecture. An integral product architecture includes a complex and overlapping relationship between functional elements and physical components (Ulrich 1995). The interfaces between modules are often not standardized, thus creating tight coupling among modules. Since the early days of industrial revolution and through much of the post-World War II period, the integral product architecture was the dominant choice by vertically integrated manufacturing firms. The inherent complexity of the interrelationship among modules in an integral architecture makes it prohibitively expensive to outsource the design and production of parts of the product (Williamson 1985). Enabled by the development of railroad and communication technology (Yates 1989), firms during this period produced products in large volume for mass markets (Langlois 2003), which required substantial capital investments. The overwhelming amount of capital investments required, in turn, acted as entrance barrier. Furthermore, in order to take a full advantage of increased production capacity from these capital-intensive resources, firms sought to minimize uncertainties in upstream and downstream activities through forward and backward vertical integrations (Coase 1937; Williamson 1985). Over time, this led to the emergence of large vertically integrated enterprises that increasingly internalized specialized production, procurement and distribution technologies for their core products (Teece 1993). As a result, the market boundary was clearly demarcated along with the products that were design to meet specific needs. The logic of mass market dominated this era.

Modular Product Architecture

During the last quarter of the past century, however, a new form of product architecture based on modularity emerged. Rooted in Herbert Simon's design theory (Simon 1996), modularity is a general strategy to deal with complexity through decomposition of a whole system into modules. A modular architecture involves specialized modules that are loosely coupled through a set of pre-specified standardized interfaces, called *design rules* (Baldwin and Clark 2000). In an ideal modular architecture, each module performs only one function.

In the literature, design rules for the modular architecture are mainly concerned hardware systems. As such, design rules for these products assume fixed and stable product and market boundary. The performance objectives of a product is assumed to be known a priori. The notion of modular product architecture therefor is tightly related to the product life cycle (Abernathy and Utterback 1978; Tushman and Anderson 1986). Firms compete during the nascent stage of the product lifecycle in order to establish its own product platform and design rule as the dominant design in the market (Anderson and Tushman 1990). The locus of innovation shifts, however, to peripheral features and improvements of performance once a dominant design is established (Anderson and Tushman 1990).

With a modular architecture, firms who are able to establish and control emerge as platform leaders (Gawer and Cusumano 2008). Once the design rules are specified, each module can be independently designed and manufactured as long as the interfaces adhere to the standard specified by the design rules (Baldwin and Clark 1997). This allows the organizations to focus only one thing that they are specialized and pursue innovation within that specific component boundary. Furthermore, by leveraging these standardized components, firms that control design rules can pursue innovations through variations. Unlike integral product architecture that is closely associated with vertically integrated firms, the modular product architecture led to the emergence of clusters of specialized component manufacturers (Baldwin and Clark 2000).

At the same time, organizations started using advanced information technology in order to outsource the design and manufacturing of components (Malone et al. 1987). The development of information technology radically reduced the communication cost among firms, which helps platform leaders to led others firms to design and produce components, as long as they follow the design rules (Langlois 2003; Sanchez and Mahoney 1996). Throughout 1990's, for example, companies like Dell and Cisco experienced enjoyed competitive advantage by mobilizing a network of distributed firms by leveraging modular product architectures. These networked organizations represented a departure from earlier vertically integrated companies.

Furthermore, the logic mass customization became the dominant market logic with the emergence of modular product architecture.

Digital Innovation and the Layered Product Architecture

In this paper, we argue that on-going and pervasive digitalization has enabled a new form of product architecture, which we refer to as a layered product architecture. The layered architecture is a consequence of two separations caused by digitalization: (a) the one between physical hardware and semiotic logic; and, (b) the other one between contents and network. Based on these two separations, a layered product architecture contains four separate layers: devices, networks, services, and contents (Benkler 2006; Farrell and Weiser 2003). These four layers are organized into loosely coupled many to many relationships through a set of interfaces that act as *generative design rules*.

The devices layer deals with the physical hardware and is further divided into a physical machinery layer (TV, PC, mobile phone, car, etc) and logical capability layer (operating systems). The logical capability layer provides control and maintenance services of the hardware and connects the physical machinery to other layers. In the case of smart phone, iPhone and Android with their respective operating systems constitute the device layer. The network layer performs the function of carrying the contents to the users. Like the device layer, it is similarly divided into a physical transport layer (including cables, radio spectrum, transmitters, etc) and a logical transmission layer (including network standards such as TCP/IP or P2P). Most smart phones has multiple components in the network layer including cellular network, wireless LAN, and bluetooth. The service layer involves deals with application functionality that directly interact with users or other stakeholders as they create, manipulate, store and consume content. Through service layer, users can listen to music, send and receive e-mails, read books, calculate financial ratios, use an ERP system, or receive navigation information. Going back to smart phone example, all the apps that are found on smart phones belong to the service layer. Finally, the content layer includes the actual data such as texts, sounds, images, and videos. The content layer also contains meta-data and directory information such as data about origin, ownership, copyright, encoding methods, content tags, and geo-time stamps. Table 1 summarizes these four layers.

<table>
<tr><th colspan="2">layers</th><th>descriptions and examples</th></tr>
<tr><td colspan="2">content layer</td><td>This layer constitutes various digitalized contents such as music, text, photos, maps, etc. This layer includes meta-data such copyright, ownership, encoding methods, contents tags and geo-time stamps. It can contain both user-created as well as supplier-created contents.</td></tr>
<tr><td colspan="2">service layer</td><td>This layer constitutes various application capabilities that allows users to create, store, manipulate, transmit and consume various forms of digital contents. Each components in this layer perform a unique set of functionalities.</td></tr>
<tr><td rowspan="2">network layer</td><td>logical transmission</td><td>This layer includes a broad set of protocols and methods that define to ensure the integrity of data transmission using various physical medium as defined in the physical transport layer.</td></tr>
<tr><td>physical transport</td><td>This layer defines physical material properties of the media that connects the device to other devices or the network. This can include both wired and wireless media.</td></tr>
<tr><td rowspan="2">device layer</td><td>operating systems</td><td>This layer defines how different physical components will be controlled and maintained. It defines how users interact the physical machinery by providing basic resources to manipulate different physical resources. An important part of operating systems includes application programing interface (API) that define how components in other layers interact with the physical layer. An operating system can be tightly coupled to the physical machinery as in the case of embedded software, or can be loosely coupled in the case of personal computers that can have more than one operating system for a single physical machine.</td></tr>
<tr><td>physical machinery</td><td>This layer defines the physical material properties of the hardware device. It can be partially open by allowing users to connect external periphery devices.</td></tr>
</table>

Table 1. A Layered Architecture of Digitalized Product

Connecting these four layers are a set of interfaces, such as APIs (application programming interfaces), that act as glue that hold heterogeneous elements together. Unlike interfaces that connect pre-specified set of modules together, these generative interfaces in a layered architecture are essentially open-ended. For example, Google Map (content layer) provides a number of interfaces in the form of APIs that can be connected to any hardware, service or network layer modules that want to incorporate Google Map contents.

Although a layered architecture share some similarities with a modular architecture (e.g., both have loose coupling between modules or layers), they differ on a number of important aspects. First, the nature of the variety is different. A modular architecture primarily focus on the hierarchical decomposition of *physical* subsystems and components. Therefore, the product architecture of PC, for example, describes how different physical components that perform specific functions are assembled (Baldwin and Clark 2000). As a result, modules and sub-modules belong to the same class of technology. Therefore, when modular products consist of different modules have *differences in degree*. On the other hand, in a layered architecture, layers represent fundamentally different *heterogeneous* classes of technology that are enabled by software. Physical device, network, application programs, and various contents are inherently different from each other, connected through digital interface. Therefore, layered products with components from different layers have *differences in kind*. While the goal with a layered architecture is not a decomposition of a complex system, the goal of a layered product is to generate new kinds of products through an assemblage of heterogeneous elements leveraging digital convergence (Lyytinen and Yoo 2002).

Second, the nature of the hierarchy is different. In a modular architecture, the relationship between module and sub-modules is the one of whole-part. Therefore, an aggregation of lower level sub-modules constitutes the focal module. Similarly, an aggregation of modules will make up the whole system. To the contrary, components in a layered architecture follows a generalization-specialization relationship. Therefore, each module within a layer is a special case of the layer, rather than its part. For example, each of 200,000 apps for iPhone represents a special case of the service layer. As such, an aggregation of all components in a layer does not make up the whole, as it is always possible to add yet another component in the layer.

Third, the direction of design knowledge flow is different. In a modular product architecture, the meaning and purpose of a given project is known and fixed *a priori* (Baldwin and Clark 2000). The knowledge of the product is used to derive the specification of design rules, which establish the components and interfaces among them. Therefore, in a modular architecture, each module is assumed to be fixed and has a pre-specified functionality (Ulrich 1995). To the contrary, in a layered architecture, a product concept is not given a priori. Returning to the example of Google Map's APIs, Google cannot know fully what are the nature of products that will incorporate its APIs. They can be other web-services, mobile phones, or cars. Therefore, product ideas are derived from the knowledge of generative design rules that specify the interfaces across layers.

Finally, the boundary of products is different. In a modular architecture, the nature of the product is known, thus establishing stable and unknown boundary of the product system. In a layered product, however, with the generative nature of the design rules and the generalization-specialization relationship, the boundary of the product system is essentially *unknowable*. Therefore, the innovation of a layered product can be indeterminate and *unbounded* (Harty 2005). For example, by using different apps, the same smartphone hardware composed of a set of physical modules can perform entirely different set of functions for different needs at the product level. Here, the flexibility of a smartphone does not come from the flexibility of physical components; rather, it comes from the ability of the physical layer to accommodate different combinations of diverse apps at the service and contents layers that are substitutable with one another (Farrell and Weiser 2003)[1].

The emergence of a layered product architecture has pronounced strategic and structural implications for firms pursuing innovations using digital technology. Firms like Google, Apple and Amazon epitomize the firms that pursue innovations based on a layered architecture. Innovations that emerge from dynamic and competitive moves taken by these companies follow non-linear, messy and dynamic patterns (Garud et al. 2002; Tuomi 2002). In order to maximize the generativity that comes from the loose coupling across layers, firms must identify, mobilize and integrate diverse pools of knowledge (Boland et al. 2007). Since no organizations have such heterogeneous pools of resources, firms are increasingly look for the required knowledge and skills outside their organizational boundaries (Chesbrough et al. 2006). Next, we explore the impact of a layered product architecture on the organizing logic of innovation.

Product Architectures and Organizing Logics of Innovation

We define *organizing logic of innovation* as the managerial rationale for designing and mobilizing specific socio-technical resources to pursue an innovation opportunities. Innovation needs to be carried out by multiple individuals because of the physical and cognitive limitations (March and Simon 1993). These individuals mobilize a variety of tools to support the innovation process (Boland et al. 2007; Carlile 2002; Ewenstein and Whyte 2009; Henderson 1991). Using these tools, individuals need to share ideas, information, representations, and materials with

[1] It is important to note that within a layered architecture of a digitalized product, one may still finds either integral or modular architectures within each layer. For example, in most cases, physical devices themselves will be designed and manufactured strictly in a modular fashion. Also, each individual apps in a service layer will be designed following a modular architecture. However, the overall product architecture of a digitalized product will follow a layered one.

others who are working on the innovation. Together, they form a socio-technical assemblage that consist of organizational actors and a myriad of heterogeneous tools. An organizing logic of innovation thus consists of individuals and tools and different forms of relationships among them. The organizing logic of innovation then represents a structure of activities that are necessary for an innovation project with particular attention to the logical dependencies as defined by knowledge flows among individuals and tools (Pentland and Feldman 2007).

Furthermore, innovation is simultaneously a cognitive and a social process. Innovation is cognitive to the extent that it involves the creation of new knowledge that is captured and translated through a series of representations before it can be materialized in new products and services (Altshuller 1984; Simon 1996). Innovation is social to the extent that obtaining, transforming and sharing knowledge is a negotiation and sense-making process, through which an actor's identity and relationships to others are negotiated and re-defined (Boland et al. 2007; Carlile 2002). As a new idea moves forward to become a reality in the form of new services and products, a growing number of individuals from diverse communities must get involved with different tools that they use in their own design practices (Berente et al. 2008). Therefore, an organizing logic of innovation must include both social and cognitive elements at the same time.

We argue that the changes in the different product architecture requires different organizing logics of innovation. Below, we will first discuss the organizing logics closely associated with the existing product architectures (integral and modular). Then, we will discuss doubly distributed innovation network as the basic organizing logic for a layered product architecture. We focus on control and knowledge heterogeneity as two key factors that affect the organizing logic of innovation.

Integral Architecture and Singular Hierarchy

Firms that produce products with an integral product architectures are likely to mobilize an organizing logic that we refer to as a *singular hierarchy*. In a singular hierarchy, the control for innovation activities is largely centralized within the boundary of hierarchical organizational structure of a vertically integrated firm and the knowledge that is mobilized is homogeneous. Therefore, the participants on a singular hierarchy are most likely the individuals and units of a single vertically integrated firms. Since these individuals share the same knowledge resources, the tools that they use in the innovation process are also likely homogeneous pool of tools. The goal of innovation for such vertical integrated firms that produce products with an integral architecture is to capitalize the economy of scale and scope (Teece 1993). As such, the innovation focus of these firms tend to exploit the existing capabilities and knowledge, and process innovation for cost cutting, rather than pursuing variance-enhancing exploration activities (Benner and Tushman 2002; Levinthal and March 1993; March 1991). Therefore, these firms are likely to pursue process innovation efforts such as CMM (capability maturity model) and TQM or ISO9000 that are driven by a single organizing vision and supported by a homogeneous set of tools are good examples.

To support innovation activities in vertically integrated firms, digital technology play two important roles. First, digital technology is used to automate the manual process in the manufacturing process in order to improve the efficiency of the physical resources (Zuboff 1988). Second, digital technology was used to enhance centralized control through various forms of management information systems and decision support systems (Gorry and Scott Morton 1971).

Modular architecture and the Distributed Network

Firms that produce products with a modular architecture are likely to mobilize an organizing logic that we refer to as *distributed network.* In a distributed network, the control for each modules are delegated to partner firms, while the control on the overall architecture and standardized interfaces are retained by the focal firm. The partner firms are often outside firms who are specialized for particular modules and sub-components. However, since these modules and sub-components belong to a relatively stable boundary of the product architecture (Henderson and Clark 1990), the knowledge resources are homogeneous. Since the participants in a distributed innovation network are relatively homogeneous from a single discipline, they often have access to a common set of tools, share a common vocabulary and have complementary knowledge.

With the modular architecture, these firms take advantage of local innovations (Langlois and Robertson 1992) pursued by individual firms. Here, individual firms decision for each module and sub-components are bound by standardized interfaces controlled by the focal firm. Participating firms work on relatively homogeneous technological platforms, and they conform to strong forms of professional standards that define structure, form and quality of the outcomes. The radical reduction of communication cost afforded by digital infrastructures enables an increasingly distributed division of labor and sharing of work outcomes in large scale networks (Chesbrough et al. 2006). As a result, innovations originating from distributed networks are likely to be economically efficient due to the impact of many concerned participants, when compared to a singular hierarchy. Firms like Dell and Cisco built their competitive advantage by mobilizing distributed network. In their cases, the participation to the distributed network was contractually bounded. The primary goal of the innovation activity in the distributed network is to effectively coordinate distributed activities, whether these distributed activities need to be connected through global supply chain like in the case of Cisco and Dell.

A key technological infrastructure for distributed network for firms producing modular products is a “net-enabled” digital enterprise architecture (Sambamurthy and Zmud 2000; Straub and Watson 2001; Wheeler 2003) and knowledge management tools to effectively share knowledge across the distributed network (Alavi and Leidner 2001; Nonaka and Takeuchi 1995). Also, the organizing logic of distributed network required organizational innovations such as heavy weight team (Clark and Wheelwright 1994) and project-based organizing (Cusumano and Nobeoka 1998; Galbraith 2002; Yoo et al. 2006).

Layered Product Architecture and the Doubly Distributed Innovation Network

In a Doubly Distributed innovation networks, the structure and dynamics is the most complex. Control of the process, structure and outcomes is distributed throughout the network and at the same time, the knowledge resources are highly heterogeneous. The types of various knowledge resources needed for innovation are not known a priori and knowledge coordination among different firms are highly ambiguous and emergent. Many teams that work on radical products or services that transcend traditional industry boundaries increasingly operate in doubly distributed innovation networks. For example, in mobile services , a myriad of previously unconnected actors (phone operators, software companies, content providers, hardware device manufacturers, advertising companies, etc) must weave together their own perspectives, business models and technological frames to establish new services and build up institutional service arrangements (Tilson et al. 2006; Yoo et al. 2005). Although telephone companies that have traditionally held tight architectural control over the phone systems might try to maintain their dominant position, their efforts are increasingly challenged by powerful actors like Nokia, Apple and Google, who are coming from other layers. Similarly, architecture, engineering and construction (AEC) industry forms doubly distributed network for radical construction projects with multiple autonomous firms from different trades who bring different knowledge resources and unique tools. Each firm follows its own unique innovation trajectory while participating in a small and dedicated community of practice. Their trajectories and their knowledge needs to be interwoven during a radical innovation so that each community can influence the other's cognitive and social translations.

The key challenge here is how to mobilize a range of potential innovators who have different and conflicting interests and widely heterogeneous knowledge bases, where no one has a complete control over the final product architecture. In addition, the heterogeneous knowledge resources available are invested and contested making knowledge leakages unlikely (Carlile 2002). A specific form of collective action is required in cases like this to mobilize actors and to overcome traps like the "prisoner's dilemma" (Hargrave and Van De Ven 2006). In a doubly distributed innovation network, knowledge coordination is highly contested, and problematic. First, the network is composed of heterogeneous and evolving technology tools and capabilities, without sharing a common cognitive schema. In addition, as new actors join, the richness and the social and technological heterogeneity of the network will expand cumulatively along the "rolling edge" of their ability to control (Berente et al. 2007). The challenges associated with knowledge coordination doubly distributed innovation networks are even more pronounced, because it involve issues of power, control and incentives.

In order to overcome these challenges, generative design rules for layered architecture must be based on dialogical relationship that allows the existence of multiple and often competing logics. The design rules must act as "boundary objects", or translations devices, in order to support discussions of the new rules of engagement, build trust and sharer visions (Star and Ruhleder 1996). In addition, these connections must remain dialogical even while the network continues to grow, and adds new actors and tools. Thus, the infrastructure is critical and in need of tight coordination and central control at the same time that it needs to be flexible and open- a requirement which is difficult to meet by information infrastructures of today.

Discussion

On June 24, 2008, Nokia, the world's largest manufacturer of mobile phones, announced that it would buy all the rights to a mobile phone operating system, Symbian, from its other owners (including Motorola, Ericsson-Sony, Panasonic and others). Symbian currently powers about 60% of the world's smart phone market. At the same time, Nokia declared that it would open source the Symbian software under the Eclipse license (http://www.eclipse.org). The trade was valued at over $400 million. Given Nokia's earlier investments in Symbian, the decision to make Symbian open source software would amount to giving away intellectual property investments close to $700-800 million. Ten years ago, such a move would have been characterized as going against all business sense. But Nokia's stock rose nearly 3% after the announcement, and industry analysts hailed Nokia's move as a "bold" one that would assure, to quote one of the analysts, "transparency, flexibility, and community" for mobile service innovation.

Nokia's bold move to open source Symbian is symptomatic of the radical changes we are seeing in the types of innovation driven by digitalization. First, digitalization requires networks where heterogeneous knowledge flows freely and where new innovation ecologies mushroom around novel products and services. Second, pervasive use of digital technologies in products and services, along with the use digital tools in the development of those products, push organizations to pursue increasingly radical innovations and generate unforeseen products and services. Rapid digital convergence, for example, has already transformed mobile phones from a single-purpose communication device to a multi-purpose computing platform. As the world around us becomes more digitized, there will be even more opportunities to transform familiar mobile phones into something alien and novel. In order to pursue such opportunities, organizations like Nokia are re-thinking and re-shaping the boundary conditions that define their innovation networks. In this case, Nokia's business acumen led them to give away their key platform in order to grow and connect it with unforeseen communities beyond the boundary of the traditional telecommunication industry.

The emergence of layered product architecture with its generative and unbounded nature requires scholars to approach to innovation with the following theoretical and methodological emphases. Traditional approach to innovation research is based on a set of assumptions that emphasize the stable and fixed nature of product and market boundary, punctuated equilibrium of the market evolution, and the importance of dominant product design. Digital innovations will likely to challenge the following key issues.

Multiple competing logics. In order to study the dynamic and unbounded nature of digital innovation with layered architecture, scholars who study innovation must study the market and product as an adaptive system that are based on complex and on-going interactions among loosely coupled independent modules from different layers. Instead of pursuing a single dominant logic that defines dominant product design, scholars conceptualize product systems tha are pregnant with multiple and competing logics. Instead of studying the rise and fall of a dominant design, scholars should explore how multiple logics are co-exist forming loosely coupled layers.

Product system as an open system. Unbounded innovation cannot be sustained if the product system has a fixed boundary. The march of unbounded innovation will stop, if the product system reaches a hemostasis equilibrium as a closed system. Instead, a product system designed for unbounded innovation must form a dissipative structures, a self-organizing form that are induced to contribute new energy into the system (Anderson 1999).

Therefore, scholars must study both social and technical conditions under which a digitalized product system with a layered architecture gets continuous injection of new knowledge resources (Berente et al. 2007).

Evolution of Products and Markets. The digitalized product with a layered architecture forms a unknowable landscape that are formed by continuous interactions among participating firms. As firms continue with its own journey of discovery with unbounded innovation with digital technology (Harty 2005), they continue to discover new possible connections with other firms. Therefore, the market condition of digitalized products can be best described as a competitive landscape with continuing changing terrains. Firms are not able to form a global or long-term perspective. Instead, the firms pursue local adaptations to the ever changing competitive conditions (Brown and Eisenhardt 1997).

The management literature is dominated by the idea that product evolves through a life cycle that follows punctuated equilibrium model (Anderson and Tushman 1990; Tushman and Anderson 1986). The key idea there is the fermenting stage of product life cycle that is chracaterized by high market and technical uncertainty, multiple compeiting product and business models, and frequent experiemtations is followed by an emergence of dominant design that leads to a sustained period of rapid expansion of the market, continuing advancements of product features and performance through incremental innovations. This model of product life cycle needs to be carefully examined with the emergence of digital innovations. One might argue that the digital innovation is a simply an early stage of product life cycle, which will eventually stablized with a dominant design. We believe that given the inherent logic of digital technology as we reviewed in this essay, even if such a dominant product design emerge for a particular product, the life span of such dominant designs will be likely to be extrememly short as new and expanded meaning of the same product is likely to emerge.

For example, digitalization of camera brought new features such as optical zoom, LCD panel, megapixel resolution and external memory storage. According to a study by Benner and Tripsas (2010), these features were adopted by more than 90% of the digital cameras by 2000, making them appear to be a dominant design of digital camera. However, another study of the history digital camera (Yoo et al. 2010) shows that the meaning of digital camera is ever expanding by integrating other digital technologies such as mobile phone, GPS, internet access, and web-services. In fact, according to the Flickr, which is one of the most popular web-sites for photosharing, the most popular 'camera' is Apple's iPhone 3G. Also, they note that since 2004, Nokia has become the world largest camera manufacturer based on the number camera lens that they sell. Therefore, even if a 'dominant' design of digital camera might have emerged around year 2000, the meaning of the camera has continued to evolve and expand, making the fixed meaning of digital camera and its dominant design less important.

Recombination and Emergence of Digital Innovation. Schumpeter noted that the most essential aspect of any innovation is recombination of existing capabilities. Modern innovation scholars also have noted the importance of recombination for innovation (Kogut and Zander 1992). Such recombinations are done by individual firms and sometimes by consumers. The outcome of such local experiments then become the source of further experimentations, sometimes influencing the design of the generative design rules themselves. It is precisely this process of recombination of multiple modules across loosely-coupled heterogeneous layers that form the basis of unbounded innovation of digitalized product as a system. Of course, the focal firm who designs the original platform (like Google's Map or Andriod, or Apple's iPhone) can influence the trajectory of this evolutionary path, by deliberatly injecting new elements and changing the nature of the generative interfaces. Yet, they must share their design agencies with other firms who participate in the continuing construction of their products in their doubly distributed innovation network.

Epistemology and Ontology of Innovation. The very notion of innovation networks suggests that the organization of the network – who or what is in the network, and how does he, she or it interrelate? – has a lot to do with the content of the innovation network, or what the actors think they are innovating about. That is, the social space of an innovation network shapes and is shaped by the technological space and its movement. In short, the ontology of the innovation cannot be separated from its epistemology: what actors innovate about is a mirror of who and what is enrolled in the network and what she or it "knows" and can do. Thus, the uncertainty, ambiguity, diversity and dynamics of innovation networks should be a main focus of innovation studies. The idea of multiple forms for innovation networks challenges current ways of measuring innovation that employ a single construct. If innovation is viewed as distributed and emergent, it is not clear where, when and how one can measure it and its progression. The concept becomes equally challenging when one compares different innovation networks, as what is being innovated changes radically across the networks. For example, the future of mobile phones emerging from the innovation network around Nokia with its vibrant and open-ended communities will be different from that of a competing innovation network that resembles more traditional forms from the telecommunication industry and its tight centralized controls.

Conclusion

Rich forms of digital technology have become an essential element of everyday life (Yoo 2010), making it critical to examine how the increased digitization affects the way organizations innovate. Our paper takes some steps in this direction by proposing a framework of digital innovation and exploring some material characteristics of digitalized products and its consequences. We noted the emergence of a new product architecture, layered product architecture, that are based on a set of generative design rules that connect loosely coupled heterogeneous layers. We further propose that the emergence of layered architecture of digialized products will lead to the doubly distributed innovation networks as the primary organizing logic of innovations, replacing earlier forms of singular hierarchy or distributed network. This is a journey that is likely to challenge familiar ideas and beliefs about products, structures, relationships and identity. Innovators need to challenge the taken-for-granted by making the familiar alien. Future theoretical and empirical work needs to expand, revise and validate the proposed model with detailed and rigorous analyses of the dynamics and behaviors of innovation networks, and of the various formations that condition the emergence of radical services and products in all walks of life.

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