

AN ECOSYSTEM MODEL OF TECHNOLOGY EVOLUTION

Gediminas Adomavicius
Jesse C. Bockstedt
Alok Gupta
Robert J. Kauffman

Information and Decision Sciences
Carlson School of Management, University of Minnesota
Minneapolis, MN 55455
{gadamavicius, jbockstedt, agupta, rkauffman}@csom.umn.edu

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ABSTRACT

We propose a new conceptual model for understanding technological evolution that identifies the impact of social (e.g., market, economic, and political forces) and technological forces. We build on theories from technological forecasting, technology evolution, and innovation research to develop the concept of a *technology ecosystem*. By considering the influence of social forces, technical forces, and the interplay between the two we demonstrate that layers of technology naturally arise. These technology layers are identified as *components, products and applications, and support and infrastructure*. We postulate that the evolution of component technologies is driven primarily by technical forces, while product and application evolution is driven by both social and technical forces, and the evolution of support and infrastructure is driven primarily by social forces. We also classify specific types of technology evolution processes by identifying the *paths of influence* that help shape the nature of technological innovations. The model provides insights for technology development and forecasting, which is demonstrated through mini-cases on the digital music and data storage industries.

Keywords: Technology ecosystem, technology evolution, innovations, social forces, technology forecasting, ecological perspective, environmental analysis, data storage, digital music

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1. INTRODUCTION

Technologies are constantly evolving, driven by research and development, as well as by consumer and corporate demand for new products and applications. Firms attempt to understand the nature of technological change and evolution to create accurate forecasts, take advantage of investment and market opportunities, and maintain or grow market shares. There has been extensive research on the nature of innovation and technological change which provides many theories for technological forecasting and technology evolution. Social forces (e.g., market environment, societal and political pressures), technical forces (e.g., research and development, dominant designs, and the capabilities of firms), and the interplay between the two have been recognized by many researchers as drivers for innovation and technology evolution (Dosi 1982, Schmookler 1966, Sahal 1985, Christensen 1992, von Hippel 1988).

The diffusion of innovations and adoption of new technologies have been extensively explored. Bass (1969) introduced a model for the adoption of new products in terms of innovative and imitative behavior. Dewar and Dutton (1986) empirically tested whether different models are needed to predict the adoption of radical innovations and incremental innovations. Loch and Huberman (1999) introduce a punctuated-equilibrium model of technology diffusion that incorporates evolutionary aspects of technological change. Bass and Bass (2001, 2004) discuss the diffusion of technology generations in the context of quickly evolving information technology (IT) products. Their research considers “IT waves” and models the impact of multiple technology generations on consumer adoption. Similarly, Kim et al. (2000) develop a dynamic market growth model for the IT market that incorporates interproduct category and technology substitution effects. Moreover, Shocker et al. (2004) propose a taxonomy of possible intercategory relationships to describe the effects of “other products” on product demand and adoption.

Another stream of research explores the product development and the management of the innovation process. Van de Ven (1986) identifies the basic problems management faces when dealing with innovation. They include the human problem of managing attention, the process problem of managing new ideas into good currency, the structural problem of managing part-whole relationships, and the strategic problem of institutional leadership. von Hippel (1994, 1998) explores the impact of “sticky”

information (i.e., costly to acquire, transfer, and use) on the innovation process. Additionally, von Hippel (1983) demonstrates the impact of users on product development by showing that semiconductor and electronic subassembly manufacturing equipment is first developed by the users and then transferred to equipment manufacturers. Furthermore, Balakrishnan and Jacob (1996) propose the use of genetic algorithms to apply natural selection techniques to the product design process.

Other researchers have explored the impact of the environment on innovation. Gjerde et al. (2002) show that the structure of the internal and external environment in which a firm operates impacts its decision to innovate. Simon (1973) notes that “the decision to apply technology is made in the matrix of our social institutions” (p. 1110). Porter et al. (1991) describe the interrelation between technology and society in the context of socio-technical change. Mowery and Rosenberg (1979) argue that insights on the nature of technological change can be gained by considering demand-driven views of innovation in concert with the views of firm capability-driven innovation. Adner and Levinthal (2001) develop a demand-based view of technology evolution that focuses on the interaction between technology development and the demand environment. Similarly, Clark and Guy (1998) review two linear models of innovation: a “technology push” model in which basic ideas in science are reorganized to create innovations with commercial potential, and a “demand pull” model, which describes the innovation process as stemming from market demand.

Based on the prior literature, we believe it is necessary to recognize both social and technical drivers of innovation. Additionally, individual technologies cannot be considered in isolation during discussions of innovation and technology evolution. In our view, there is an opportunity to develop a model that describes the nature of technological change and evolution as a *technology ecosystem*. Technology changes feed upon themselves and can drive changes in society, as concepts are refined and developed. Similarly, society is constantly changing and producing conditions that drive new technological changes. In this paper, we adopt a symbiotic view of social and technological forces to develop a model that considers multiple sources of influence in technology evolution. Our model demonstrates that *three distinct forms of technology*—component, product and application, and support and infrastructure—arise

from the *interplay between the technological and social forces that drive innovation*. It outlines a technology ecosystem that provides insights for technology development and forecasting.

The term *technology ecosystem* best describes our model because of its parallels to the traditional notion of an ecosystem, which is a habitat for a variety of different species that co-exist, influence each other, and are affected by a variety of external forces (such as climate changes and natural disasters). The evolution of one species in an ecosystem affects and is affected by the evolution of other species. Similarly, there are many factors that influence the evolution of a specific technology and our model considers the interrelated set of technologies and forces (especially social and technical forces) that may impact innovation, development, and adoption. The strength of such an ecosystem view of technology evolution is that it provides a robust and comprehensive picture of innovation by considering multiple sources of influence. Through our proposed model, we seek to answer the following research questions:

- How can we explain the evolution of a technology and account for the social and technological forces that influence its development?
- How can related technologies and their evolution be modeled with respect to the analysis of the evolution of a given technology?
- How can a new model of technology evolution be leveraged in managerial settings for technology development decision making and forecasting purposes?

We validate our model by analyzing mini-cases involving digital music and data storage technologies.

2. MODELING THE TECHNOLOGY ECOSYSTEM: A NEW THEORETICAL PERSPECTIVE

Our model provides an ecosystem view to explain technology evolution. According to Ziman (2000), technical innovations in an industry are so interrelated that one might describe it as an *ecological system of co-evolving artifacts*. We refer to *technology* generally as Dictionary.com does—the application of science, especially to industrial or commercial objectives—and our definition is not restricted to material objects. We use the term *technology evolution* to refer generally to the change of technology over time including the development of new technologies and refinement of existing technologies. We recognize

that the biological definition of evolution is not completely analogous to our discussion of the evolution of technologies. Biological evolution assumes blind (or natural) and random drivers for selection and variation and it can be argued that technical change is fueled by the planned process of design (Ziman 2000). Our research is based on the general understanding of evolution presented above and does not explore the debatable differences between natural biological evolution and technological change.

First, we identify *technology-shaping forces* that act as drivers of technological change. Second, based on the technology-shaping forces, we identify *technology layers* to represent three different forms of technology. Third, we discuss *time* and *paths of influence* to classify types of technological innovations. The combination of these concepts enables a new *model of technological change and evolution*.

2.1. Technology-Shaping Forces

Society is continuously evolving in its environment, market, and social aspects. It develops new needs and uses for technology, thus driving innovation. At the same time, technology is continuously improving, building on pre-existing technologies, often exceeding the capacity of society to fully adopt it. Prior research has shown that there is an important interrelationship between technology and society in the context of technological evolution. Frick (1974) identifies two broad classifications of technological forecasting based on two philosophical viewpoints of technological process. First, the *ontological view* holds that science and technology change in response to scientific and technical opportunities.

Technology is seen as a self-generating process, and thus, if one observes this process and gathers appropriate data on its past and present behavior, conclusions can be drawn concerning its future course. The second viewpoint, the *teleological view*, holds that science and technology change in response to social, economic, political, and other factors in the total environment. In this view, technology is a servant or by-product of society.

Other research has also recognized the importance of both social and technical forces in the analysis of technology evolution and forecasting. Porter et al. (1991) identify *structural technology forecasting methods* that analyze the relationship between technology and context. For example, the senior

management team of a software firm may feel that the success of their new product depends on the technological improvements in certain brands of personal computers and operating systems, as well as on the rate of adoption of their own product relative to other vendors' products. Similarly, Pacey (1983) proposes a model for technology evolution that combines cultural, organizational, and technological aspects into one system of technology practice. Mokyr's (2000) model involves a double-layered process of technology evolution in which both technological forces (such as manufacturing process refinement) and social forces (such as market pressures) affect the selection and adoption of new technologies. Messersmith and Szyperski (2003) define a software ecosystem that incorporates perspectives from technologists and non-technologists that impact the software industry. They consider users, policy makers, lawyers, engineers, and others in their definition of the software ecosystem. Similarly, Iansiti and Levien (2004) define a business ecosystem related to a specific industry, which emphasizes the need to consider multiple sources of influence (i.e., multiple firms and organizations) for strategic purposes. However, this model was not designed to explain the processes of technology evolution and innovation. Building on the concepts outlined above we suggest that the forces and needs impacting technological change and evolution can be generalized into two broad categories: *social forces* and *technical forces*.

Social forces are pressures from societal, economic and market-based, and political sources that shape technological innovation. Vincenti (2000) argues that any complete model of technological evolution must include the physical world, since the relationship between the technology and the structure of the rest of the world and society can determine the fate of the technology. The *social constructivism in technology* perspective argues that all technology is socially constructed. Thus, it purely reflects the interests of relevant social groups rather than any "selection" on the basis of rational technical criteria (Constant 2000). Social forces can be viewed as *pull effects*: technological innovations are the artifacts of a needs-driven society. For example, current societal and political pressures for cheap, safe, and environmentally-friendly power are drivers of technical innovation in hydrogen fuel cell research. How social forces are shaping technological innovations is apparent in the medical industry too. Political and economic pressures for improved medical care quality, as well as pressures for lower operating costs in

healthcare, are driving development and deployment of electronic medical records. In both examples, social and environmental forces are primary drivers in the development of new technologies.

Technical forces represent pressures and needs for technological change formed by technical barriers and opportunities. In his review of evolutionary economics, Nelson (1995) introduces the *theory of cumulative technology*. It proposes that today's technologies build from and improve upon the technology that previously existed, while tomorrow's technologies build on today's. Nelson suggests that once the gasoline engine had been developed to a point that was demonstrably superior to the capabilities of electrical and steam engines, investments in these alternatives dried up. Instead, resources were focused primarily on gasoline engine development. This, in turn, led to an automotive standard for gasoline engines, and then future innovations built on the new gasoline engine technology. Similarly, evolutionary economics theorists believe that technological innovations come from deliberately planned research. Technical progress occurs as an incremental cumulative process that follows *technological paths* that are evaluated within a selection environment (Duysters 1996). Technical forces can be considered as *push effects* that cause new innovations to be built on the shoulders of scientific discoveries and existing technologies. For example, microprocessor speeds naturally progress to faster levels as a result of refined technological processes and investment in resources dedicated to ongoing development. Similarly, the mega-pixel capacity of CMOS sensors has steadily increased since the introduction of digital cameras. Focusing resources on continued R&D has led to natural technical progress.

Most technological innovations are shaped by the *interplay* between social and technical forces. Our ecosystem model emphasizes the importance of considering the complexity this interplay creates when analyzing technology evolution. For example, consider the Apple iPod. Technologies such as the MPEG Audio Layer 3 (MP3) compression format and high-capacity micro-drives provided the technical push for the iPod. Demand for digital music and mobile devices, the popularity of P2P file sharing, music piracy and legal issues are social forces that "pulled" the iPod into existence as a product. (See Figure 1.)

2.2. Technology Layers

When we discuss technology, we must consider different levels at which innovation and change can

take place. We take an ecosystem-based viewpoint: to understand technology evolution one must analyze the evolution of the *totality of the interrelated technologies*, as opposed to the evolution of a specific technology in isolation. Based on the role they play within an ecosystem, we classify these interrelated technologies into three types: *component technologies*, *product and application technologies*, and *support and infrastructure technologies*. In addition, the interplay between social and technical forces provides an intuitive way to organize the technological innovations into three “layers”: technologies where innovation is driven primarily by technical forces (Layer A); technologies where innovation is driven both by technical and social forces (Layer B); and technologies where innovation is driven primarily by social forces (Layer C). (See A, B and C in Figure 2.) The remainder of this subsection explores the different roles of technology within an ecosystem and their relationships with the three layers defined above.

Figure 1. Social and Technical Forces that Shape Technology

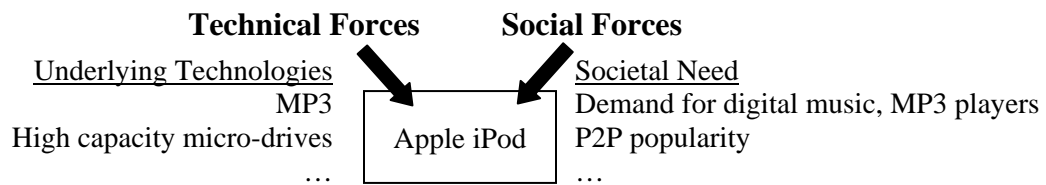
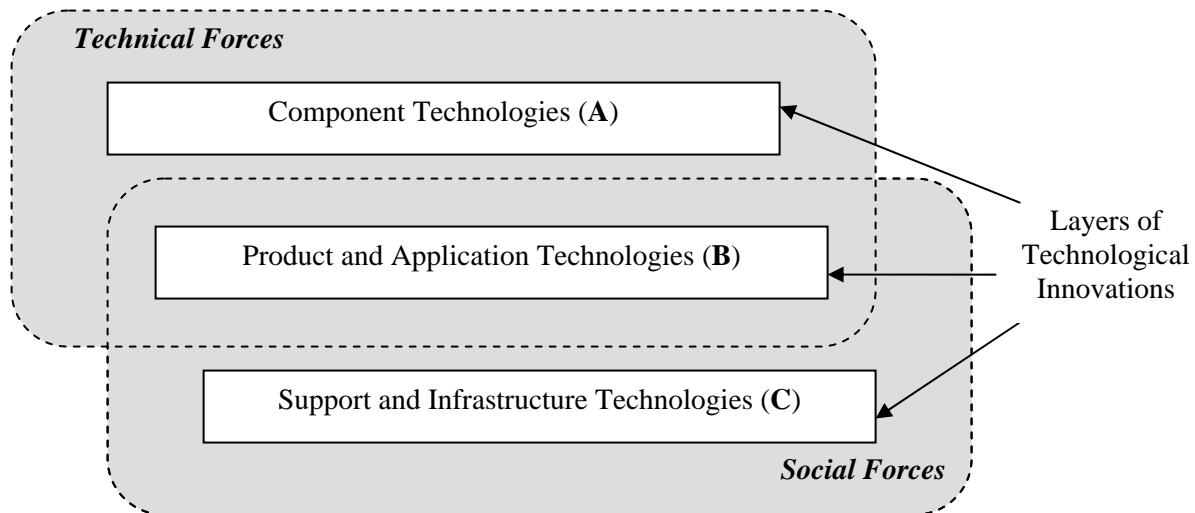


Figure 2. An Ecosystem Model of Technology Evolution: Technology Layers



The *component layer* (Layer A) encompasses technologies that are commonly used as components in complex technologies. Innovation in this layer is driven by technical forces, since component

technologies often begin as tangible examples of theoretical breakthroughs in science or engineering without immediate real world applications. As component technologies are used in products and applications, resources are devoted to ongoing incremental development. Examples of component technologies include microprocessors, hard drives, and carbon nanotubes. Carbon nanotubes are a breakthrough for science and engineering. But real world applications are still far off (Bard 2004) and may require demand in the marketplace for specific applications of the technology to create social value and become successful. This leads to our first proposition:

- **Proposition 1 (Component Technologies Proposition).** Innovations in component technologies are primarily driven by technical forces.

The *product and application layer* (Layer B) represents combinations of component technologies that address a specific societal need. Product and application technology innovations require both the push of existing component technologies and the pull of market demand and social needs. Examples include the personal computer, digital camera, and mobile phone. All of these technologies were built upon innovations in component technologies. But they came into existence and became successful because they addressed specific societal needs and fulfilled readily identified market demand. For example, mobile phones utilize components that range from color liquid crystal displays (LCDs) to microprocessors and solid state storage. On their own, these components do not address any specific societal need. But, in combination with one another, these technologies create products for which there is significant market demand. This leads us to state our second proposition:

- **Proposition 2 (Product and Application Technologies Proposition).** Innovations in product and application technologies are driven by a combination of technical and social forces.

The *support and infrastructure layer* (Layer C) has technologies developed in response to the social forces surrounding product and application technology adoption, diffusion, and use. As Layer B product and application technologies are adopted, technologies that support them emerge. Most microcomputer software is supporting technology for the PC, for example. And, affordable personal photo-quality color printers and digital photo printing kiosks support digital cameras. Our third proposition follows:

- **Proposition 3 (Support and Infrastructure Technologies Proposition).** Innovations in support and infrastructure technologies are primarily driven by social forces.

Many factors can influence the evolution of a specific technology. Technical and social forces shape future innovations by manifesting themselves through the historical evolution and the current state of the technology ecosystem. For example, component technologies can impact innovations in both the product and application layer and the support and infrastructure layer. In particular, component technologies can be combined through the design process to create new product and application technologies. Innovations and improvements in component layer technologies can also drive improvements in the designs of existing product and application technologies. Consider the Intel Centrino mobile chipset. This innovative component technology has driven development of a new series of integrated wireless laptops.

Similarly, component technologies can impact support and infrastructure layer technologies through the development of standards. For example, eXtensible Markup Language (XML) can be viewed as a component technology, but as a result of its adoption as an industry standard, a technological infrastructure for web services has been developed for information sharing in electronic commerce (van den Hoven 2000). Note, however, that technologies can also fail if there is a lack of social need or application demand. Integrated services digital network (ISDN) technology was developed in the 1980s as a system for digital phone connections that allows simultaneous transmission of voice and data using end-to-end digital connectivity (Becker 2003). But ISDN never evolved into a successful telecomm infrastructure. It initially lacked an “anchor” application and specific market demand to promote adoption of the technology (Handler 1998). When market conditions were favorable, more advanced technologies were already being developed (e.g., fiber optic networking, Internet, etc.). This is a setting in which both social and technical forces were necessary to drive successful technology innovation.

The technology layers provide the necessary structure for classifying different types of technology in a given ecosystem. Component technologies are pieces that only achieve value when they are combined to produce a product or application. Product and application layer technologies address a specific societal need and require component layer technologies to exist. Support and infrastructure layer technologies

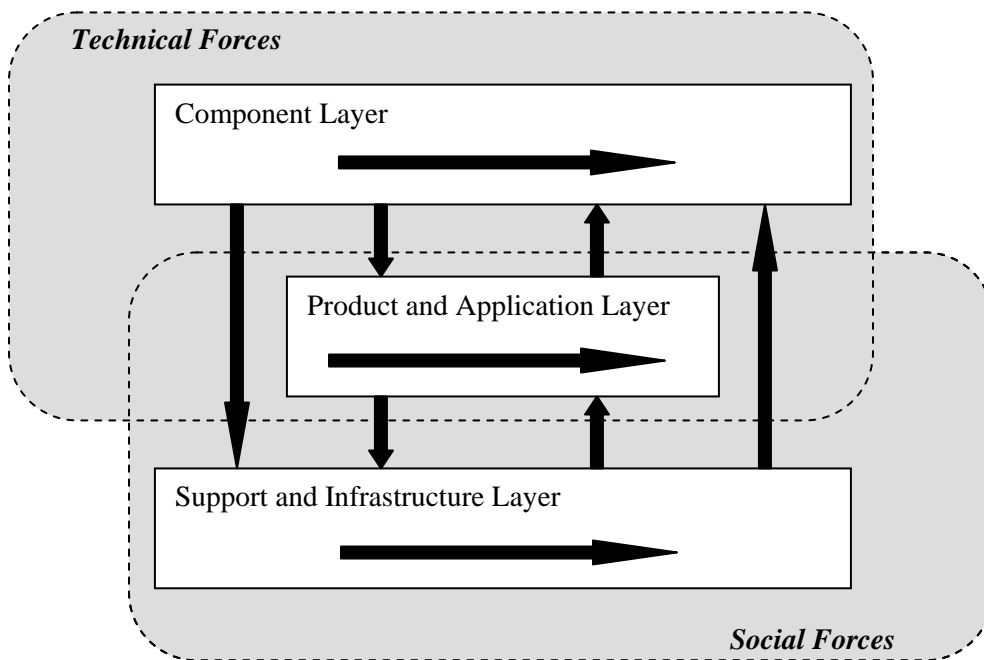
typically exist to facilitate improving the business and social value of applying the product layer technologies. Each layer’s innovations can influence the other layers. But a specific technology’s evolution cannot be analyzed alone. Robust and comprehensive analysis of technology evolution must consider the component, product and application, and support and infrastructure technologies involved.

2.3. Temporal Aspects of Technology Ecosystem: Evolution and Paths of Influence

To provide the conceptual structure for understanding technological evolution, we combined the technology-shaping forces and our three technology layers that comprise the technology ecosystem. These layers can influence themselves or any other layer based on the underlying technological and social forces that drive technological innovations. For instance, a component technology can evolve into a newer version, which can then drive innovations in the other two layers.

Technologies change over time and any comprehensive model of technological evolution must consider the *temporal aspects* of such change. To represent the influence that current technologies have on future technologies, we define *paths of influence* within a technology ecosystem. (See Figure 3.)

Figure 3. Technology Ecosystem Model Constructs: Technology Layers and Paths of Influence

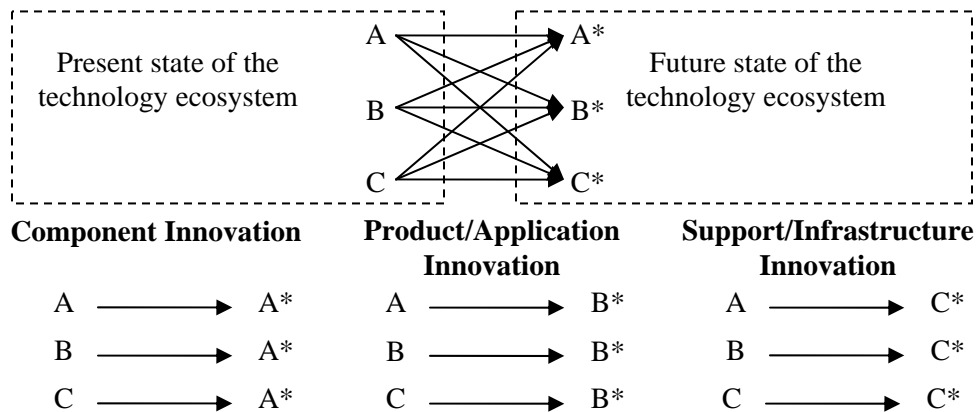


Note that paths of influence occur within or across technology layers and describe relationships between technology layers over time. Let the component layer be represented by State A, the product and

application layer by State B, and the support layer by State C. Layer A can influence technology developments in layers A, B, or C and technology evolution can take many paths through the layers within a technology ecosystem. Paths of influence are possible between any of the current states (States A, B, C) and any of the future states (States A*, B*, C*).

We classify the paths of influence into three groups according to the resulting innovation. Paths from any current state to the component future state (A*) are *component-oriented paths of influence*. Similarly, paths that end with B* are *product-oriented paths of influence* and paths that end with C* are *support-oriented paths of influence*. (See Figure 4).

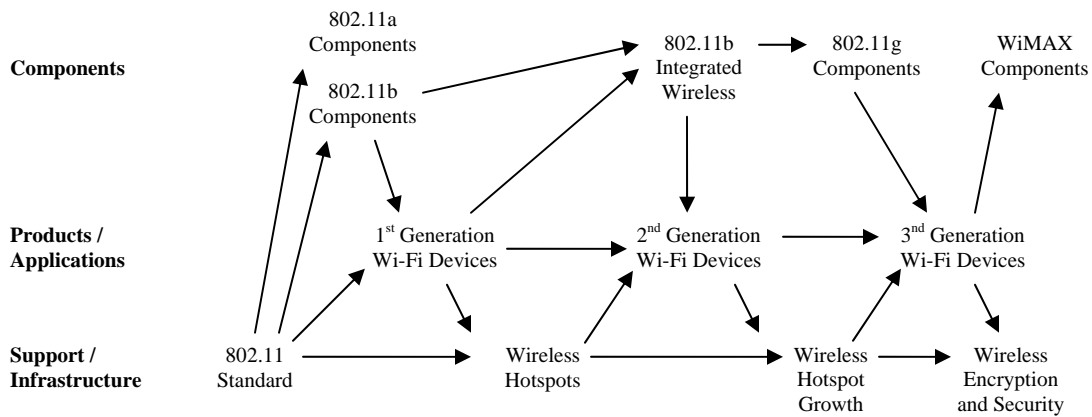
Figure 4. Paths of Influence within a Technology Ecosystem



An Example: Wi-Fi Technology Evolution. To provide a temporal view of a technology ecosystem, it is necessary to consider the entire ecosystem of technology innovations. Figure 5 depicts the paths of influence in the evolution of Wi-Fi technologies. Innovations in and adoption of product layer technologies have driven both component and support layer technologies. The demand for mobile laptop computers, wireless network interface cards, and Wi-Fi base stations facilitated the evolution of Wi-Fi component technologies from the original 802.11a and 802.11b equipment to the more powerful 802.11g components and eventually to long distance WiMAX components (Economist 2004). These component innovations have built on their predecessors as well as on advances in product and support technologies. Similarly, product technologies have advanced from add-on Wi-Fi PC adapters, to laptops

with integrated 802.11g chipsets (e.g., Intel Centrino technology). As Wi-Fi-enabled devices have become widely adopted, improvements in supporting technologies have emerged. These include low cost, wide coverage Wi-Fi base stations and new encryption technologies, such as Wired Equivalent Privacy (WEP) and Wi-Fi Protected Access (WPA). The market success of wireless technologies and the growth of wireless network coverage are additional drivers in the continuing development of wireless technology. Innovations within the Wi-Fi technology ecosystem are interdependent and further drive technologies within each of the technology layers.

Figure 5. Representation of a Fragment of the Evolution of Wi-Fi Technology



This Wi-Fi example makes it apparent that an ecosystem view of technology evolution provides useful insights, and that our representation of the paths of influence provides a systematic way to classify the temporal impacts that technological innovations have on each other within a technology ecosystem.

3. CLASSIFYING TECHNOLOGY INNOVATIONS WITH PATHS OF INFLUENCE

When we consider the temporal aspect of technology evolution there are many paths innovation can take. As we introduced before, innovations in component technologies can influence innovations in product and application technologies as well as support and infrastructure; product and application innovations can influence component and support and infrastructure technologies; and innovations in support technologies can drive changes in product and application technologies or component technologies. We next explore each path of influence in detail and provide supporting examples.

3.1. Component-Oriented Paths of Influence

Component technology innovation occurs primarily in response to technical forces and needs, as a result of breakthroughs in science and engineering as well as by building on existing component technologies. These technical forces can be triggered by new developments in the product and support layers, which may have resulted from social needs and pressures.

Component Evolution ($A \rightarrow A^*$). The component evolution path of influence occurs as the result of continued research and development in component technologies. As component technologies are used in product and application technologies, resources are invested in continued development and a natural evolution results. Moore's law is a classic example of component evolution. It states that the processing power of integrated circuits will double every 18 months. Similarly, Gene's Law states that power consumption of integrated circuits will decrease exponentially over time. Due to the continued resource investment in development and research, these rules have held true and microprocessor performance has steadily evolved over time. We have seen similar improvements in digital camera mega-pixel resolution and in the battery life of mobile phones. In this case, existing components often provide a strong foothold for the innovations that result in next generation components.

Product-Driven Component Development ($B \rightarrow A^*$). As products become successful, demand for improved component technologies increases. Improved components may be cheaper, higher performing, or smaller in size, but in all these cases the component innovations can be driven by the success of the product technologies that use them. For example, the success of the DVD player has driven the development of new DVD component technology equipment: blue-ray readers, writers, and discs. Blue-ray DVDs are recordable and have higher storage capacity than the original red-ray technology permitted. Fast adoption of DVD players helped fuel the development in these component technologies. Similarly, the widespread adoption of mobile phones and PDAs has fueled development in component technologies, such as solid state storage and color liquid crystal displays. Without product technology success, there is a lack of demand for component technologies and, therefore, component technology innovation.

Infrastructure-Driven Component Development (C→A*). The expansion and development of infrastructure and supporting technologies can also drive component technology developments. For example, the expansion of the Internet and World Wide Web led to advancements in the underlying component technologies, such as Dynamic HTML (DHTML) and XML, router and communication technologies, security and encryption, and many others. Growth of support and infrastructure technologies means that more products and applications are in use, with the result that there is higher demand for component technologies. While the development and evolution of support and infrastructure technologies is primarily in response to the social success of product and application technologies, support technologies can also use component technologies in their design. For example, while self-service photo printing kiosks are a support technology for digital cameras, they also help drive the development of the components they use.

3.2. Product-Oriented Paths of Influence

Innovations in the product and application layer are driven by both social and technical forces.

Design and Compilation (A→B*). Product technology innovations develop through the unique compilation of component technologies and design processes. For example, digital cameras combine core component technologies such as image sensors, color capture equipment, storage devices, lenses, and battery technologies. Similarly, PDAs combine component technologies such as microprocessors, communication devices, and touch screen technologies. Engineers and designers must understand the user, social setting, and available technology to fit social needs with technological solutions. Social forces such as demographics, religion, law, social psychology as well as the technological forces of available component technologies can shape the design process of product and application technologies.

Product Integration and Evolution (B→B*). Product and application layer technologies can be integrated to create new products. Additionally, they can evolve to include new features, versions, or designs. For example, camera phones are a product layer technology that integrates a cell phone with a digital camera. The Dell Axim X3i PDA is an updated version of the original X5 that has a faster processor, more memory, integrated Wi-Fi, and other additional features. Product technologies naturally

evolve as designs are refined and updated to include new features, eliminate unnecessary features, or simply to fix bugs. Software companies regularly release updated versions of their products, such as email clients and word processors, which have minor improvements or refinements, but relatively unchanged core component technologies. In this path of influence the primary drivers of innovation are the existing product technologies and the social needs and market demand that surround them.

Infrastructure-Leveraging Product Opportunities (C → B*). Once an infrastructure or set of supporting technologies exists, there is an opportunity for additional products to be built that leverage this infrastructure and support. For example, the wide adoption of instant messaging has created a support layer for the introduction of new technologies, products, and services distributed through the instant messaging client. Examples are games, downloads, and file transfers. Similarly, the diffusion of mobile phones and wireless networks provides opportunities for new products and services such as camera phones and text messaging. The forces at work are technological and social. This process leverages support technologies and requires an understanding of the existing technological and social environments.

3.3. Support-Oriented Paths of Influence

Support and infrastructure technologies evolve to meet social needs created by widespread adoption of product and application technologies.

Standards and Infrastructure Development (A → C*). New component technologies directly influence the support and infrastructure technology layer by supporting or creating new standards and infrastructure. For example, XML by itself can be viewed as a component technology. However, when industry leaders and government bodies agreed to make it a standard for describing data, a support technology was created. Selecting a set of component layer technologies as a standard can create the infrastructure to support future products, applications, and services. The use of radio frequency identification tags (RFID) tags is another example. At first glance, RFID tags are a straightforward component technology. However, when an industry leader such as Wal-Mart announces all of its suppliers must comply with RFID supply chain management, support and infrastructure technologies develop. The primary forces at work in standards and infrastructure creation are political and economic.

Business alliances or consortia may decide to adopt a component technology to increase network competition, improve supply chain efficiency, and promote industry growth. Similarly, government bodies may select a standard or implement infrastructure based on a component technology for regulation purposes. For example, a standardized electronic medical record specification would promote ease of data transfer among healthcare systems in the American medical system.

Diffusion and Adoption (B→C*). Products and applications that lead to infrastructure and supporting technologies do so through wide diffusion and adoption. Popular products present an opportunity for the development of supporting technologies. PCs have become ubiquitous in both corporate and home environments. The Microsoft Windows operating system, in turn, has become a widespread support technology for PCs. Additionally, Windows has created an opportunity for additional supporting technologies and infrastructure, such as internetworking and database technologies. Another example is apparent from the rapid adoption of the digital camera, and the collateral emergence of digital photo-editing software, affordable personal photo-quality color printers, and self-service digital photo printing. The primary forces at work in this path of influence are social and economic. Adoption and diffusion is fueled by exposure, word of mouth, price, quality, and usability.

Support Evolution (C→ C*). While the development and evolution of support and infrastructure layer technology is primarily in response to adoption and diffusion of product and application technologies, natural evolution of support technologies also takes place. For example, cell phone networks have grown in size over the past twenty years to provide wider coverage areas and new services for users. In the past five years there has been an increase in the number of Wi-Fi hotspots and Wi-Fi support and infrastructure. Another example of a continually evolving support layer technology is the expansion of the Internet. As more and more users log on, new technologies are necessary to support effective communications and improve the cost economics and the telecommunications capabilities.

Table 1 summarizes the paths of influence and emphasizes one of the major contributions of our *ecosystem model of technology evolution*: a classification of technological innovations. (See Table 1.)

3.4. An Ecosystem Model of Technology Evolution

We combine the paths of influence defined above with our conceptual model to represent our ecosystem view of technology evolution. (See Figure 6.) Technologies exist in layers and technology-shaping forces create paths of influence that drive innovations within each layer. The effectiveness of the ecosystem-based model is its ability to capture the dynamic nature of technology evolution. Our model provides structure for understanding the continuous interplay between the technical and social forces, the needs of society, and the dynamics between various technology forms within an ecosystem.

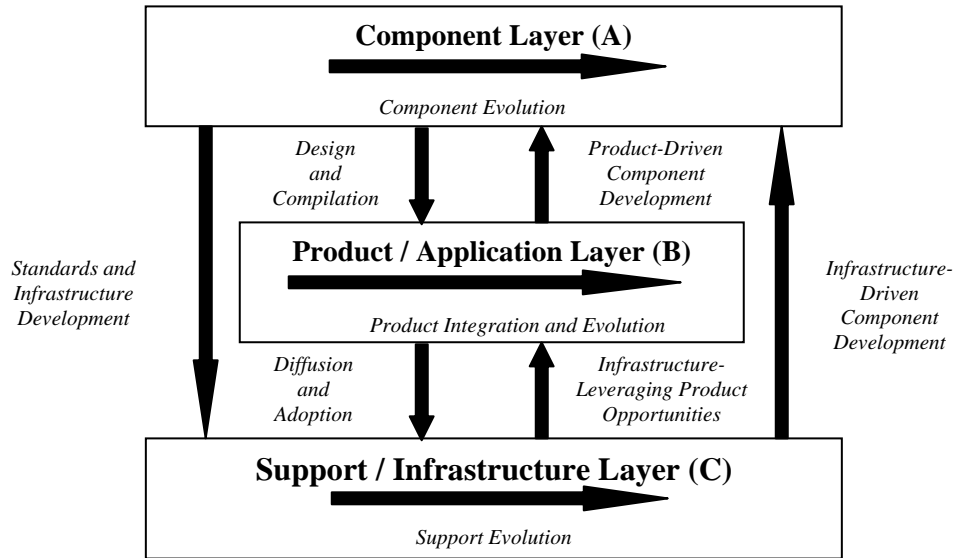
Table 1. Paths of Influence: Characteristics and Examples

	COMPONENT-ORIENTED PATHS OF INFLUENCE	PRODUCT-ORIENTED PATHS OF INFLUENCE	INFRASTRUCTURE-ORIENTED PATHS OF INFLUENCE
	A*	B*	C*
A	Component Evolution Examples: microprocessors and Moore's law, digital camera mega pixels.	Design and Compilation Examples: digital camera, iPod, personal computer	Standards and Infrastructure Development Examples: XML, RFID
B	Product-Driven Component Development Examples: Blue-ray DVD, Microsoft Janus	Product Integration and Evolution Examples: camera phones, Dell Axim X3i PDA	Diffusion and Adoption Examples: digital camera infrastructure, software applications designed for Windows OS
C	Infrastructure-Driven Component Development Examples: Internet technologies, 802.11g WiFi equipment	Infrastructure-Leveraging Product Opportunities Examples: instant messaging services, picture mail	Support Evolution Examples: growth of mobile cellular phone network, Internet, Planet Lab

The technology evolution and innovation processes are complex and include a combination of influences. So, the development of a new technology or improvements to an existing technology may be triggered by multiple paths of influence. Referring back to Figure 5, the development of second generation wireless devices, such as laptops with integrated wireless chipsets, was influenced by innovations in all three technology layers. The value of our ecosystem model is that it provides both descriptive and prescriptive analysis viewpoints of technology evolution. For example, a cell phone manufacturer can be more accurate in its product adoption forecasts by considering the newest innovations in related component, infrastructure and support, and other product technologies. Similarly, a

struggling wireless component manufacturer can evaluate the current state of the wireless technology ecosystem to support strategic decisions.

Figure 6. Full Conceptual Model of a Technology



4. MODEL VALIDATION

To support the validation of our model, we explore two mini-cases of business technology evolution: the recent innovations in the digital music industry and the development of intelligent storage technologies. We apply the concepts of the ecosystem model to explain the roles and relationships of technologies and create predictive capabilities for industry players operating within the ecosystem including manufacturers, suppliers, product developers, and service providers, among others.

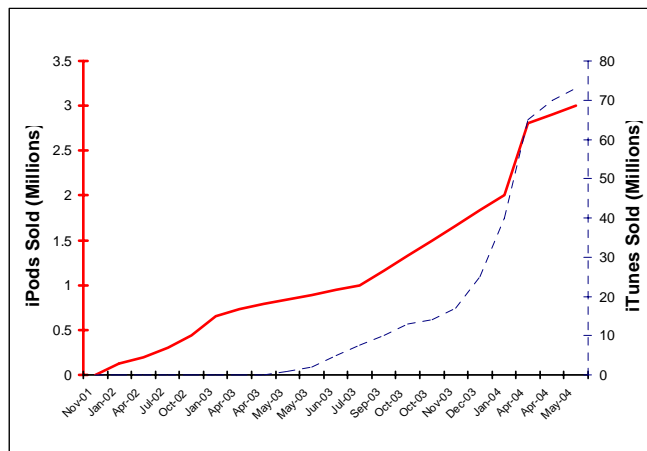
4.1. Mini-Case I: Innovations in the Digital Music Industry

In recent years, consumer demand has grown dramatically for digitally-formatted music files, players, and services, and a new digital music market has developed with many technological innovations and rapid consumer adoption. For example, the number of people who have purchased digitally-formatted songs from Apple iTunes increased from 861,000 in July 2003 to 4.9 million in March 2004 (Borland and Fried 2004). The digital music industry involves multiple players that include artists, record labels, Internet service providers, online digital music retailers, and electronics and computer manufacturers.

The MP3 audio compression format, originally patented in Germany in 1989, was patented in the United States in 1996, and the first portable MP3 player became available commercially in the US in 1998. In 1999, peer-to-peer file sharing networks gained rapid acceptance, sparking legal battles and the development of new encryption and file-tracking technologies. In 2001, mass storage digital music players entered the scene and, shortly thereafter, digital music retailers made deals with the major record labels to offer digitally formatted music tracks for sale online.

The technologies are evolving quickly in the digital music industry. For example, consider the popular Apple iPod MP3 player. The first incarnation of the iPod was made available for sale in October 2001. It included a 5 GB hard drive, was compatible only with Apple computers, and was priced at \$399. In March 2002, a 10 GB iPod was released with a price of \$499. In July 2002, PC-compatible versions were released including a 20 GB model. In addition, a new touch-sensitive scroll wheel was introduced on the 10 GB version, and prices dropped: to \$299 for 5GB, \$399 for 10 GB, and \$499 for 20 GB. In April 2003, Apple’s third generation iPods were released alongside the new iTunes Music Store. Figure 7 depicts the rapid adoption of Apple iPods and the use of the iTunes music service. Notice that as consumers continued to adopt the iPod player, the supporting music service iTunes grows in popularity. Specifically, note that as sales of iPods reached 1.5 million, the sales of iTunes began to increase rapidly.

Figure 7. Sales of iPods and iTunes



Source: iPodLounge.com

The digital music industry is a dynamic environment with rapidly evolving component, product, and support technologies. The ecosystem model of technology evolution provides a lens for viewing its interrelated technologies. A manager working for a portable digital music player manufacturer must consider the entire digital music ecosystem when making strategic decisions. A leading question for analysis is: How does the portable digital music player manufacturer identify the important technologies and relationships to pay attention to in the dynamic digital music ecosystem? We answer with our model.

Identifying Technologies. Using the technology ecosystem view, we can see that technology innovation in the digital music industry portrays a complexity that goes beyond the statistics of new iPods and iTunes sales. Innovation is occurring at the component level, the product and application level, and the infrastructure and support level. At the component level, the evolution of smaller-sized hard disk drives has led to large-capacity digital music players, like the new 40 GB iPod. Flash Media solid-state storage has made it possible to develop more rugged small players, like the Creative Nomad MuVo. Similarly, MP3 and other compression technologies, encryption technologies (e.g., digital watermarking), and new interface designs provide the technical underpinnings of the digital music industry. At the product level, digital music files and streaming audio have given consumers a new music format, and portable digital music players are among the most popular consumer electronic products available today. In addition to the iPod, companies such as Dell, Creative, Rio, iRiver, and Sony all offer portable digital music players with storage capacities ranging from 64 MB to 40 GB in a variety of sizes and shapes.

At the infrastructure and support level, online digital music retailers such as Apple iTunes, Sony Connect, and Microsoft's MSN Music support digital music players and the consumers who use them by providing complimentary products and services. Griffin Technology produces an entire product line of accessories that include FM transmitters, voice recorders, and car chargers that specifically provide support for the Apple iPod. Additionally, digital music file standards have developed as players in the music industry have created specific support networks for their products. For example, Apple iPod and iTunes are designed to work with music files formatted in the AAC standard, while MSN Music supports Microsoft's WMA standard. Innovation and technology evolution is occurring rapidly and through many

paths in this industry. Table 2 provides our classification of the component, product, and support technologies in the digital music industry. (See Table 2.)

Identifying Paths of Influence. Besides identifying the technologies within the ecosystem, the manager must also consider the relationships between technologies. Component and support and infrastructure technologies helped shape the current digital music market and provide opportunities for digital music products. The simultaneous development and adoption of peer-to-peer networks and the MP3 format ($A \rightarrow C^*$ and $C \rightarrow A^*$) helped to fuel their joint success and, in turn, the development of the first portable MP3 players ($C \rightarrow B^*$ and $A \rightarrow B^*$). Adoption and diffusion of portable digital music players has further led to the development of new support technologies, such as online music stores and accessories ($B \rightarrow C^*$); and has promoted research and development of better encryption, storage, and interface technologies ($B \rightarrow A^*$). Moreover, at all three levels of technology, we see the occurrence of continuous incremental evolution. At the product level, new versions of digital music players are being released ($B \rightarrow B^*$). At the infrastructure level, online music stores and P2P services are providing new and innovative services ($C \rightarrow C^*$). And at the component layer, underlying technologies such as storage and encryption have been evolving and becoming less expensive ($A \rightarrow A^*$).

Table 2. The Digital Music Technology Ecosystem

LAYERS	TECHNOLOGIES
Component (Layer A)	Hard disk drives Solid-state (flash media) storage MP3 compression format Small electronics components Interface designs and software Encryption technologies (Microsoft Janus, watermarking)
Product/Application (Layer B)	Digital music players (Apple iPod, Creative Nomad MuVo, Rio Carbon, Sony Network Walkman) MP3 music files Digital music audio streams
Infrastructure/Support (Layer C)	Digital music playing services (Windows Media Player, Real Player) P2P networks (KaZaA, Morpheus, WinMX) Online music services (Apple iTunes, Sony Connect, Real Networks Rhapsody, MSN Music) Standards (AAC, WMA, RealAudio) Accessories (Griffin Technology)

Insights and Opportunities. Our ecosystem model of technology evolution provides interpretive structure for the dynamic environment of digital music technology evolution. Classifying the important technologies and relationships within the digital music ecosystem offers a way to decompose a complex and dynamic system into a set of technologies and relationships. This allows analysts to focus on specific issues while considering the many factors within the ecosystem. Portable digital music manufacturers can now create a dashboard of specific component, support, and competing product technologies to monitor. They also can identify potential product opportunities based on the impact of innovations in related technologies. For example, Apple recently announced the release of the iPod Photo, a portable digital music player with the ability to store and display digital photos. A competing digital music player manufacturer can recognize that the evolution of color LCD screens and disk drives made this product innovation possible. Also, the manufacturer may forecast that digital video will be adopted, along with the services supporting the distribution of these files. The ecosystem model of technology evolution forces the analyst to consider the interrelatedness of all technologies within the ecosystem.

4.2. Mini-Case II: Development of Intelligent Storage Technologies

Over the past 25 years, hard disk drive (HDD) areal density has increased steadily as the number of bits stored per unit of HDD media has about doubled every year since 1980. Over the same time, HDD prices have decreased by about five orders of magnitude (\$/MB), and the cost of storage systems has fallen about 2.5 orders of magnitude (Morris and Truskowski 2003). Storage systems and storage devices have evolved to combine raw storage capabilities (such as HDDs) with layers of hardware and software to provide storage products that are reliable, manageable, high performance solutions to match demand for data storage. Among the most important social forces driving storage technology evolution is the fact that data storage is being increasingly treated as a strategic resource by firms (CXO Media 2003). Storage technologies continue to evolve and a recent trend in the data storage industry is the development of autonomic or *intelligent storage technologies*.

Intelligent storage will impact component, product and application, and infrastructure and support technologies within the data storage ecosystem and is likely to become the new focus of the industry.

While the industry lacks a clear definition of “intelligence” in the context of storage technologies, the University of Minnesota Digital Technology Center Digital Intelligent Storage Consortium (DISC) offers the following explanation (dte.umn.edu/programs/disc_what.html):

- Intelligence implies that the storage devices not only store data, but they are aware of the data objects and storage resources contained within the storage device.
- Intelligence further implies that the storage device can act on those objects and manage its storage resources explicitly or implicitly.
- Intelligence also implies that the storage device can be made aware of the data object content (what is inside the data object) and possibly the context (how they relate to other data objects and the rest of the world) also.
- Finally, intelligence implies that a generic intelligent storage device can be taught to perform new tasks dynamically as the data requirements and the world around it change.

As intelligent storage systems develop, players in the data storage ecosystem must consider the opportunities these new technologies provide. Specifically, data storage device manufacturers will want to identify the important applications of intelligent storage technologies and capitalize on these new trends. In the first mini-case we demonstrated how a player in the digital music industry can apply the ecosystem model. Here we illustrate the use of this model for technology forecasting purposes. In particular, we focus on one specific aspect of the data storage industry and show how the model can be used to provide insights about the future evolution of intelligent storage technologies. The leading question is: What kinds of insights can a storage device and systems manufacturer draw about the evolution and application of intelligent storage technologies?

Identifying Technologies. By adopting the technology ecosystem view of technology evolution, the manufacturer can identify the component, product and application, and infrastructure and support technologies involved in data storage evolution. The manufacturer can also identify examples of the types of innovations that have emerged (and have the potential to emerge) in the data storage industry. Raw storage technologies include HDDs, tape, and optical storage and can be thought of as component

layer technologies. These technologies provide the technological foundations for products and applications in the data storage industry. However, to become useful in the industry, these raw storage technologies must be integrated with other technologies to form storage products that satisfy specific storage needs. Product layer technologies include electronic devices that use storage components (e.g., PCs, PDAs) in addition to specifically designed storage systems and storage devices.

An HDD could once be considered a storage system and a product to the manufacturer, but storage systems have evolved to include other value-adding services, such as connectivity and maintenance functionalities that support the need for highly usable data storage ((Morris and Truskowski 2003). As storage systems have evolved, so too have the infrastructure layer technologies that support the widespread use of these systems. For example, many specific protocols have been developed to provide consistency in storage system operation. The Network File System (NFS) and the Common Internet File System (CIFS) have become standard network protocols for storage system communication. Similarly, as communication technologies such as Ethernet LAN and TCP/IP have become more widely adopted, networked storage systems, such as Storage Area Network (SAN) and Network Attached Storage (NAS), also have become more commonly used. Table 3 classifies existing storage technologies that the device manufacturer can use as a starting point for understanding the data storage ecosystem. (See Table 3.)

Table 3. The Storage Technology Ecosystem

LAYER	TECHNOLOGIES
Component (Layer A)	Hard disk drives Tape-based storage Optical storage (DVD, CD) Solid-state storage (RAM, flash) Computer interfaces (serial, parallel, IEEE 1394 Firewire, USB, SCSI, PCMCIA, ATA, Fiber Channel)
Product/Application (Layer B)	Enterprise storage systems (RAID, SAN, NAS, object-based) Microcomputers / laptops Servers Personal devices (MP3 players, digital cameras, PDAs, personal video recorders)
Infrastructure/Support (Layer C)	Ethernet Internet and database connectivity Communication protocols (HTTP, FTP, TCP/IP) File systems (NFS, CIFS, OSD file systems)

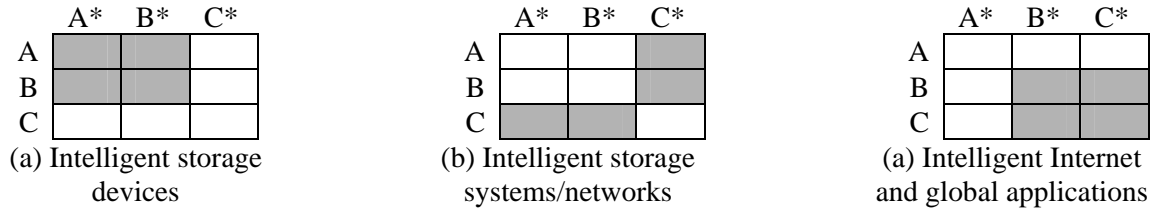
Identifying Paths of Influence. Based on the prior definitions of intelligence in the data storage industry and our classification of the core storage industry technologies, we can identify technical and social forces that may impact the development of specific intelligent storage technologies. Continuous research innovations in raw storage technologies drive the increase in HDD capacity ($A \rightarrow A^*$). The need for personal devices with stable interchangeable storage capabilities, such as PDAs, drives innovations in flash media and other solid state storage technologies ($B \rightarrow A^*$). From a component and supporting technology perspective, Fiber Channel became a predominant networking technology ($C \rightarrow A^*$) when large storage systems such as IBM TotalStorage Enterprise Storage Server used the protocol to attach multiple storage servers and build storage networks (Hartung 2003). Similarly, the development and adoption of Ethernet LAN and TCP/IP technologies has increased interest in SAN technologies (Morris and Truskowski 2003) ($C \rightarrow B^*$). The CIFS and NFS file system protocols evolved to become standards in the storage industry and thus part of the storage industry infrastructure ($A \rightarrow C^*$). In addition, the popularity of the Fiber Channel medium helped to fuel the innovation of networked storage support technologies ($A \rightarrow C^*$). In the data storage industry, the Internet has provided opportunities for wide coverage networked storage, and the FTP and HTTP protocols provide opportunities for storage device communication and database connectivity ($C \rightarrow C^*$).

Based on these trends the data storage system manufacturer can predict that intelligent storage devices will expand the functionality of existing storage systems through software layer programming and the integration of additional hardware ($A \rightarrow B^*$, $B \rightarrow B^*$). The manufacturer can further expect that there will be continued adoption of object storage devices that incorporate attribute-based object-oriented file systems into traditional storage devices ($C \rightarrow B^*$).

Insights and Opportunities. The manufacturer can recognize that the data storage ecosystem is evolving to include intelligent storage technologies. Based on the classification of the core storage technologies and the recognition of existing relationships between technologies, the manufacturer may predict that intelligent storage technologies are being developed in all technology layers and will likely be

applied in three key areas: devices, systems and networks, and the Internet and global applications. Based on the paths of influences prevalent in these three areas of development, the manufacturer would be able to identify three corresponding patterns of technological innovations. (See Figure 8.)

Figure 8. Evolutionary Patterns in the Intelligent Storage Technologies Ecosystem



In the development of intelligent devices, the manufacturer is likely to see simultaneous component evolution and the design of new products and applications (Figure 8a). As intelligent systems and networks evolve, they will incorporate new component and product technologies to provide the support infrastructure for the emerging storage needs (Figure 8b). Additionally, the Internet will continue to become more intelligent and provide the supporting infrastructure technologies for global and distributed applications (Figure 8c). Below we provide examples to illustrate these evolutionary patterns.

First, devices can develop intelligence by using object and attribute-based storage techniques and providing support for specific file types. These techniques use advanced file systems to provide smarter and faster searches as compared to the current *de facto* standard hierarchical file systems. For example, Microsoft’s next generation operating system, Longhorn, will utilize an attribute-based file system (Ricciuti 2002) to simplify searches and increase usability. Storage component technologies such as HDDs for PCs and storage product technologies such as enterprise storage devices will evolve to support and improve on this intelligence ($A \rightarrow A^*$). Similarly, the emergence of small (mobile) personal electronic devices, such as MP3 players and PDAs ($A \rightarrow B^*$), has created a greater demand for storage devices that are high in capacity, smaller in size, and extremely stable ($B \rightarrow A^*$). These personal devices may have specific storage application needs based on the type of data being stored. Storage technologies such as high capacity micro drives and solid state storage will likely evolve as components and provide intelligent support for small electronic devices ($A \rightarrow A^*$). “Smart” personal media devices that utilize attribute based

storage techniques could evolve to meet consumer media management requirements ($A \rightarrow B^*$, $B \rightarrow B^*$).

For example, personal digital media devices can potentially incorporate storage devices that manage large photo and video collections based on attributes such as the location of a recording or the subject.

The second area for intelligent storage development is in system and network use. Businesses and organizations rely on storage systems to provide functionality that reduces management and maintenance costs while simultaneously providing for increased data availability (Morris and Truskowski 2003). Additionally, the general trend towards networked storage systems also raises support issues. Intelligent storage technologies are being developed to address various support issues, such as maintainability, recovery, and network and system performance ($C \rightarrow A^*$, $C \rightarrow B^*$). For example, DISC is investigating technologies for decentralized secure file sharing (Kher and Kim 2003) and parallel archival systems using object storage devices (www.dtc.umn.edu/programs/DISC_projects.html). DISC is also developing potential uses for non-hierarchical, attribute-based file systems and functionality. Recognizing the demand for intelligent storage products to address business needs we can predict that self-maintaining, self-evaluating, and self-repairing “smart” storage systems will likely evolve to provide value to firms that manage large amounts of data and provide rich content to consumers. Intelligent storage components will provide the foundation for the development of these products and supporting technologies ($A \rightarrow B^*$, $A \rightarrow C^*$). Administrators will potentially be able to roll back to any past state of a storage system for file recovery to support the maintenance needs of storage systems and networks.

The expansion of global communications and the growing and interconnected reach of the Internet also provide opportunities for storage technology evolution. As Internet users’ storage requirements evolve, so will the technologies that support them. Storage device manufacturers may develop “smart” products, applications, and supporting technologies to manage the large capacity complex storage issues of the internet. For example, Google’s new email system, Gmail, offers subscribers 1 GB of space for personal email storage and utilizes a search engine technique for mail organization. This signals a new trend for online free storage and storage products. These products will likely evolve to manage large amounts of data across the Internet using intelligent storage technologies ($B \rightarrow B^*$). The current research

being conducted by the PlanetLab project provides another example of global and Internet based storage trends. PlanetLab is a multi-institutional effort to replace the current “dumb” Internet with a much smarter network capable of monitoring itself for viruses and worms, managing traffic, and providing portable personal computing environments and storage to any terminal on the planet (Roush 2003) ($C \rightarrow C^*$). PlanetLab is implementing “smart” nodes to increase the intelligence of the Internet and increase its usability ($B \rightarrow C^*$, $C \rightarrow B^*$). Smart nodes will allow users to access files and desktops anywhere they have Internet access regardless of location.

By identifying the important technologies and relationships within the data storage ecosystem, manufacturers can create the structure necessary to understanding the evolving data storage industry and its use of intelligent storage technologies. The ecosystem view of technology evolution provides analysts with a tool for dissecting the interplay between the multiple factors in the process of technology evolution. In the data storage industry we considered component, product and application, and infrastructure and support technologies, as well as the technical forces and potential social forces that drive innovation in storage technologies. Our model also provided the structure necessary to make realistic predictions about the evolution of intelligent storage technologies and helped identify important opportunities for new products, components and services that use intelligent storage technologies.

5. DISCUSSION AND DIRECTIONS FOR FUTURE RESEARCH

In this paper we have presented a model for understanding technology evolution through the lens of a technology ecosystem. We identified technology shaping forces, technology layers, and paths of influence to provide structure to the highly dynamic system of interrelated technologies involved in the evolution of technology. We used exploratory research methods to identify relationships and issues related to the ecosystem model of technology evolution that will provide structure for future research.

We recognize that there are some limitations that must be addressed in the ecosystem model of technology evolution. First, defining the boundaries of an ecosystem may prove to be a difficult task especially in highly complex information systems and high-tech industries. Ecosystems may overlap and

it is up to the user of the model to define boundaries for analytical purposes. Second, it should be noted that as technologies evolve, the role a technology plays within an ecosystem may change. As ecosystems become more complex, product technologies may be considered component technologies and the analyst may find difficulties clearly classifying all the technologies involved. This model is meant to provide a starting point for the analysis of the interrelated technologies within an ecosystem.

The future directions for research incorporating the ecosystem model are abundant. Our first charge is to develop empirical research methods to understand the characteristics of the ecosystem model. Specifically, we plan to focus on identifying the important characteristics of the nine paths of influence identified in the model and analyzing whether some paths of influence are more dominant under certain circumstances. We hope to investigate and compare the paths of influence at both the firm and industry level to fully develop a generalized ecosystem model of technology evolution. Additionally, we hope to investigate how specific relationships between technologies within an ecosystem affect the outcome of technology evolution. We also recognize that ecosystems and technologies within different industries will behave differently. We plan to validate our model further by working with experts in specific context areas (such as intelligent storage and digital music) to further refine our model.

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