

Unbounded Innovation with Digitalization: A Case of Digital Camera¹

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Abstract

A four-layer model of generic architectural innovation is proposed that explain loose couplings between different layers of digital innovations. We develop the model based on key design features of digital technology – *homogenization of digital data*, *universal programmable digital computer*, and the *self-referential nature of digital technology*. We show how these features and the new layer architecture affects innovation outcomes (convergence, and digital materiality) and processes (generativity, heterogeneity, locus of innovation, and pace). We illustrate the emergence and evolution of these features by investigating the history of digital camera and its transformation from a single purpose analog product into a complex product laden with multiple meanings consisting of web of loosely coupled capabilities associated with digital imaging. The unbounded, chaotic and dynamic nature of digital innovation was discussed for its implications for future research and practice.

Introduction

On November 2009, Willard Boyle and George E. Smith received Nobel Prize in Physics for their invention of charge-coupled device (CCD), a key component of digital cameras. When they invented CCD in 1969 at AT&T Bell Labs, little did they know that their invention would affect the lives of billions of people around the world three decades later. Conceived merely as a technical exercise, the original digital camera was first built by Steven Sasson at Eastman Kodak in December 1975. It weighed 8 pounds with its toaster-size body, and took 23 seconds to capture an image of 0.01 megapixels on a cassette tape. It required a separate TV to see the image, which took another 23 seconds to retrieve. 30 years later, however, digital camera has become ubiquitous. By the end of 2003, the sales of digital camera outpaced that of film-based camera. By 2009, digital camera is out-sold 35mm film-based camera by 4:1 ratio. Digital camera now is integrated with other technologies like mobile phones, GPS, wireless network, and the web going beyond the original concept of just being a replacement of analog camera. Now, most pictures taken by digital cameras are never printed on paper, but instead, uploaded on photo-sharing sites like Flickr or Picasa, millions of blogs, and social networking sites such as Facebook.

The history of digital camera is not merely a replacement of technology to capture and store the impacts of light from chemical-based film to silicon-based flash memory with digital light sensors. Instead, it shows that digital innovation is a broad horizontal “domain” of technologies that have strong generative and non-linear effects on innovation outcomes and processes (Arthur 2009). As a consequence, what we witness as the evolution cameras is as much about changes in the meaning of what a ‘camera’ is, and what people can or should do with it (Bijker 1995), as it is the changes of the technology itself. These changes emerge in non-linear, and often surprising, ways by combining multiple previously unrelated technologies and social contexts over time. Conventional theories of innovation diffusion and evolution (Anderson and Tushman 1990; Rogers 1995) fail to explain

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this type of complex pattern of technology transmogrification along with its functional expansion and geographic diffusion, as they assume the technology's meaning does not change while it stretches over new capabilities, time and across space. At most, these studies reveal how the technology's performance/cost ratio develops over time and how such development affect its diffusion and position in the market.

In this paper, we argue that due to the malleability and generativity of digital technology (Zittrain 2006), we need a new model of innovation evolution that accounts for the on-going, fast and deep changes in the meaning of the digital technology as it evolves. Such a theoretical account must take the unique and evolving material characteristics of digital technology into consideration. To this end, the goal of this paper is to fill the gap in innovation theories by developing an architectural model of digital innovation and tracing how the impacts of digitalization have evolved from their humble beginnings to a deep transformation in how innovation spaces and dynamics are created. We derive our theoretical explanations drawing on the fundamental properties of digital technology and recent studies of the consequences of digitalization — the process by which digital technology is embedded into previously non-digital use contexts. By doing so we hope to contribute to the innovation literature by explicitly recognizing the unique nature of digital technology and how it affects the ways innovations will unfold over time.

Past Studies on Evolution of Innovations

By *innovation*, we mean a creation and adoption of an idea, a product, a technology, or a program that is new to the adopting unit (Gupta et al. 2007). Past studies often conceptualize innovation primarily as a linear, sequential process (Attewell 1992; Cooper and Zmud 1990; Fichman and Kemerer 1997; Swanson 1994) or a punctuated model of consecutive stages (Abernathy and Utterback 1978; Anderson and Tushman 1990; Utterback 1994). Main theoretical positions that explain the evolution of innovation are (a) diffusion theories, (b) continuous innovation theories, (c) evolutionary theories (d) heterogeneous innovation theories, and (e) theories of technology shaping.

Diffusion theories see an innovation as an unproblematic object that needs to be diffused into a homogeneous population of adopters. Some of these theories try to identify factors that are internal to technology systems or innovators that explain the diffusion of innovations (Damanpour 1991; King et al. 1994). Other diffusion theories try to identify a set of social and economic factors external to the innovators that affect diffusion of innovations (Rogers 1995). In particular, one of the goals of these theories is to identify a set of antecedents that determine early and late adopters of innovations (King et al. 1994; Rogers 1995).

Continuous innovation theories emphasize the role of users, particularly lead users, in the evolution of innovations (von Hippel 1998). Recently, this theory has evolved to explain open and distributed forms of innovation that have become common place due to the radically reduced communication costs (Chesbrough 2003; von Hippel 2005; West 2003). This perspective sees innovation as a result of on-going communication and implicit collaboration between the innovator and users, and explores contexts under which such collaboration can more effectively take place. Here, innovation is seen as essentially being co-produced by both the innovator and users. However, no particular evolutionary logic is offered in this model.

Evolutionary theories narrate a life cycle of an innovation (Abernathy and Utterback 1978; Anderson and Tushman 1990). Often drawing on punctuated equilibrium concept, these theories define specific and consecutive stages in the evolution of an innovation. In the fermentation stage, many competing ideas sprout based on different cognitive models (Abernathy and Utterback 1978; Kaplan and Tripsas 2008; Tushman and Anderson 1986).

Here, firms engage in exploratory learning (March 1991) in their search for superior solutions and to make sense the emerging market needs and new potential of the technology. Once a dominant model emerges through market competitions, firms seek to maximize their efficiency by engaging in exploitation (March 1991). In this model, a technology discontinuity occurs through random external events, and thus incumbent firms' dominant logics are likely to create inertia and these firms will often fail to foresee emerging technologies that will eventually displace their current technology.

Most recently, an emerging body of studies on *heterogeneous innovation theories* has focused on innovations where heterogeneous actors get involved. These studies emphasize network effects, messiness and ambiguity, due to increased innovation combinability (Boland et al. 2007; Lyytinen and Damsgaard 2001; Tuomi 2002; Van De Ven et al. 1999). The innovation process is seen as an arena that is highly dynamic and volatile, subject to political influence, and spanning across multiple heterogeneous communities. These studies show that increased network diversity promotes new combinations, fosters learning and enables faster diffusion (Tuomi 2002), but at the same time it can build thicker boundaries for their non-spread (Ferlie 2005). Accordingly, innovation scholars stress the need to examine specific types of interactions among packs of innovators (Van De Ven 2005), often mediated by IT artifacts (Carlile 2002, Boland et al 2007), and constrained by network topologies (Ahuja 2000; Obstfeld 2005) as how they combine new ideas when communities expand and crisscross (Tuomi 2002).

Finally, *theories of technology social shaping* point out that innovation process is not only about inventing and bringing new functionality or behaviors to market place, it is as well a process of rendering something which is originally alien and rare to something, which is familiar and common (Hargadon and Douglas 2001). This process involves acts of creating, negotiating and stabilizing the meanings of the technology among would-be-adopters and other critical stakeholders (sponsors, regulators) (Bijker 1995). In this sense, innovation involves social shaping, re-shaping and legitimization of the technology (Williams 1997). Most of these studies have pointed out the necessity to stabilize and familiarize the meanings of singular technologies. What they have not addressed is that due to increased generativity afforded by digital technologies meanings have become increasingly fleeting and ambiguous and in need of constant renegotiation and expansion, thus creating new challenges and opportunities for innovators.

Taken together, most studies in the past assume that the nature and meaning of the innovation is relatively stable and fixed, or in need of fixing. While some of these studies do explore how dominant designs emerge out of competition among multiple alternative technologies, these alternatives are assumed to have the same purpose and functional meaning. At most, some studies have looked at processes through which meaning closures are achieved among a set of innovations. Yet, with the penetration of digital technology into non-digital products, such assumptions cannot be sustained. Digital technology is highly malleable and generative (Zittrain 2006). As such, digitalized products are less fixed in their meaning and usages than their non-digital counterparts – in a way they are new sets of capabilities in search for meaning and purpose. Furthermore, much of the past innovation research adopts a perspective that treats technology as a black box (Arthur 2009). In order to understand the generative nature of digital technologies and its impact on the evolution of innovations, one must seriously come to grips with the substantial nature of digital technology and open the black box. In the following section, we put forward a theoretical exposition on the nature of digital technology and digitalization aiming to reveal the main contours of the inner workings of the black box.

Digital Technology and Digitalization

By *digital innovation*, we mean an innovation enabled by digital technologies that lead to the creation of new forms of digitalization. By *digitalization*, we mean the transformation

of existing socio-technical structures that were previously mediated by non-digital artifacts or relationships into ones that are mediated by *digitized* artifacts and relationships with newly embedded digital capabilities. Digitalization goes beyond a mere technical process of *digitization* that involves the encoding of diverse types of analog information in digital format and the embedding of an ability to process such digital information using a set of pre-programmed instructions. Digitalization, therefore, involves organizing socio-technical structures with digitized artifacts as well as the changes in artifacts themselves. Although digitalization is fundamentally enabled by technical digitization, it also includes the reconfiguration of broader socio-technical structures that were previously mediated by non-digital artifacts. 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 (Brynjolfsson and Saunders 2009; Kurzweil 2006). Subsequent digitalization requires the reconfiguration of socio-technical structures by applying digital technology across different industrial and organizational contexts (Tilson et al. 2010; Yoo 2010). When this application involves elements of newness by transforming the creation, storage, and distribution of content, applications/products, and services in industries in ways that it reshapes the underlying value propositions, we call it a digital innovation. Examples of technical digitization can be found when the telecom industry installed digital switching in the 70's, which did not change the socio-technical context. Examples of digitalization can be found in the disruptive transformations in mobile media, emerging Internet-based TV, digital publication, or digital camera. In these examples of digitalization, significant innovation came from not only the digitization of artifacts such as mobile phones, TVs or books, but also much broader socio-technical reordering of organizing logics among heterogeneous firms and marketplace that are connected through a common digital infrastructure.

While digital technology shares many common characteristics with its non-digital counterparts, we argue in this paper that it has some distinct and unique characteristics that make digital innovation in fundamental ways different. Moreover, these characteristics are often combined into new forms of innovation that result in essentially different phenomena that are unique and transformative. 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 and unbounded without falling prey to simplistic versions of technology determinism.

Digitalization and Digital Materiality

Design characteristics of digital technology

Ongoing digitalization in our material world adds new material properties to previously non-digital, industrial age products and processes (Arthur 2009; Yoo 2010). Among others, we focus on three design characteristics of digital technology play pivotal roles in facilitating digital innovations and its unique consequences.

First, unlike analog signal that maps changes in one continuously varying quantity on changes in another continuously changing quantity, digital signal represents analog signals into numbers and ultimately bits (a contraction of binary digits) (Tilson et al. 2010). 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 radio waves through cables and space. As such, there is a tight coupling between analog data and devices. As Tilson et al. (2010) note, the tight coupling between data and device led to the emergence

of vertically integrated industry structure for different media and the separation of producer and consumer of these media, due to the high fixed cost investment in building facilities for data storage and transmission. However, technical digitization of analog data means that any type of analog data (audio, video, text and image) can be stored and transmitted using the same device. Once digitized, data from different sources can be transformed and manipulated and further combined with other data, dissolving the boundaries between different media. The efficiency of data transmission and storage can be radically improved by multiple types of data can be sent and stored using the same networks and devices.

Second, rooted in what is known as Von Neumann Architecture, modern digital computers use a processing unit and a separate storage unit to hold both instructions (programs) and data. Unlike earlier computing machines that had fixed programs, modern digital computers can perform many different functions, and act like clocks, calculators, word processors, or web browsers – all in the same device. Technical digitization of previously non-digital artifacts means embedding software capability following Von Neumann Architecture into the physical artifacts. This digitization will lead to the separation between the semiotic logic (represented in programs) and the physical hardware device itself. Unlike other non-digital devices, therefore, digital artifacts can be flexibly programmed and re-programmed for multiple purposes.

Third, digital innovation requires the use of digital technology. This self-referential nature of digital tool means that pervasive diffusion of digital innovation requires ubiquitous access to digital tools, such as PCs as a design platform and the Internet as a communication network. Therefore, more use of digital technology accelerates the diffusion of digital tools, creating strong network externality and positive feedback loops. Thanks to Moore's law, performance-price and performance-size ratio of computers has radically improved over time making digital computers ubiquitous and connected to a ubiquitous global network – the Internet. The wide availability of computers and communication networks then has created a powerful feedback condition that further accelerates the creation and diffusion of digital innovations. By late 1990's, PCs and the Internet became accessible to unprecedented number of users, who could now experiment with various forms of innovations using these technologies. Unlike industrial technologies requiring extensive capital, users could access new technology platforms to experiment with digital technology. This in turn opened the floodgates of new forms of innovation (Tuomi 2002; von Hippel 2005).

These three design characteristics – *homogenization of digital data*, *universal programmable digital computer*, and the *self-referential nature of digital technologies* – form a powerful set of reciprocal and mutually re-enforcing forces that have created distinct and unique socio-technical dynamics of digital innovation.

Properties of digital materiality

An important impetus of digital innovation is the digitalization of previously non-digital artifacts. These digitalized artifacts have different material properties that differentiate them from their non-digital counterparts. Yoo (2010) notes seven such properties. **First**, at the most fundamental level, small, and low-powered microprocessors make it possible to embed programmable digital architecture into what used to be fixed, mechanistic non-digital artifacts. The feature of *programmability* refers to the ability of a now digitized artifact to accept new sets of instructions to modify its behaviors. Using these software-enabled capabilities, artifacts become programmable following Von Neumann Architecture. As a result, these artifacts become capable of performing additional and extensible functions, above and beyond the original purpose, thus making them malleable (ITU 2005). **Second**, the program-

mable memory chips (e.g. RFID) make individual artifacts addressable; that is, each digitalized artifact can be uniquely identified within their context. This feature of *addressability* refers to the ability of a digitalized artifact to individually recognize a message addressed to it. Together with programmability, addressability permits digitalized artifacts enroll into the global information infrastructure, such as Internet of Things. **Third**, the integration of sensors will enable artifacts to sense and record multiple types of information about their environment. Here, *senseability* refers to the ability of a digitalized artifact to sense and respond (due to programmability) to the changes in its environment, making it context aware (Dourish 2001). Senseable artifacts form the edge of the digital infrastructure that is constantly evolving. **Fourth**, the digitalized artifacts interact with other artifacts, infrastructures, and human actors through embedded communication capabilities. The *communicability* refers to the ability of a digitalized artifact to send and receive any type of digitized messages. Combined with senseability, the communicability generates new relationships between actors and digital artifacts. For example, individuals now connect sensors to their Twitter accounts in order to monitor their environment, homes, and even movements of a fetus in a mother's womb. **Fifth**, digitalized artifacts need to have memory capacity in order to be addressable and programmable. As a result, the artifacts will become increasingly memorizeable. The *memorizeability* refers to the ability of a digitalized artifact to record and store information that it has generated, sensed, or communicated (as to maintain a state of a process). As a result digitalized artifacts will have the capability to remember where they were, who used them, the outcomes of the interactions, etc. **Sixth**, senseable and memorizeable artifacts and new relationships among these artifacts and actors will produce expansive digital traces for their conditions, properties, movements, and interactions, making them over time and space. The notion of *traceability* refers to the ability of a digitalized artifact to chronologically identify, memorize and inter-relate events and entities in time. **Seventh**, new software innovations like Semantic Web (Berners-Lee et al. 2001) enable knowledge associated with actors, artifacts, places and events to become associable and inferable, making new folksonomies possible. The idea of *associability* refers to the ability of digitalized artifacts to be related to and identified as something along with other entities (such as other artifacts, place and people) and inferring some future states and associations based on this. Together, these seven properties of digital materiality — programmability, addressability, senseability, communicability, memorizability, traceability, and associability — form the new material properties of digitalized artifacts.

A four-layered generic model of digital service architecture

An important consequence of digitalization of products is the emergence of *a generic model of digital service architecture with four layers*: devices, networks, services, and contents (Figure 1) (Benkler 2006). The device layer is further divided into physical machinery (TV, PC, mobile phone, car, etc) and logical device OS (operating system) that provides logical scripts that control the hardware device. The network layer is further divided into the physical transport layer (including cables, radio spectrum, transmitters, etc) and the logical transmission layer (including network standards such as TCP/IP or P2P). The service layer deals with application programs that provide directly interact with users as they create, manipulate, store and consume different contents. Using the service layer, users can listen to music, send and receive e-mails, read books, watch videos, and receive navigation information. Finally, the content layer includes actual data such as texts, sounds, images, and videos. The content layer also contains a wealth of meta-data including ownership, copyright, encoding methods, content tags, and geo-time stamps which all can be critical in delivering the service.

This type of architectural stack is not new with computer and network technologies. What is new here is that with increasing digitalization of previously non-digital products and services, this four-layered architectural view of digitalized service has become more broadly applicable for all types of digitalized products. A digital service architecture represents how physical components and logical semiotic layers of a digitalized product will be organized to render a set of functions (or services) delivering certain contents. We call it *service architecture* as due to digitalization a physical product can be programmed to render multiple services.

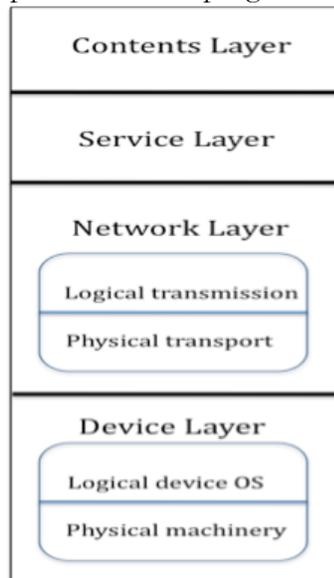


Figure 1. A Four-layer Generic Model of Digital Service Architecture

Before digitalization, these four layers were tightly coupled together within a particular media, industry or product boundary. Or, in the case of purely physical or mechanical products (such as furniture, car, hammer, and cloths), such layers simply did not exist. However, as a result of digitalization, these four layers will be increasingly de-coupled and thus become loosely coupled. This de-coupling is accomplished through the integration of general purpose computing capabilities through the implementation of Von Neumann Computing architecture and general-purpose network capabilities through IP network standard that allow abstracting specific aspects of service rendering to distinct layers based on the four level architecture.

The emergence of the four-layered digital service architecture has pronounced strategic and structural implications. How open and closed this architecture is and which focal firms control different parts or elements of the architecture, especially connection points between layers, have direct and significant strategic and structural implications. Overall, the layered digital service architecture and its organization for a given set of services reflect a stream of strategic decisions implemented technically over time. To exemplify how such decisions emerge, we will examine next the evolution of camera from analog to digital imaging technologies.

Evolution of Digital Camera: An Illustration of Digital Innovation

In this section to illustrate an evolution of a product architecture that underlies an industry and its products into the four layered digital service architecture, we present a history of digital camera. We draw on publicly available resources including Wikipedia and other photography related

websites and publications of the histories of major camera companies including Canon, Nikon, Kodak, and Sony.

A brief history of analog camera

Camera is a phenomenal product that changed the life styles of nearly all people. At the same time, it has undergone radical changes over a few centuries. The concept of camera evolved from a device called camera obscura. The earliest record of such a device was made by an Arab scientist who described this device in his book on optics in 1021 A.D. It uses a pinhole or lens to project an image of the scene onto a viewing surface. Couple centuries later, Leonardo da Vinci wrote the first detailed design of camera obscura in his Atalantic Codex. In 1825, Nicéphore Niépce took what is known to be the world first permanent photograph by making a reproduction of a Dutch painting. Although there were others who took photos before this, none of them were permanent as they all faded quickly. According to his own handwritten record, it took eight hours for Niépce to take his picture. Early cameras, known as Daguerrotype cameras weighed 120 pounds and a complete kit required a horse-drawn wagon to move it around².

Over the following decades, however, cameras using gelatin dry plates became much smaller in size, making it possible to introduce handheld cameras. Yet, the basic key idea remained the same. In 1888, George Eastman started making “Kodak” cameras, a fixed focus lens, single focus length at a relatively low price. These cameras were preloaded with 100 exposures roll. Once the roll is finished it needs to be sent back to manufacturer for reloading and processing. This led to the birth of film³.

After the invention of film-based camera, 35mm camera and Single Lens Reflex (SLR) camera were invented in 1913 and 1928, respectively. One of the major innovations in SLR camera was the eye level viewfinder that was first introduced in 1947. Prior to this, the SLR cameras had a waist-level focusing screens⁴. Polaroid then introduced the instant cameras in 1948 (Tripsas and Gavetti 2000). It was an instant hit and remains as one of the top best selling cameras of all time. By the 1960s, low-cost electronic components made it possible to build cameras with light meters and automatic exposure systems.

Invention of Digital Camera

A digital camera records still images in a digital format. Unlike analog cameras that record light onto photographic film, digital cameras use a solid state, light-sensitive, silicon chips. The chip’s electrical charges are converted into discrete numbers for storage on a flash memory card or optical disc⁵.

The origin of the digital camera can be traced back to the US space program. NASA and the US intelligence agencies that used space satellite images to gather intelligence needed an efficient way to take images in the space and transmit them back to the earth⁶. A major step towards digital photography was the invention of the charge-coupled device (CCD) by Willard Boyle and George Smith at Bell Labs in 1969. The CCD is a light-sensitive integrated circuit that stores information,

² http://en.wikipedia.org/wiki/History_of_the_camera

³ <http://www.kodak.com/global/en/corp/historyOfKodak/historyIntro.jhtml>

⁴ http://en.wikipedia.org/wiki/History_of_the_camera

⁵ http://www.pcmag.com/encyclopedia_term/0,2542,t=digital+camera&i=41298,00.asp

⁶ <http://www.thehistoryof.net/the-history-of-digital-cameras.html>

represented by discrete packets of electric charge. Soon after its invention, the CCD was established as a versatile and robust optical detector for cameras. Although Texas Instruments patented the first non-film electronic camera in 1972, it never built a prototype. Instead, it was Steven Sasson at Eastman Kodak who built the first digital camera in 1975⁷. In 1981, Sony unveiled the first commercial electronic camera, Mavica. This was an analog camera that recorded analog signals on floppy disks with a 0.3-megapixel resolution, which was not good enough quality to print⁸. In 1987, Kodak introduced the professional Digital Camera System (DCS) with a megapixel sensor. In 1990, Kodak introduced a professional digital camera with a 1.3-megapixel resolution, by casing DCS into Nikon's F-3 body⁹. These early digital cameras were only used by news media and were not available to the consumers.

Then, Apple introduced Quick Take 100 in 1994 as the first consumer-oriented digital camera with the resolution of 640 x 480, with an internal memory that can store up to 8 images¹⁰. Apple's act was quickly followed by others, including Olympus, Sony and Ricoh. In 1999, Nikon introduced the D1, a 2.74 megapixel camera that was the first digital SLR developed by a major manufacturer. D1 that cost about \$6000 used Nikon F-mount lenses, which meant professional photographers could use many of the same lenses they already owned¹¹. Since 2003, digital cameras have out-sold film cameras.

Evolution of Digital Camera

Digital camera consists of several key components whose development have contributed to the unpredictable twists and turns of the development the technology. The most essential component of digital camera is the digital image sensor. The size and the quality of the sensor determine the resolution of the camera, which has been one of the main criteria of competition during the early stage of the digital camera development.

Another key design feature of digital camera is its user interface. Casio made a key innovation when it introduced LCD panel on the back of the screen in 1995. The addition of LCD made instant review and immediate feedback possible, along with many other additional features that were not available in the analog cameras¹².

Also, a key component of digital camera is the storage media. Kodak introduced the use of compact flash memory card in 1996, which improved the storage capacity and transportability of the pictures that were taken. Over years, several different competing storage technologies such as secure media (SD), MiniSD, MicroSD, and Memory Stick by Sony, are developed, increasing the memory capacity while reducing the size¹³. Digital camera storage capability is also influenced by different file formats that compress the size of the picture without compromising the quality of the picture. In 1997, Hitachi and Sony each introduced a camera based on public digital imaging standards, MPEG and JPEG, respectively, that markedly improved the efficiency of the file storage¹⁴.

⁷ <http://www.digicamhistory.com/FINDER.html>

⁸ <http://www-users.mat.uni.torun.pl/~olka/historia.html>

⁹ <http://inventors.about.com/library/inventors/bldigitalcamera.htm>

¹⁰ <http://www.applematters.com/collections/apple-quicktake-100/>

¹¹ <http://www.nikon.com/about/info/history/corporate/index.htm>

¹² <http://blogs.zdnet.com/ITFacts/?p=5125>

¹³ http://en.wikipedia.org/wiki/Flash_memory

¹⁴ <http://www.thehistoryof.net/the-history-of-digital-cameras.html>

Finally, another key area of hotly contested area of competition was to print and share digital photos. Again, Kodak took early initiatives by aggressively partnering with Microsoft and Kinko's, where digital image editing workstations that enabled customers to edit and print photos and create PhotoCDs. Kodak first introduced the concept of PhotoCDs in 1990 and made it available in 1992 (Benner 2010). Hewlett-Packard introduced PhotoSmart Printer in 1997, which allowed users to print digital photos on glossy papers. However, what made digital camera distinctively different from its analog counterparts is its ability to share pictures via the Internet. The first Internet photography site was PhotoHighway.com that started in 1999. Kodak introduced its own on-line site called Kodak Gallery in 2003. Yahoo acquired Flickr in 2004, which became one of the most popular websites for photo sharing. Flickr is particularly popular among bloggers to host images that they embed in blogs and social media, instead of printing pictures¹⁵.

Integration with other technologies

Over time, digital camera has been integrated with other technologies. First, cameras have become an integral part of mobile phones. These phones are generally referred to as camera phones. The first camera phone, J-SH04, was manufactured by Sharp in 2000 for J-Phone, a Japanese mobile operator¹⁶. It had a 0.1-megapixel resolution and a 256-color LCD color display. Although it was widely criticized due to its limited specification including low quality picture, narrow bandwidth, small memory capacity and inability to send or print pictures, camera phone soon became very popular. By the end of 2009, more than one third of the mobile phones have an embedded camera (some has two – front and back). Since 2004, the sales of camera phone is bigger than the sales of digital and analog cameras combined. In 2006, Nokia became the world largest camera manufacturer¹⁷. Many of the camera phones routinely feature powerful digital camera capabilities. The integration of digital camera into mobile phones changed the way people produce and consume digital pictures, as it started to integrate more directly to various forms of internet services including blogs and social network sites (Van House and Davis 2005).

Second, another important technology that is integrated with digital camera is Global Positioning Systems (GPS) technology. In 2005, Ricoh introduced the world first GPS-ready digital camera, ProG3. Using Compact Flash GPS card or an external GPS connected through Bluetooth, ProG3 produced geocoded pictures that included latitude, longitude and altitude information. In 2008, Altek introduced the world first digital camera that has an embedded GPS chip. Furthermore, many of the camera phones, including Apple's iPhone and Nokia's N-series phones, include both digital camera and GPS, produced geocoded pictures. As geocoded photography becomes popular, many of the photo sharing sites, including Flickr and Google's Picasa, started supporting geocode, integrating digital maps and photos¹⁸.

Finally, communication technology was integrated into digital camera. Most digital cameras can now connect directly to a computer to transfer data via USB. An alternative is inserting the cameras removable memory card into a computer equipped with a card reader. Increasingly, however, digital cameras embed wireless connections such as Bluetooth or WiFi. Of course, most camera phones allow users to send photos to others using Multi-Media Service (MMS) or as an e-mail attachment. Recent smart phones such as Apple's iPhone or Google Android allow direct uploading to popular photo sharing internet sites such as Flickr, Picasa, Facebook and Twitter. In 2007, Eye-Fi

¹⁵ <http://en.wikipedia.org/wiki/Flickr>

¹⁶ http://en.wikipedia.org/wiki/Camera_phone

¹⁷ <http://en.wikipedia.org/wiki/Nokia>

¹⁸ <http://en.wikipedia.org/wiki/Geotagging>

introduced an SD card with integrated WiFi and GPS capabilities, allowing ordinary digital camera to capture geocoded photos and wireless upload those photos to popular websites directly¹⁹.

Discussion

Unbounded Innovation of Digital Camera

Our analysis of the evolution of digital camera shows an unbounded nature of digital innovation. At the beginning, the core idea of digital camera was a simple technical replacement of chemical-based photographic film with a light-sensitive solid-state silicon chip. During the initial wave of digital camera evolution, there was no fundamental change in the function and the meaning of the camera. However, over time, continuing digitalization of different components and the integration with other digital technologies such as mobile phone, network technology, GPS and the Internet, transformed digital camera and its usages in a way that was not originally intended by the early inventors. Our analysis of the evolution of digital camera shows that digital innovations seem to follow three different phases.

The first phase takes place through the embedding of a set of digitalized instructions to control its physical device, which leads to the separation of logical layer and physical device logic. While a digital camera still has an optical lens and a shutter, the way the shutter and the lens are controlled to manipulate the amount of light exposure is primarily controlled by programmable software, rather than by tightly configured physical components. At this phase, digital technology does not offer new functions. Instead, it simply performs the same function that non-digital devices performed with some additions and intelligence. Other examples of the first phase of digitalization include the transition from 1G to 2G cellular network and the emergence of CD in the music industry (Tilson et al. 2010). In the first phase, the industry experiences the significant cost reduction with “more of the same” services, following the image of “paving the cow paths” (Tilson et al. 2010).

Over time, however, designers and entrepreneurs add more programming capabilities such as on-screen edit and extensive file management capabilities. Furthermore, as digital cameras begin embracing other digital technologies such as network, GPS and network capabilities, the logical layer of the camera function (what we called service layer in Figure 1) begins to emerge as a distinctive layer apart from the device layer. As a result, digital ‘cameras’ begin to house a host of different services. Similarly, we see the emergence of a separate network layer in digital cameras as designers add diverse communication capabilities. Furthermore, the emergence of separate layers of service and network apart from the device offers new services that were not considered in the past. For example, new digital cameras come now with on-board YouTube and Flickr applications so that pictures and video clips can be directly uploaded without connecting to a PC. This in turn demand development of more robust operating systems underlying the functions of digital cameras to control simultaneously multiple software and hardware resources required by these new services. So, in this second phase of digitalization, we begin to see the separation of the device, network, service, and content layers that have been tightly coupled in the past. The separation of these four layers becomes more pronounced when one considers the rapid integration of mobile phone and digital camera. For example, the physical components of digital camera embedded in an iPhone (device layer) can be used not only by the default camera application that comes with an iPhone, but by many other third-party camera applications (service layer).

¹⁹ <http://en.wikipedia.org/wiki/Eye-Fi>

Furthermore, there are now many dedicated applications for photo editing and Internet service on iPhone platform, which have created a set of features in the service layer. Therefore, the continued separation of these four layers lays the foundation of more versatile use of digital camera over time.

One can observe similar pattern in digitalization of other technologies such as Voice over IP (Benner forthcoming) and Digital TV (Tilson et al. 2010). For example, voice service becomes completely independent of device and network, and the same quality voice service can be delivered whether the user is using a fixed line phone, a desktop computer, or a mobile phone. Similarly, other media services, such as music, books, e-mail and movie can be delivered over multiple different types of networks using multiple devices. An important consequence of the second wave is the separation of four layers. Furthermore, the separation enables experimentations at each layer with minimum constraints set up by other layers leading to the rapid growth of the possible uses of digitalized products.

In the third and final phase of digitalization, we begin to see the emergence of novel products and services through mash-up across different product architectural boundaries. Devices, networks, services, and contents that were created for specific purposes are now being *re-mixed* in order to re-purpose its usage (Lessig 2008; Tilson et al. 2010). For example, location stream services such as Yahoo's Fire Eagle (<http://fireeagle.yahoo.net/>) can be mixed with other services and contents. Here, the key development is the convergence of multiple contents from heterogeneous sources thanks to the homogenization of digital data at the service layer. In the realm of digital camera, embedded GPS capability integrates geocode data with the digital photos. Geocoded photos then can be mixed with, for example, weather data stream on the Internet. As a result, digital photos can include not only the time and location information, but also the weather information. Similarly, information about people on the photo can be integrated into digital photos. This allows people to be 'tagged' on digital photos stored on the social networking sites. These mash-up services can be further re-combined creating incessant stream of new innovation possibilities. As results, digital camera and digital photography now imply something more dynamic and heterogeneous than what it was originally conceived. People take pictures not only more frequently in larger quantity, but differently (Van House and Davis 2005). Instead of printing on a paper and storing them in frames, people now share digital photos on the Internet, combining them with other forms of digital data. As digitalization continues, digital cameras are being equipped with increasingly diverse set of capabilities. It is conceivable that in a near future we may see a 'smart' digital camera that has full-featured operating systems such as Android in order to provide more flexibility and control to the users and new services. It is also possible to see digital photography capability integrated with other digitalized devices such as MP3 players or navigation systems, which in turn might transpire new sets of innovations as can be seen in Google digital earth service.

This last phase of digitalization can be found also in other domains. Small and powerful computing devices now can be embedded into previously non-digital artifacts. With these digital capabilities, digitalized artifacts can now capture and transmit different types of information that were not captured, and interact with other digital artifacts and services. For example, a simple insertion of an RFID chip into a pair of running shoes enable a runner to capture various information (such as pace, location, and biometric data) that were not available in the past. Once captured, such information can be shared through one's social network services like Facebook or Twitter, or can be mashed-up with other media such as Google Earth or Flickr photo services. Or one's own running record can be simply juxtaposed with others' record. As a result, in the third phase, vast amount of information that used to be simply lost now can be captured. What used to be simply physical product in the past

now has a layer of multiple semiotic logics. The separation between the physical artifact and semiotic logics at the device and network layers of previously non-digital artifacts, and subsequent loose coupling of the four layers of the digital service architecture form the basis of continuing and unbound innovations that characterize the third wave of digitalization.

New dimensions of Digital Innovation

An analysis of digital innovation of camera suggests that later waves of digitalization are fundamentally re-shaping how, where, when and why firms and other stakeholders innovate around camera based products and services. Consequently we posit that the onslaught of digital innovation will introduce six new dimensions to innovation outcomes and processes: (1) convergence, (2) digital materiality, (3) generativity, (4) heterogeneity, (5) locus of innovation, and (6) pace. We argue that these features are characteristic to digital innovation across products and industries during the third wave of the digital innovation when the four layers are fully established and are becoming increasingly loosely coupled. The main features of these six characteristics are summarized in Table 1 and will be discussed below in more detail.

Overall, we note that these six characteristics are material consequences of pervasive digitalization to both *innovation outcomes* (convergence, and digital materiality) and *innovation processes* (generativity, heterogeneity, locus of innovation, and pace). We also posit that these dimensions highlight new aspects of innovation outcomes and processes that make digital innovation essentially distinct from non-digital forms. We also note that these six dimensions are not mutually exclusive. Rather, they interact and reinforce each other in an ongoing virtuous cycle of digitalization, ever increasing the complexity and dynamism of innovation processes and outcomes.

Table 1. Six Dimensions of Digital Innovation

Dimensions	Descriptions
Convergence	Continuous integration of diverse and heterogeneous technologies through homogenization of digital data; multi-modality of technologies; layered and loosely coupled connections across devices, networks, services and contents.
Digital Materiality	Inseparability of digital material from social interactions, constituting new tangible aspects of all innovation processes and outcomes; loose coupling of physical materials and semiotic logics; embedding of digital capabilities with seven unique materiality into physical artifacts; emergence of digital service architecture of previously non-digital products and services.
Heterogeneity	Integration of diverse forms of data, information, knowledge; intensified need to coordinate across multiple social and technical worlds; increased horizontal integration across different stacks of digital service architecture.
Generativity	High degree of equivocality enabling reinterpretation, expansion and refinement of products and services; design characteristics of digital representations that foster unbounded innovations through incessant recombination and modification of different elements in digital service architectures; pervasive diffusion of digital tools and low cost communication enabling waves of innovations.
Locus of Innovation	Dramatic geographical and social dispersion of innovation sites and processes due to low communication and storage cost; independent innovation trajectory at different layers of digital service architecture; increasing movement of innovation activities toward the periphery of the innovation network.

Pace	Increase in the clock speed of innovation cycle due to programmability and convergence; increased velocity of innovation due to re-combination as a mode of innovation; a common digital infrastructure facilitating distributed innovation activities which in turn accelerate the pace of innovation
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Convergence

The on-going progress of digitalization with its seven features has made *digital convergence* a reality (Lyytinen and Yoo 2002; Yoo 2010). Digitalization transforms now all analog data into a common digital format. Due to this convergence, digitized technologies offer now unified points of intersections where they can share the same infrastructural capabilities to provide new capabilities (Tilson et al. 2010). Based on unifying digital format, digital convergence allows a combination and re-combination of devices, networks, services and contents that were originally created for different purposes. As we saw in the case of digital camera, as these four layers become loosely coupled, digital representations within and across these layers can be manipulated and re-combined in ways that create new families of representations *ad infinitum*. Through this re-combination process, digital convergence creates a space for novel products and services that can be created through unforeseen combinations of digital representations and capabilities. For example, so-called ‘triple-play’ (combining broadband internet, phone and TV services) or ‘quadruple-play’ (adding mobile internet) is an outcome of digital convergence in media content, storage and distribution mechanisms. Similarly, digital convergence has created major innovations such as iTunes, YouTube, Slingbox, or with digital camera with tools like Flickr.

The impacts of digital convergence are not limited, however, to communication and media. Many artifacts that used to be non-digital are now composed of digital components enabling them to interact with other digital devices, to connect to the Internet, or to interact with the environment in which they operate. This offers organizations and innovators new ways to differentiate customer or user experience. For example, GPS (Global Positioning Systems) service in digital cameras and mobile phones, when combined with comprehensive digital maps and sensors in buildings, cars or clothing, is spurting a stream of service and product innovation that connects previously unconnected user experiences and creates a new kind of virtual physical world.

Digital convergence also changes the nature of products towards digital platforms. For example, digital camera is now emerging not simply as a product with a single function, but a platform on which a number of different services can be rendered – the reason we call it digital camera is just based on past conventions. However, the degree to which such innovation takes place is controlled by how the underlying architecture is designed. For example, the current operating systems of most digital camera is still tightly controlled by the manufacturer, making diverse set of experimentations with different services difficult, if not impossible. On the other hand, the relatively open nature of recent mobile phones such as iPhone or Android, makes it possible to rapidly expand such experimentations. As such, such technical decision on the openness of the platform of the product will eventually determine the fate of the evolution of digital innovation.

Digital Materiality

Digital innovations require scholars take digital ‘materiality’ – i.e. what it is that the digital capability does or what is its semiotic logic – seriously. Yet, at the same time, as we have seen in the case of digital camera, digital innovation is more than mere technical digiti-

zation. Effective research on digital innovation, therefore, must consider both material characteristics of digital technology and broader socio-technical structures. Past research on innovation research in the organization science literature has broadly neglected the unique material characteristics of digital innovation. As Lavie (2006) notes, “referring technological change as an exogenous event is a conventional assumption in technological discontinuities research” (p. 154). Technology innovations are essentially black-boxed and described as a stochastic process (Anderson and Tushman 1990). Summarizing the literature, Benner (2007) notes that “*responding* to environmental change is a critical challenge for firms, and whether and how organizations *adapt* is a central topic in organization theory and strategy research” (p. 93, *italic is ours*). Therefore, past studies on digital innovation in the organization science literature tend to focus on organization’s reactive adaptation to the disruptive changes caused by external technological developments. To the contrary, past research on digital innovations in engineering and design science area has heeded solely to technology artifacts, thus excluding social and organizational elements accompanying digitalization and innovation. In consequence, this body of literature tends to de-contextualize the material from the social elements of digital technology (Hevner et al. 2004).

Scholars in the socio-technical system literature have long recognized this rift and have been promoting more nuanced treatment of social and material aspects of innovation (Bijker 1993; Bijker 1995; Hughes 1983; Latour 2005; Latour and Woolgar 1979). Recently, materiality has received a greater attention in the context of digital innovation where products or services are IT enabled (Leonardi and Barley 2008; Orlikowski 2007; Orlikowski and Barley 2001). This view suggests that when we approach digital innovations through digitalization processes, we must consider how digital materiality is intertwined with physical materiality within products and process. As digital and physical materiality become increasingly intertwined, innovation scholars must also consider how they mutually shape and interpenetrate each other as they accommodate and resist human agencies (Pickering 1993; Svahn et al. 2009). The shifting and dynamic interface between the physical and digital materiality, therefore, bears particular theoretical significance for future digital innovation research.

As seen in the history of digital camera, embedding digital materiality into previously non-digital products with a Von Neumann computing architecture and general purpose network capability lead to the transformation of purely physical product into a hybrid product that shared both physical materials and components endowed with a digital service architecture separating four distinct layers of devices, networks, services and contents with different functionality. Through digital service architecture, digital innovations generate an increasing dependence on digital models and data with all seven properties of digital materiality. This raises new challenges of representing domains that were previously not represented. Therefore, innovators, designers, engineers and entrepreneurs must be aware of not only the limits of their digital models and data, but also the new possibilities that the new digital capabilities offer in terms of cost, accuracy or predictability.

As noted earlier, embedding of digital materiality into products requires new designing and managing new digital service architectures and establishing alternative and new architectural control points. An architectural control point refers to a system component that enables or constrains the design of complementary components through visible information (e.g., interfaces) that can be manipulated by designers. By strategically managing the architectural control point, the focal firm can make the digital service architecture of a product more or less open and closed. To the contrary, traditional models of coordination of innovation and architectural control followed organizational structures that reflected hierarchical product architectures (Baldwin and Clark 2000). Such product architecture assumes a tight coupling between physical or logical semiotic layers. This assumption, however, is increasingly

questioned due to lateral and loosely coupled relationships among digital components (Benkler 2006). Given digitalized products and services have both physical components and digital layers (Svahn et al. 2009), how to integrate the traditional hierarchical control with later coordination methods has become an important challenge in digital innovation.

Generativity

As we saw in the case of digital camera and the evolution of the Internet (Tuomi 2002; Zittrain 2006), digital innovation is likely to increase the level of generativity. Generativity refers to the direct quality of digital technology that allows actors, who were not directly involved in the original creation and maintenance of products and services to create new forms of products, services, contents and services which may or may not consistent with the original purpose of the artifacts due to re-combinability and reflexivity of digital technology (Zittrain 2006). The history of digital camera shows that a higher level of generativity was a direct consequence of the very nature of digital representation underlying digital cameras. The programmability of digital technology endowed new possibilities for repurposing existing camera products. Furthermore, the homogenizing of digital allowed mash-up of different streams of digital data to be combined with digital pictures, which opened up new innovation possibilities.

Heterogeneity

Digital convergence combines resources and components in wide and unforeseeable ways, thereby requiring the integration and reconciliation of previously unconnected knowledge, activities, artifacts and capabilities (Yoo et al. 2008). In the case of digital camera, we saw increasingly diverse actors from different communities over time are drawn into the realm of digital camera innovations. Originally the terrain of chemists, micromechanics and optics, the camera industry integrated memory technologies, software, mathematics (compression techniques), general-purpose computers, sensors and material technologies among others. As these new designers, engineers, entrepreneurs and users envision new services, products and processes by drawing upon digital capabilities for digital imaging they have to entertain foreign vocabularies, invoke unfamiliar tools and methods, meeting equivocal and even contradictory social worlds (Arthur 2009; Carlile 2002; Nonaka et al. 2009). An important challenge resulting from this convergence is, therefore, how to manage knowledge heterogeneity during innovation processes.

The focal firm, however, still can control to some extent the level of heterogeneity through architectural control points (West 2003). Different levels of architectural control through the selection of control points and levers create alternative topologies of innovation networks with different degree of heterogeneity. If a firm, for example, exercises more control over critical elements of the digital service architecture, the heterogeneity of the innovation network will decrease. To the contrary, when the firm lowers the architectural control and increases the loose coupling across four layers in digital service architecture, the heterogeneity of the innovation network will increase with unbounded scale. Therefore, the design decision on architectural control point often affects the level of social heterogeneity (Van De Ven et al. 1999; Yoo et al. 2008; Yoo et al. 2005). Therefore, the ideas of combinative platforms and two-sided markets are important to generate and sustain heterogeneity to drive innovation (Evans et al 2006; Eisenman et al. 2006). Heterogeneity, combined with generativity, provides thus a basis for unbounded expansion of innovations where continuing cycles of innovation spread lead to the distinct evolution patterns of innovations that are

bound by the previously known problem domains, offering incessant opportunities to form new combinations while these components themselves are becoming increasingly programmable (Arthur 2009).

Locus of Innovation

Digital technology radically reduces communication costs, thereby making participation of distributed and previously non-connected actors into the innovation process affordable. As such, innovation processes can become an open source project utilizing crowds as sources of idea contributions and different forms of controlling the intellectual property. This trend has brought a fundamental shift in the locus of innovation. We are increasingly seeing organizations and innovators moving to innovation spaces that is simultaneously distributed and heterogeneous that substantially differ from vertically integrated singular forms of innovation (Yoo et al. 2008). De-centering of innovation activity reflects the increasingly loose coupling in the digital service architecture and the heterogeneity of knowledge requirements that is necessitated by the convergent and generative nature of digital innovation.

Therefore, new forms of innovation processes such as open source and crowd sourcing are moving the locus of innovation from the inside of an organization to its edges and periphery (Malone 2004; von Hippel 1998). Digital technologies enable multiple forms of distributed intelligence benefiting from a large number of distributed actors coming together to innovate. For example, much of the recent innovation with digital camera is not carried out by the major camera manufacturers. Instead, it is often Internet service providers, or mobile handset manufacturers who are pushing the boundary. Similarly, much of the innovations spurred by Apple's iPhone came from thousands of app developers, rather than Apple itself. While Apple played a significant role for creating the digital platform with its iPhone and iTunes stores, it was the small developers who are at the edge of the Apple's innovation network that produced most innovations. Therefore, the distributed locus of innovation activities has led to the increased levels of social heterogeneity of the innovation network, which in turn, leads to increasingly unbounded and divergent form of digital innovations.

A key challenge caused by the de-centering of the locus of innovation is the governance of intellectual property often expressed in its form of control and enforcement. Digital innovation causes a radical shift from hierarchical and centralized forms of control where value is extracted through single locus of control and ownership to distributed and horizontal coordination. In particular, how to balance tensions between the value creation and value capturing with appropriate forms of intellectual property governance through choosing and establishing an architectural control is an extremely important strategic issue that requires simultaneously strategic and technical design considerations (West 2003; West and Gallagher 2006). On one hand, the innovating firms need to seek novel forms and mechanisms of architectural control. On the other hand, the firm needs to capture the value flexibly by implementing a value logic implied by available forms of architectural control. As such, the new digital platforms by which architectural control is technical implemented act increasingly as business platforms that foster new forms of organizing that empower the diverse set of actors to co-create and distribute the value.

Pace

Finally, by pace, we mean the rate at which change to 'new' is enabled within the digitized forms. The idea of pace has been well known in the research community since Men-

delson and Pillay's (1999) study of the "clock-speeds" of industries that note how frequently organizations need to innovate, what is the allowed speed of innovation, and what is the necessary speed of innovation diffusion. The increased speeds in all digitized domains have resulted in the situation where innovation needs to be continuous, relentless, and fast. Furthermore, the pace has accelerated in every year – a condition called a singularity in recent debates around innovation within digital age (Kurzweil 2006). A quick glance of the evolution of digital camera clearly shows the accelerating pace of digital innovation as more components become digitalized and more stable digital service architectures emerge with loose couplings across the four layers. This loose coupling facilitates rapid local experimentation by more and increasingly large set of actors and diverse players within each layer further fueling the acceleration of the digital innovation pace.

Conclusion and Implications

Digitalization with its three design characteristics – homogenization of data, general purpose computing architecture, and self-referential nature – has generated six new dimensions of innovations in the digital age. With these six dimensions – convergence, digital materiality, heterogeneity, generativity, distributed locus of innovation, and pace – digital innovation in its full might will bring along fundamental changes in the innovation outcomes and processes. One of the most significant changes in the innovation outcomes is the emergence of four-layered generic digital service architecture for all types of digitalized products and the resulting increasingly loose coupling across the four layers of devices, networks, services and contents. The digital service architecture (innovation outcomes) can be characterized by convergence and digital materiality. The loose coupling across the four layers of the digital service architecture in turn sets up a powerful condition for expansive unbounded innovation processes and generativity. This new innovation process can be characterized by heterogeneity, generativity, locus of innovation and pace. This new innovation landscape with distinct outcomes and processes requires new and different approaches to the scholarship related to innovation.

The emergence of the digital service architecture with loosely coupled four layers as innovation outcomes and the expansive and unbounded evolutionary pattern as innovation processes suggest that conventional model of innovation diffusion, which assumes more or less fixed meaning of the products over time needs to be re-considered. Instead, the emerging picture of digital innovation suggests a much more volatile, dynamic and emergent nature of innovation process in line with some arguments made earlier by scholars of social shaping of technology (Williams 1997, Bijker 1995). Here, however, it is not about stabilizing the meaning of a single product or service like a bicycle or Bakelite, but what makes these meanings fluid and shifting (Bauman 2000), and how the old sense making needs to be replaced with battles over the meaning and unexplored spaces of meaning (Verganti 2009). Scholars and practitioners alike must learn how to deal with multiplicity and ambiguity of product meanings as the same product can bears multiple, and often conflicting, meanings and how to position these meanings in ways which evokes new possibilities and excitement. In short, the innovation is as much about what does it mean to use or interact with certain services as it is about the physical properties or functions, as echoed with new verbs in our language as "to google" or "to tweet". This significantly challenges the past innovation research on cognitive schemes about product based on the notion of reasonably stable technological frame (Bijker 1995; Kaplan and Tripsas 2008; Tripsas and Gavetti 2000) and associated identity (Tripsas 2009). The evolutionary pattern of digital camera and associated digitalized products also shows that the evolution of innovation within domains should be best understood as a generative, evolutionary process that involves complex, chaotic emergent properties with new meanings to re-generate the field (Arthur 2009; Maturana and Varela 1998; Miller and Page 2007).

The dynamic and unbounded nature of digital innovation also represents a major challenge to firms that want to engage in digital innovations (Henfridsson et al. 2009; Svahn et al. 2009). These firms are likely face never-ending and unbounded innovation challenge in order to stay up with the generative nature of digital innovations. This requires them to organize themselves in multiple and different way with embedded contradictory logics. Furthermore, this suggests that organizational identity becomes highly dynamic and ephemeral reflecting the unbounded nature of the product and services that the firms produce (Tripsas 2009). Even with non-digital products, the importance agility, flexibility and creative destruction have been always important (Brown and Eisenhardt 1997; D'Aveni 1994; Eisenhardt and Tabrizi 1995; Schumpeter 1942; Teece et al. 1997). In digital innovation, however, not only the need for flexibility and dynamic capability is much more pronounced, but also the scope of change goes beyond the boundaries of the technology and organization that was previously considered to be possible or relevant.

Finally, the focal firm can assert significant influence the nature and the dynamics of digital innovations through design decisions about its architectural control points. The architectural control influences the degree to which four layers of digital service architecture are loosely coupled, and affect heterogeneity and generativity of digital innovations. Thus, it can severely constrain or enable unbounded digital innovations. As a consequence, what used to be technical domain now became inexorably strategic and social.

References

- Abernathy, W.J., and Utterback, J. "patterns of industrial innovation," *Technology Review* (June-July) 1978, pp 40-47.
- Ahuja, G. "Collaboration networks, structural holes, and innovation: A longitudinal study," *Administrative Science Quarterly* (45) 2000, pp 425-455.
- Anderson, P., and Tushman, M.L. "Technological discontinuities and dominant design: A cyclical model of technological change," *Administrative Science Quarterly* (35) 1990, pp 604-633.
- Arthur, M.B. *The nature of technology: What it is and how it evolves* Free Press, New York, 2009.
- Attewell, P. "Technology diffusion and organizational learning: The case of business computing," *Organization Science* (3:1) 1992, pp 1-19.
- Bauman, Z. 2000. *Liquid Modernity*. Blackwell Publishers Inc., Malden, MA.
- Benkler, Y. *The Wealth of Networks: How Social Production Transforms Markets and Freedom* Yale University Press, New Haven, CT, 2006.
- Benner, M. "The incumbent discount: Stock market categories and response to radical technological change," *Academy of Management Review* (32:3) 2007, p 703.
- Benner, M.J. 2010. Securities analysts and incumbent response to radical technological change: Evidence from digital photography and internet telephony. *Organization Science*.
- Berners-Lee, T., Handler, J., and Lassila, O. "The Semantic Web," *Scientific American*:May) 2001, pp 34-43.
- Bijker, W. "Do not despair: there is life after constructivism," *Science, Technology and Human Values* (18:4) 1993, pp 113-138.
- Bijker, W.E. *Of Bicycle, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change* The MIT Press, Cambridge, MA, 1995.
- Boland, R.J., Lyytinen, K., and Yoo, Y. "Wakes of innovation in project networks: The case of digital 3-D representations in architecture, engineering and construction," *Organization Science* (18:4) 2007, pp 631-647.
- Brown, S.L., and Eisenhardt, K.M. "The art of continuous change: Linking complexity theory and time-paced evolution in relentlessly shifting organizations," *Administrative Science Quarterly* (42:1-34) 1997.

- Brynjolfsson, E., and Saunders, A. *Wired for innovation: How information technology is re-shaping the economy* MIT Press, Cambridge, MA, 2009.
- Carlile, P.R. "A pragmatic view of knowledge and boundaries: Boundary objects in new product development," *Organization Science* (13:4) 2002, pp 442-455.
- Chesbrough, H. *Open Innovation: The new imperative for creating and profiting from technology* Harvard Business School Press, Boston, 2003.
- Cooper, R.B., and Zmud, R.W. "Information Technology Implementation Research: A Technological Diffusion Approach," *Management Science* (36:2) 1990, pp 123-139.
- D'Aveni, R.A. *Hypercompetition: Managing the Dynamics of Strategic Maneuvering* The Free Press, New York, 1994.
- Damanpour, F. "Organizational innovation: A meta-analysis of effects of determinants and moderators," *Academy of management Journal* (23:3) 1991, pp 555-590.
- Dourish, P. "Seeking foundation for context-aware computing," *Human-Computer Interactions* (16:2-3) 2001, pp 229-241.
- Eisenhardt, K.M., and Tabrizi, B.N. "Accelerating adaptive processes: Product innovation in the global computer industry," *Administrative Science Quarterly* (40) 1995, pp 84-110.
- Eisenman, T., Parker, G., and Van Aystyne, M.W. "Strategies for Two-sided Markets," *Harvard Business Review* (84:10) 2006, pp 92-101.
- Ferlie, E. "Conclusion: From Evidence to Actionable Knowledge?," in: *Knowledge to Action? Evidence-based Health Care in Context*, S. Dopson and L. Fitzgerald (eds.), Oxford University Press, New York, 2005, pp. 182-197.
- Fichman, R.G., and Kemerer, C.F. "The assimilation of software process innovations: An organizational learning perspective," *Management Science* (43:10), October 1997, pp 1345-1363.
- Gupta, A.K., Tesluk, P.E., and Taylor, M.S. "Innovation at and across multiple levels of analysis," *Organization Science* (18:6) 2007, pp 885-897.
- Hargadon, A.B., Y. Douglas. 2001. When innovations meet institutions: Edison and the design of the electronic light. *Administrative Science Quarterly* **46** 476-501.
- Henfridsson, O., Yoo, Y., and Svahn, F. "Path creation in digital innovation: A multi-layered perspective," *Sprouts: Working Papers on Information Systems* (9:20) 2009, pp <http://sprouts.aisnet.org/9-20>.
- Hevner, A., March, S., Park, J., and Ram, S. "Design science in information systems research," *Management Information Systems Quarterly* (28:1) 2004, pp 75-106.
- Hughes, T. *Networks of Power: Electrification in Western Society, 1880-1930* Johns Hopkins University Press, Baltimore, MD, 1983.
- ITU "The internet of things," International Telecommunication Union, Geneva.
- Kaplan, S., and Tripsas, M. "Thinking about technology: applying a cognitive lens to technical change," *Research Policy* (37:5) 2008, pp 790-805.
- King, J.L., Gurbaxani, V., Kraemer, K.L., McFarlan, F.W., Raman, K.S., and Yap, C.S. "Institutional factors in information technology innovation," *Information Systems Research* (5:2) 1994, pp 139-169.
- Kurzweil, R. *The Singularity is Near: When Humans Transcend Biology* Viking Penguin, New York, 2006.
- Latour, B. *Reassembling the Social: An Introduction to Actor-Network Theory* Oxford University Press, New York, 2005.
- Latour, B., and Woolgar, S. *Laboratory Life: The Social Construction of Scientific Facts* Sage, Beverly Hills, CA, 1979.
- Lavie, D. "Capability reconfiguration: An analysis of incumbent responses to technological change," *Academy of Management Review* (Jan 1 2006).
- Leonardi, P., and Barley, S. "Materiality and change: Challenges to building better theory about technology and organizing," *Information and Organization* (18:3) 2008, pp 159-176.

- Lessig, L. *Remix: Making art and commerce thrive in the hybrid economy* The Penguin Press, New York, 2008.
- Lyytinen, K., and Damsgaard, J. "What's wrong with the diffusion of innovation theory: The case of a complex and networked technology," in: *Diffusing Software Product and Process Innovations*, M.A. Ardis and B.L. Marcolin (eds.), Kluwer Academic Publishers, Norwell, MA, 2001, pp. 173-190.
- Malone, T.W. *The Future of Work: How the New Order of Business Will Shape Your Organization, Your Management Style, and Your Life* Harvard Business School Publishing, Boston, MA, 2004.
- March, J.G. "Exploration and Exploitation in Organizational Learning," *Organization Science* (2:1) 1991, pp 71-87.
- Maturana, H.R., and Varela, F.J. *The Tree of Knowledge: The Biological Roots of Human Understanding* Shambhala, Boston, MA, 1998.
- Mendelson, H., and Pillai, R. "Industry clockspeed: Measurement and operational implications," *Manufacturing & Service Operations Management* (1:1) 1999, pp 1-20.
- Miller, J.H., and Page, S.E. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life* Princeton University Press, Princeton, NJ, 2007.
- Nonaka, I., Toyama, R., and Hirata, T. *Managing Flow: A Process Theory of Knowledge-based Firm* Palgrave Macmillan, New York, 2009.
- Obstfeld, D. "Social networks, the *tertius iungens* orientation, and involvement in innovation," *Administrative Science Quarterly* (50:1) 2005, pp 100-130.
- Orlikowski, W. "Sociomaterial Practices: Exploring Technology at Work," *Organization Studies* (28:09) 2007, pp 1435-1448.
- Orlikowski, W.J., and Barley, S.R. "Technology and Institutions: What can research on information technology and research on organizations learn from each other?," *MIS Quarterly* (25:2) 2001, pp 145-166.
- Pickering, A. "The mangle of practice: agency and emergence in the sociology of science," *American Journal of Sociology* (99:3) 1993, pp 559-589.
- Rogers, E. *The Diffusion of Innovation (4th Ed.)* The Free Press, New York, 1995.
- Schumpeter, J.A. *Capitalism, Socialism and Democracy* Harvard University Press, Cambridge, MA, 1942.
- Svahn, F., Henfridsson, O., and Yoo, Y. "A Threesome Dance of Agency: Mangling the Sociomateriality of Technological Regimes in Digital Innovation," in: *The 30th International Conference on Information Systems*, Phoenix, AZ, 2009.
- Swanson, E.B. "Information systems innovation among organizations," *Management Science* (40:9) 1994, pp 1069-1092.
- Teece, D.J., Pisano, G., and Shuen, A. "Dynamic capabilities and strategic management," *Strategic Management Journal* (18:7) 1997, pp 509-533.
- Tilson, D., Lyytinen, K., and Sørensen, C. "Desperately seeking the infrastructure in IS research: Conceptualization of "digital convergence"," in: *43rd HICSS*, 2010.
- Tripsas, M. "Technology, Identity, and Inertia Through the Lens of "The Digital Photography Company"," *Organization Science* (20:2), Mar 1 2009, pp 441-460.
- Tripsas, M., and Gavetti, G. "Capabilities, cognition, and inertia: Evidence from digital imaging," *Strategic Management Journal* (21) 2000, pp 1147-1161.
- Tuomi, I. *Networks of Innovation: Change and Meaning in the Age of the Internet* Oxford University Press, New York, 2002.
- Tushman, M.L., and Anderson, P. "Technological discontinuities and organizational environments," *Administrative Science Quarterly* (31) 1986, pp 439-465.
- Utterback, J. *Mastering the Dynamics of Innovation* Harvard University Press, Boston, MA, 1994.
- Van De Ven, A.H. "Running in packs to develop knowledge-intensive technologies," *MIS Quarterly* (29:2) 2005, pp 368-378.

- Van De Ven, A.H., Polley, D.E., Garud, R., and Venkatraman, S. (eds.) *The Innovation Journey*. Oxford University Press, New York, 1999.
- Van House, N.A., and Davis, M. "The social life of cameraphone images," Pervasive Image Capture and Sharing: New Social Practices and Implications for Technology Workshop (PICS 2005) at the Seventh International Conference on Ubiquitous Computing, Tokyo, Japan, 2005.
- Verganti, R. 2009. *Design-Driven Innovation: Changing the Rules of Competition by Radically Innovation What Things Mean*. Harvard Business School Publishing, Boston, MA.
- von Hippel, E. "Economics of product development by user: Impact of sticky local information," *Management Science* (44:5) 1998, pp 629-644.
- von Hippel, E. *Democratizing Innovation* MIT Press, Cambridge, MA, 2005.
- West, J. "How open is open enough? Melding proprietary and open source platform strategies," *Research Policy* (32:7) 2003, pp 1259-1285.
- West, J., and Gallagher, S. "Challenges of open innovation: The paradox of firm investment in open-source software," *R&D Management* (36), May 18 2006, pp 319-331.
- Williams, R. 1997. The Social Shaping of Information and Communication Technologies. H. Kubicek, Dutton, William H. & Williams, Robin, ed. *The Social Shaping of Information Superhighways: European and American Roads to the Information Superhighway*. Campus, Frankfurt, 299-338.
- Yoo, Y. "Computing in everyday life: A call for research on *experiential computing*," *MIS Quarterly* 2010.
- Yoo, Y., Boland, R.J., and Lyytinen, K. "Distributed Innovation in Classes of Network," The 41st Hawaiian International Conference on Systems Science, IEEE, Big Island, Hawaii, 2008.
- Yoo, Y., Lyytinen, K., and Yang, H. "The role of standards in innovation and diffusion of broadband mobile services: The case of South Korea," *Journal of Strategic Information Systems* (14:3) 2005, pp 323-353.
- Zittrain, J. "The generative internet," *Harvard Law Review* (119) 2006, pp 1974-2040.