TECHNOLOGY ROLES IN AN ECOSYSTEM MODEL OF TECHNOLOGY EVOLUTION

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ABSTRACT

We propose a new conceptual model for understanding technological evolution that highlights dynamic and highly interdependent relationships among multiple technologies. We propose that, when technology evolution is discussed, a single technology cannot be considered in isolation. Instead, we argue that technology evolution is best viewed as a dynamic system that includes the totality of interrelated technologies. We build on theories from technological forecasting, technology evolution, and innovation research to develop the concept of a *technology ecosystem*. By considering the interdependent nature of technology evolution, we identify three roles that technologies play within a technology ecosystem. These roles are *components, products and applications*, and *support and infrastructure.* Technologies within an ecosystem interact through these roles and impact technological evolution. We also classify types of interactions between technology roles, which we term *paths of influence*. The model provides insights for technology development and forecasting. We demonstrate the use of this model through a business mini-case on the digital music industry.

Keywords: Ecological perspective, environmental analysis, innovations, paths of influence, technology ecosystem, technology evolution, technology forecasting, technology roles.

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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. In this paper, we review a variety of relevant perspectives and propose a new conceptual model of technological evolution that incorporates key concepts from the prior literature and offers new ideas as well.

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) go on to 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) developed a dynamic market growth model for the IT market that incorporates inter-product category and technology substitution effects. Moreover, Shocker et al. (2004) propose a taxonomy of possible inter-category relationships to describe the effects of “other products” on product demand and adoption.

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 the decision to innovate. Simon (1973, p. 1110) notes that "the decision to apply technology is made in the matrix of our social institutions." 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) developed a demand-based view of technology evolution that focuses on the interaction between technology development and the demand environment. Similarly, Clark and Guy (1998) reviewed 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.

A key point of this paper is that individual technologies cannot be considered in isolation during discussions of innovation and technology evolution. Instead, it is necessary to consider the system of interrelated technologies and environmental factors that influence the evolution of a given technology. By considering concepts from two streams of literature, we define a new perspective for analyzing technological evolution, *the technology ecosystem*.[1] The *population approach to technology evolution* from evolutionary economics provides the perspective of viewing multiple interrelated technologies as a population whose characteristics and members change over time (Saviotti 1996). The *technology and product hierarchy approach* to technology evolution identifies specific levels of technologies and the modes of coevolution both across and within these levels (Rosenkopf and Nerker 1999). We introduce a *technology*

[1] Throughout the paper we introduce a number of terms used in our conceptual model. A table summarizing these terms and their definitions can be found in the appendix.

ecosystem approach that considers a complex system of determinants of evolutionary outcomes. This system includes a population of interrelated technologies with specific *technology roles* and overlapping *technology hierarchies*, as well as a set of *external environmental forces* that shape technological evolution. This paper defines the major constructs of the technology ecosystem perspective, including three specific roles that technologies can play within an ecosystem: the *component* role, the *product and application* role, and the *support and infrastructure role*.

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. Our model considers the interrelated set of technologies and environmental 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 complex system of factors 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 technological innovations in the digital music industry.

2. RELEVANT TECHNOLOGY EVOLUTION PERSPECTIVES

According to Ziman (2000), technological innovations in an industry are so interrelated that one might describe them as occurring in 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 the 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, whereas technical change is fueled by the planned process of design (Ziman 2000).

In the development of our technology ecosystem model we build on concepts from two streams of prior research. First, we review the population perspective of technology evolution from evolutionary economics. Second, we review key concepts of coevolution within product and technology hierarchies.

2.1. The Population Approach to Technology Evolution

Although it is out of the scope of this paper to debate the differences between natural biological evolution and technological change, the biological analogy does provide some grounding for the evolutionary economic approach to technological change. Saviotti (1996) describes the key concepts of the *evolutionary approach* to economics by summarizing relevant literature across economics, organizational science, and biology. Variation, selection, reproduction, and inheritance are common concepts in biological theories of evolution that can be carried over to the discussion of technological evolution. Similarly, fitness and adaptation are key metrics for analyzing success and predicting evolutionary outcomes. The evolutionary approach typically considers a population and three possible types of interaction between pairs of species (Maynard Smith, 1974, p. 5). The first is *competition*: each species has an inhibiting effect on the other. The second is *commensalism*: each species has an accelerating effect on the growth of the other. The final one is *predation*, in which one species (the "predator") has an inhibiting effect on the growth of the other (the "prey") which has an accelerating effect on the growth of the predator. In economics, these interactions can translate into forms of competition and collaboration between firms (Saviotti 1996). For example, Metcalfe and Gibbons (1989) define *innovation competition* as technological differences between firms that results in continuous change in the economic performance of firms. Finally, an evolutionary approach typically considers the influence of external environments on evolutionary outcomes.

Of the concepts above, we are most interested in the population approach to technology evolution. Saviotti and Metcalfe (1984) argue that technologies are best represented by their technical characteristics and service characteristics. The former refers to the internal structure of a technology and the latter captures services performed by a technology. The *population perspective* (Saviotti and Metcalfe 1991) focuses on the importance of acknowledging the variance and differences in properties among the members of a population.[2] With respect to technological evolution, analysis using the population perspective considers a population of technologies represented as a "cloud of points" in "characteristics space" (Saviotti 1996).

Over time, the properties of technology populations can change. For example, population density can change, a single population may fragment into multiple subpopulations, and individual populations may converge to form a new population. Within the population

[2] The *population perspective* is the opposite of the *typological perspective* often used in the biological sciences, which states that a given species (or class of products) can be adequately represented by the properties of the average or representative individual within the species (class of products).

perspective, Saviotti (1996) proposes five basic processes in a model of technology evolution: birth, death, incremental innovation, technology transfer and diffusion, and emergence of new technological populations.

2.2. The Hierarchical Model of Technology Evolution

The population perspective provides a basis for considering a system of multiple technologies in the process of evolution. But to analyze and describe the *structure* of the population we look to the literature on product and technology hierarchies. It is intuitive to think of complex products and technologies as *systems* (Tushman and Rosenkopf 1992) and *hierarchies* (Clark 1985). In fact, several studies have considered the interdependent relationships among evolving components of complex technologies. (See Henderson and Clark 1990, Iansiti and Khanna 1995, Tushman and Murmann 1998 for examples.)

Rosenkopf and Nerkar (1999) provide a thorough review of the relevant literature on technological evolution within hierarchies. Their summary identifies three distinct levels within a technology hierarchy: components, products, and systems. Products are comprised of identifiable components and are coordinated into systems of use. Complexity arises in the analysis of the technological evolution within hierarchies because interdependent technologies may coevolve within each level of the hierarchy (*within-level coevolution*) and evolution at any level can impact evolution across other levels of the hierarchy (*cross-level coevolution*).

Tushman and Rosenkpf (1992) point out that evolution of “leading” components or “core subsystems” can spark evolution in other technologies at the same level of the hierarchy. For example, a key advancement in microprocessor design by one firm may cause other firms to achieve new design innovations to stay competitive, thus exemplifying a within-level coevolution of components.

Cross-level coevolution is more closely related to ideas in biology. One such idea is *downward causation* from Campbell (1990, p.4), who states: “the laws of the higher level selective system determine in part the distribution of lower level events and substances. […] For biology, all processes at the lower levels of a hierarchy are restrained by, and act in conformity to, the laws of the higher levels.” For an example in technological evolution, consider that a design of a personal computer may become obsolete or be replaced with a new one, and thus drive the obsolescence or new innovation of the components it used. Another concept known as *whole-part coevolutionary competition* (Campbell 1994, Rosebkopf and Nerkar 1999) applied to technology evolution suggests that selection among variants at one level of a technology hierarchy can conflict with selection at other levels.

3. MODELING THE TECHNOLOGY ECOSYSTEM

Considering the concepts of the population perspective, the product hierarchical model and new insights from our own research, we develop a new conceptual model for analyzing technological evolution. This section develops the major concepts of our model.

3.1. The Motivation for the Ecosystem View

Our initial motivation for this model stemmed from a review of common technological forecasting methods. We found that there were numerous methods that consider multiple approaches—from analytical extrapolation of trends to expert panel discussions. (See Frick 1974 and Porter et al. 1991 for examples.) The most important conclusion we developed from this review was that forecasting technological evolution is extremely complex and difficult. Many factors impact the development of a technology and it is nearly impossible to accurately capture the influence of them all. We looked to evolutionary economics, organizational theory, and even biology to gain insights. Biological ecosystems are composed of a population of organisms (including enemies such as predators, parasites etc.), a set or resources, and external environmental forces. The idea of an ecosystem struck us as an intuitive way of representing a set of coevolving technologies.

Iansiti and Levien (2004) define a *business ecosystem* related to a specific industry, which emphasizes the need to consider multiple sources of influence (e.g., multiple firms and organizations) for strategic purposes. However, their model was not designed to explain the processes of technology evolution and innovation. In the following sections, we develop our ecosystem model of technology evolution, focusing on the roles technologies play within an ecosystem and the interactions that are mediated by these roles which shape the evolution of technologies.

3.2. Defining the Ecosystem View

The population perspective gives a conceptual view of multiple related technologies existing as a single population. In the model presented by Saviotti (1996), a population consists of specific technologies (such as personal computer models) that are similar based on technical and service characteristics. We extend this view to consider a population of technology classes based on the interdependence between each class. For example, our view of an ecosystem of personal computer technologies includes the PCs themselves, as well as the components (hard disk drives, processors), competing technologies (laptops), and peripheral or collaborating technologies (printers, software, scanners).

We posit that, within the technology ecosystem, multiple overlapping hierarchies exist that capture the interdependent relationships between technologies. From the PC example above, it is apparent that component-level technologies are necessary for the development of PC technologies. Similarly, peripheral technologies such as software and printers require the existence of the PC technologies to add value to the system of use. The hierarchal nature of products and technologies identifies specific roles that technologies can play within the ecosystem. By acting through these roles, classes of technologies can influence the evolution and development of each other within the ecosystem.

Additionally, an ecosystem model must consider the influence of external environmental forces on the evolutionary outcomes of technologies. Specifically, we argue that three major types of external environmental forces exist: social and governmental forces, economic forces, and technical forces. *Social and governmental forces* are pressures from societal and political sources that shape technological innovation. For example, 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). *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*. This theory proposes that today's technologies build from and improve upon the technology that previously existed, while tomorrow's technologies build on today's. Similarly, evolutionary economic theorists believe that technological innovations come from deliberately planned research. *Economic forces* are captured by market dynamics and the demand for new products and technologies. For example, Mokyr's (2000) model of technology evolution considers market pressures as a driver of the selection and adoption of new technologies. These external forces are complex and important in the shaping of technological evolution. However, in the remainder of this paper, we will focus on the roles which technologies themselves play within an ecosystem and leave further discussion of the nature of external forces for future research.

3.3. Technology Roles

Based on the relationships within an ecosystem, we identify three roles that technologies can play within an ecosystem: *component, product and application, and support and infrastructure.*

The *component role* identifies technologies that are used as components in more complex technologies. For example, there are several technologies that act as components for the personal computer: RAM chips, microprocessors, hard disk drives, etc. When a technology acts as a component, the more complex technology depends on the component to function. This is an important relationship in the ecosystem because individual technologies can act as components in multiple technologies and contain components themselves. For example, take the hard disk drive. It acts as a component in PCs, MP3 players, and many other devices. But the hard disk drive also has a set of component technologies itself. They included DC spindle motors, actuators, and platters, and so on.

The *product and application role* identifies technologies that use components to perform a set of functions or satisfy a set of needs. Technologies in the product and application role compete with other technologies in this role. They are defined by the components they use and the services they provide. For example, an MP3 player plays a product and application role because it is composed of several components and is designed to provide a specific service to its user. Additionally, MP3 players can compete with related technologies such as CD players, and satellite radio devices.

The *support and infrastructure role* identifies technologies that work in conjunction or collaboration with, or as a peripheral to other technologies. The distinction between the component role and the support and infrastructure role is that components are necessary for the design and are part of the physical structure of a technology, while support and infrastructure technologies simply work in combination with other technologies. A key point about the support and infrastructure role is that technologies add value to the technologies they support. For example, a printer is not physically necessary for the design and use of a PC, but it supports the PC's functionality, and together they provide additional value and services to their users.

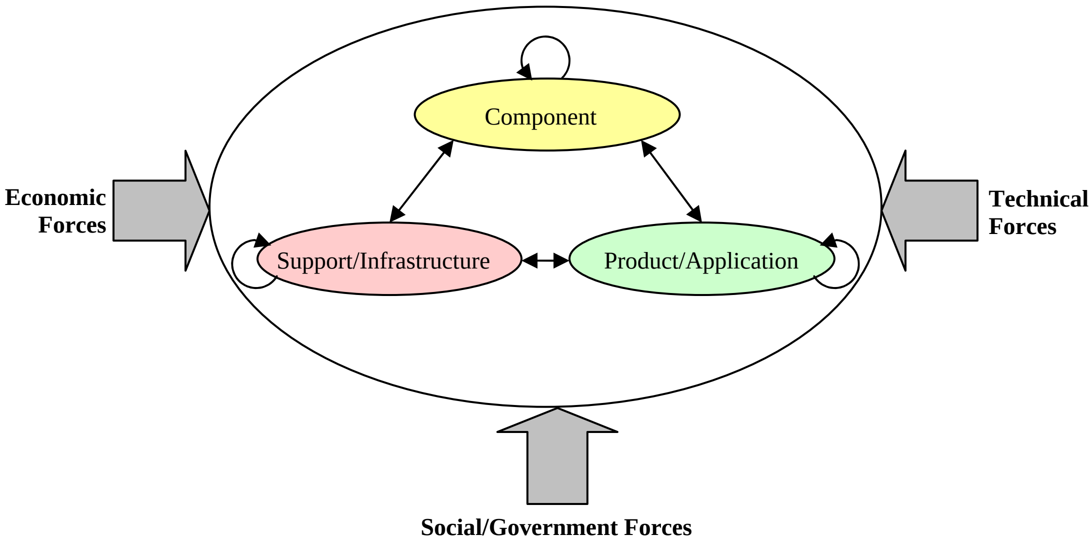
From the definitions above it is obvious that, depending on the perspective, technologies can play multiple roles within an ecosystem or across multiple ecosystems. This is an important aspect of the perspective that we offer in this paper. A technology ecosystem is meant to be a view of a system of interrelated technologies.

3.4. Identifying the Technology Ecosystem

Figure 1 captures our model by emphasizing the multiple relationships that exist within a technology ecosystem. Technologies act through roles in the ecosystem and can influence technologies in the same role or other roles. Additionally, external environmental forces help shape the dynamics of the ecosystem. Figure 1 does not include hierarchical structures because, while product hierarchies may exist, our model is more focused on capturing relationships between technology roles, which may or may not be hierarchical in nature.

The general view of an ecosystem can be very complex, with technologies playing multiple roles and having multiple relationships. In practice, however, an analyst is interested in performing a specific analysis of a specific set of technologies. A *specific* ecosystem view is defined by identifying the technologies and their roles that are relevant to the analysis at hand. The analyst defines a focal technology and a context for identifying the relative technology ecosystem view. Then the analyst can identify the technologies immediately related to the focal technology within the given context. For example, a product manager in a PC manufacturing firm may wish to better understand the dynamic nature of the technologies used for wireless communication (the context) related to the PC (the focal technology).

Figure 1. The Technology Ecosystem



3.5. Steps for Identifying Technologies and Their Roles

We next propose a set of steps to help an analyst identify a specific technology ecosystem, which consists of the various technologies that are related to the focal technology.

- **Step 1 (Identification of Focal Technology).** The manager should choose a focal technology, or a starting point for mapping out the ecosystem, and a specific context for identifying related technologies. A natural choice would be the product produced by her company (e.g., a personal computer) with a context related to a specific business decision (e.g., wireless technology).
- **Step 2 (Identification of Competing Technologies).** The manager should identify any other types of technologies that compete with the focal technology to provide the same service or functionality. These correspond to technologies playing the product and application role with respect to the focal technology. For example, laptop computers, personal digital assistants, and servers may all be classes of technologies competing with

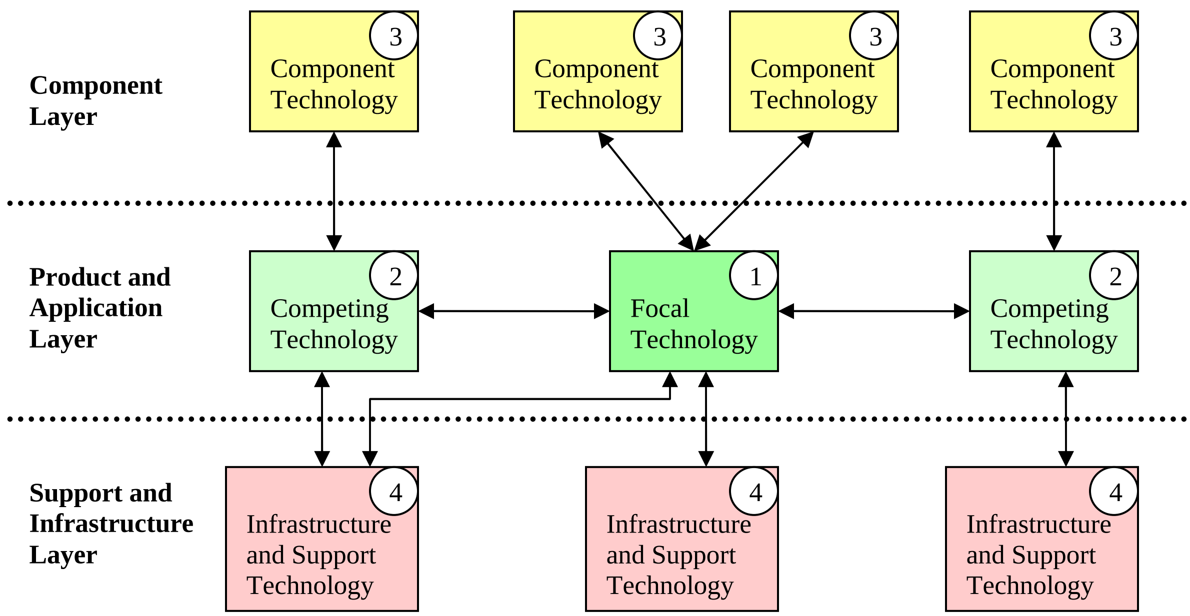
the focal class.

- **Step 3 (Identification of Component Technologies).** The manager should identify the various technologies that are used as components in the focal technology and its competing technologies. This set of technologies plays the component role with respect to the focal technology.
- **Step 4 (Identification of Support and Infrastructure Technologies).** The managers should next identify the various technologies that use and work with the focal technology or its competitors to increase value to the user. These technologies play the support and infrastructure role with respect to the focal technology. Technologies that support the focal technology should be identified, as well as the technologies that the focal technology supports. From the previous example, this can include printers, scanners, and software.

Thus, the process that we specified provides a view of the ecosystem that is centered on the focal technology and pertains to the given context. In a specific ecosystem view, a *technology layer* is defined by a set of technologies playing the same role with respect to the focal technology. Therefore, by following the process above, the analyst will be able to reliably produce a view that captures the three basic layers of relationships for the focal technology and provides a starting point for identifying potential interactions in the ecosystem. (See Figure 2.)

Figure 2 outlines the process of identifying an ecosystem view of a focal technology. The numbers correspond to the steps in the process above. This process provides the *first level* of analysis: it considers the focal technology and technologies *immediately* related to it. The ecosystem view could be expanded to consider additional levels of analysis, such as the components of components of the focal technology. For the remainder of the paper, we will analyze an ecosystem view at this first level of analysis only and further explore how technologies in this ecosystem can affect each other over time.

Figure 2. Identifying the Technology Ecosystem Relative to a Focal Technology



4. CLASSIFYING TECHNOLOGY INNOVATIONS WITH PATHS OF INFLUENCE

To provide the conceptual structure for understanding technological evolution, we defined the technology ecosystem and the roles technologies can play within this system. Technologies can influence other technologies in the same role or in the other two roles in the ecosystem. For instance, a component technology can evolve into a newer version, which can then drive innovations in the products, and the support and infrastructure technologies.

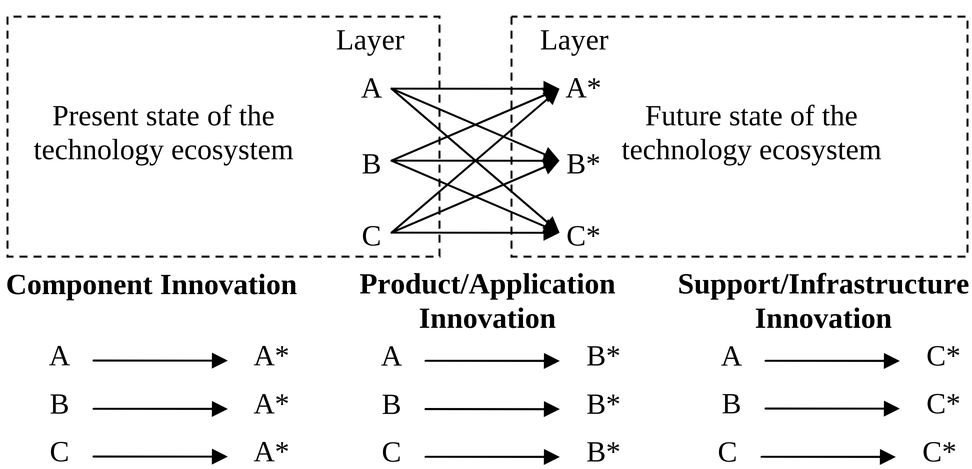
4.1. A Primer on Paths of Influence

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. As we demonstrated in the previous section, identifying the technology ecosystem relative to a focal technology generates layers of technologies based on the roles they play with respect to the focal technology. Paths of influence occur within or across these technology layers within the ecosystem and they describe relationships between technology layers over time.

For notational simplicity, let A, B, and C denote the present state of the *component layer, product and application layer*, and *support layer*, respectively, and let A*, B*, and C* denote the future states of these layers. Paths of influence are possible between any of the current states (A, B, C) and any of the future states (A*, B*, C*). Therefore, technology evolution can take many paths through the layers within a technology ecosystem. For example, the current component technologies (A) can potentially influence the development of new product technologies (B*), representing a specific path of influence A→B*.

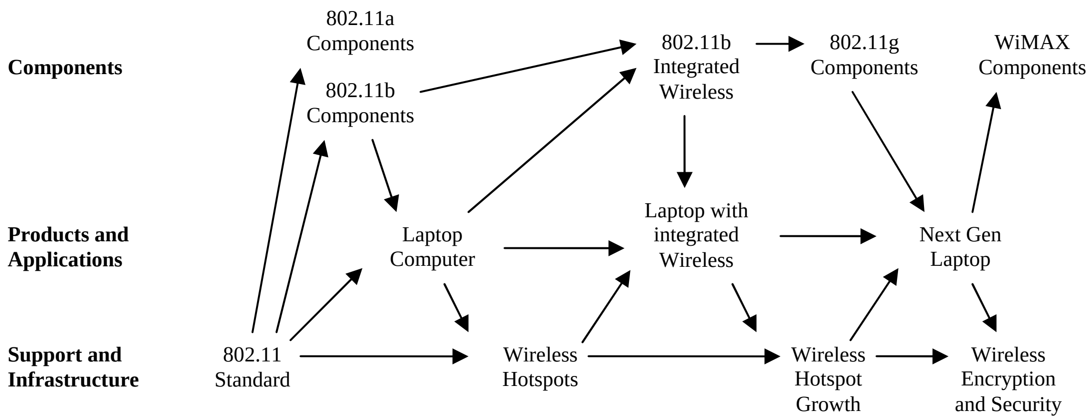
We classify the paths of influence into three groups according to the resulting innovation. Paths from the current state of any layer to the future state of the component layer (A*) are *component-oriented paths of influence*. Similarly, paths that end with B* are *product-oriented paths of influence* and paths that end with C* are *support-oriented paths of influence*. (See Figure 3.)

Figure 3. Paths of Influence between Technology Layers in a Technology Ecosystem



Example: Wi-Fi Technology Evolution. Consider laptop computers as a focal technology, and the ecosystem context as Wi-Fi technologies. Figure 4 depicts the paths of influence in the evolution of Wi-Fi technologies.

Figure 4. A Representation of a Fragment of the Evolution of Wi-Fi Technology



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 innovations in the component layer 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.

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 between technology layers provides a systematic way to classify the temporal impacts that technological innovations have on each other within a technology ecosystem. We next explore each path of influence in detail and provide supporting examples.

4.2. Component-Oriented Paths of Influence

The component evolution path of influence occurs as the result of continued research and development in component technologies.

Component Evolution (A→A*). 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 an integrated circuit doubles 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→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.

4.3. Product-Oriented Paths of Influence

Product technology innovations develop through the unique combination of component technologies and design processes.

Design and Compilation (A→ B*). 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. The evolution of available component technologies can shape the design process and in turn impact the outcome 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.

Infrastructure-Leveraging Product Development (C →B*). Once an infrastructure of technologies exists, there is an opportunity for new products to leverage this 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 include 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.

4.4. Support-Oriented Paths of Influence

Support and infrastructure technologies evolve to meet the 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 that all of its suppliers must comply with RFID supply chain management, support and infrastructure technologies develop. 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 easier 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.

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, 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.

4.5. Paths of Influence: Summary

Table 1 summarizes the paths of influence between technology layers, and emphasizes one of the major contributions of our *ecosystem model of technology evolution*: a classification of technological innovations. (See Table 1.) Furthermore, we combine the paths of influence defined above with our conceptual model to represent our *ecosystem view of technology evolution*. (See Figure 5.)

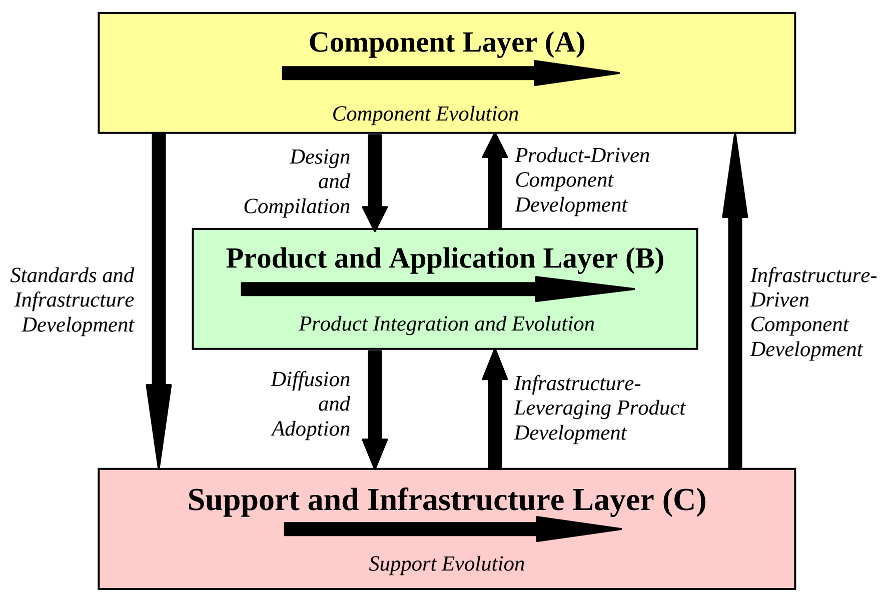
Table 1. Paths of Influence: Characteristics and Examples

	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, MP3 players, PCs	**Standards and Infra-structure Development** Examples: XML, RFID
B	**Product-Driven Component Development** Examples: Blue-ray DVD, Digital Encryption Technology	**Product Integration and Evolution** Examples: camera phones, Wi-Fi enabled PDAs	**Diffusion and Adoption** Examples: digital camera infrastructure, software applications designed for Windows OS
C	**Infrastructure-Driven Component Development** Examples: Internet technologies, 802.11g Wi-Fi equipment	**Infrastructure-Leveraging Product Development** Examples: instant messaging services, picture mail	**Support Evolution** Examples: growth of mobile cellular phone network, Internet 2.0

The effectiveness of the ecosystem-based model lies in its ability to capture the dynamic nature of technology evolution. Our model provides structure for understanding the dynamics between various technology forms within an ecosystem.

We noted before that 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 4, the development of second generation wireless devices, such as 802.11b network interface cards and 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 5. Paths of Influence between the Technology Layers: A Conceptual Diagram



5. MODEL APPLICATION: AN ANALYSIS OF THE DIGITAL MUSIC INDUSTRY

We now provide a fuller demonstration of the analysis approach that our ecosystem model of technology evolution permits in the context of the digital music industry.

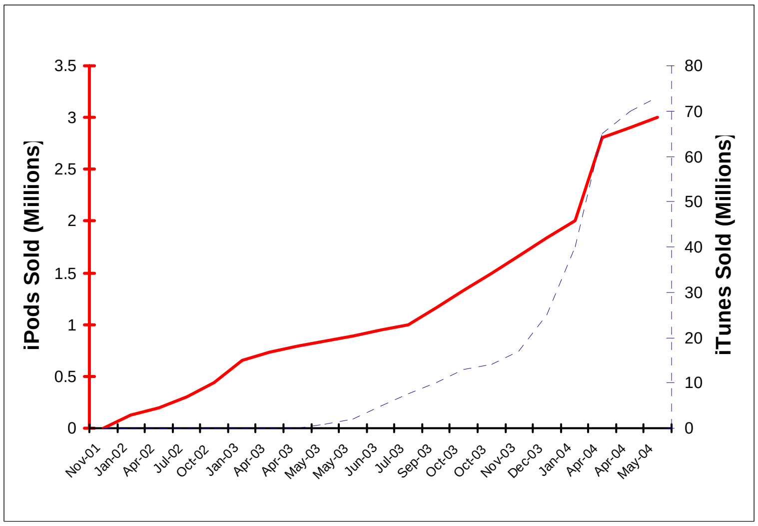
5.1. Background of the Digital Music Industry

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 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: artists, record labels, Internet service providers, online digital music retailers, and electronics and computer manufacturers. The MP3 audio compression format was originally patented in Germany in 1989. It was patented a second time in the United States in 1996, and the first portable MP3 player became available commercially there 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 were introduced 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 6 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, grew in popularity. Specifically, note that as sales of iPods reached 1.5 million, the sales of iTunes began to increase rapidly.

Figure 6. 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 product 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? Our model offers a means to answer this question.

5.2. Identifying the Ecosystem: Components, Products and Application, and Infrastructure and Support

Step 1 (Identification of Focal Technology). 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. The MP3 player manufacturer can follow the process outlined in Section 3 to identify the various technologies related to the disk drive-based portable MP3 player.[3] Innovation is occurring at the component level, the product and application level, and the infrastructure and support level—all three levels.

Step 2 (Identification of Competing Technologies). In the product role, there are multiple classes of portable music players. In the digital music class, there are disk drive-based players, such as the iPod and the Dell DJ and flash storage-based players, made by Creative, Rio, iRiver, and Sony. Other portable music devices such as CD players and mini-disc players are other technologies at this level.

Step 3 (Identification of Component Technologies). In the component role, the evolution of smaller-sized hard disk drives has led to large-capacity digital music players, like the 40 GB iPod. Flash Media solid-state storage has made it possible to develop more rugged small players, like the Creative Nomad MuVo. MP3 and other compression technologies, encryption technologies (e.g., digital watermarking), and new interface designs (e.g., iPod click wheel by Synaptics) provide the technical underpinnings of the digital music industry.

Step 4 (Identification of Support and Infrastructure Technologies). Finally, in the infrastructure and support role, digital music files and streaming audio have given consumers a new music format, and the 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 which

[3] We recognize that AAC, WMA, and other digital audio formats are not all considered MP3 formats, but for the purposes of this discussion we use MP3 generally to represent all downloadable compressed digital music files.

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. Table 2 provides our classification of the component, product, and support technologies in the digital music industry with respect to the disk-drive based portable MP3 player. (See Table 2.)

Table 2. The Digital Music Technology Ecosystem: Layers and Technologies

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 and Application (Layer B)	Digital music players (Apple iPod, Creative MuVo, Rio Carbon, Sony Network Walkman) Traditional portable music players (CD Walkman, minidisk player)
Infrastructure and Support (Layer C)	Digital music files Digital music audio streams 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)

5.3. Analyzing the Paths of Influence

Besides identifying the technologies within the ecosystem, the manager must also consider the relationships between them. It is apparent that the success of MP3 player technologies is having an impact on other technologies in the ecosystem. For example, the rapid success of the Apple iPod has had an impact on the success of its component and support and infrastructure technologies. The stock prices of Audible.com (a service that sells downloadable audio books for the iPod) surged 145% in 2004, Synaptics (a manufacturer of the iPod click wheel component) gained 36% in the same time period, and PortalPlayer (a manufacturer of chipsets used in the iPod) jumped 15% from November 2004 to February 2005 (La Monica 2004).

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→C* and C→A*) helped to fuel their joint success and, in turn, the development of the first portable MP3 players (C→B* and A→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→C*), and has promoted research and development of better encryption, storage, and interface technologies (B→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→B*). At the infrastructure level, online music stores and P2P services are providing new and innovative services (C→C*). And at the component layer, underlying technologies such as storage and encryption have been evolving and becoming less expensive (A→A*). Table 3 organizes some of the paths of influence in this ecosystem.

Table 3: Paths of Influence for the Digital Music Ecosystem

	COMPONENT-ORIENTED PATHS OF INFLUENCE	PRODUCT-ORIENTED PATHS OF INFLUENCE	INFRASTRUCTURE-ORIENTED PATHS OF INFLUENCE
	A*	**B***	**C***
A	**Component Evolution** Steady evolution of storage devices development, LCD screens and rechargeable batteries.	**Design and Compilation** New color display and steadily increasing capacity in MP3 players.	**Standards and Infrastructure Development** Development of multiple audio file formats: MP3, AAC, WMA, RealMedia.
B	**Product-Driven Component Development** Adoption of MP3 players has driven the development of new component technologies, like the iPod click-wheel.	**Product Integration and Evolution** Cell phones playing digital music, integration of digital photos with MP3 players	**Diffusion and Adoption** MP3 accessory development such as FM transmitters and voice recorders.
C	**Infrastructure-Driven Component Development** P2P networks have driven new requirements for encryption technologies.	**Infrastructure-Leveraging Product Development** Development of MP3 players that work with multiple digital music providers.	**Support Evolution** Revised digital rights management rules, new services at online music sellers such as downloadable album art.

5.4. Insights and Opportunities

Based on our preliminary observations, we see that portable digital music manufacturers can now create a monitoring “dashboard” for specific component, support, and competing product technologies that will influence the technologies that their business is based upon. They also can identify product opportunities based on the impact of innovations in related technologies.

Looking at Table 3 and considering recent developments of technologies within the digital music ecosystem, the analyst is able to identifiable specific opportunities for product development and positioning. In the recent past, an analyst could have observed that the evolution of component technologies has provided opportunities for the newest generation of MP3 players. The increasing capacity and decreasing physical size of hard-disk drives and processors provided opportunities for larger MP3 players with more sophisticated operating systems. Similarly, the evolution of LCD screen technology provided opportunities for new MP3 player displays. It is reasonable to have anticipated the development of Apple’s latest incarnation of the iPod, the iPod photo, which leverages all of these component technology advancements. Similarly, the analyst can see that with the evolution of these component technologies, digital video may be the next opportunity for services and products supporting the distribution of digital files.

After reviewing the technology ecosystem and paths of influence, it is also reasonable to anticipate product convergence in the digital music industry. Improved LCD screens and support for digital photos suggest an opportunity for an MP3 player integrated with a digital camera. Similarly, many of the components used in MP3 players are also used in mobile phones. It is easy to predict that new mobile phones will provide MP3 playing capabilities. In fact, Motorola recently announced that it provides support for the iTunes music store and file format on its new line of mobile phones (CNN.com 2005).

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 that help us to understand how changes are occurring that characterize the evolution of this technology context. This allows analysts to focus on specific issues while considering the many factors within the ecosystem.

6. CONCLUSION

This paper offers a number of new contributions to knowledge. We presented a model for understanding technology evolution through the lens of a technology ecosystem. We defined the technology ecosystem and the roles technologies can play in it. We also provided a process for identifying a specific ecosystem view with respect to a given focal technology and context. We introduced the concept of technology layers, which group technologies with similar roles, and the concept of paths of influence, which provide structure around the highly dynamic system of temporal relationships between technology layers. 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 also assessed the analytical utility and efficacy of our approach as a means to gauge the validity of its constructs and analysis process in the context of digital music related technologies.

Previous models of technology evolution relied on individual opinions and perspectives. Our model provides a clearly defined process for identifying a technology ecosystem that leads to a structured view of interrelated technologies in a given context and provides a starting point for analysis and discussion. Specifically, firms making decisions regarding technology investment, product development, and product placement and marketing must consider the dynamic set of relationships between multiple technologies in an ecosystem. The technology ecosystem model provides insights for visualizing and analyzing these complex relationships.

This model is a first step in a line of technological evolution research that focuses on the complexity of interrelated systems of technologies. The model can be extended to address a richer set of research questions.

How does an analyst, using our proposed analysis process, clearly define the boundaries of an ecosystem? This may prove to be a difficult task, especially in highly complex information systems and high-tech industries. Ecosystems may extend indefinitely as the analyst considers extensive series of relationships between technologies. Additionally, ecosystems may overlap where technologies exist in multiple systems. This question provides rich opportunities for studying the application of the ecosystem model in multiple contexts.

How do technologies' roles change over time in an ecosystem? As ecosystems become more complex (e.g., product technologies might be viewed as components for some other technologies), the analyst may find that it becomes more difficult to easily classify all of the technologies involved.

What are the characteristics of the nine paths of influence? Another important research direction is to identify the important characteristics of the nine paths of influence in the model and analyze 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 refine our model further by working with experts in specific context areas (such as digital music or RFID).

What are the influences and characteristics of external environmental forces? We suggested three possible classes of environmental forces: social and governmental, economic, and technical. A natural next step for this research stream is to further develop the concepts and explore the causes and effects of external environmental forces and their relationships with technology roles.

What role do firms and other economic agents play in this model? Our current model focuses on the technologies themselves and not on the firms or the agents behind the technologies. We can extend the ecosystem view to capture these agents and consider their impact on technology evolution.

APPENDIX. SUMMARY OF KEY TERMS AND DEFINITIONS

TERM	DEFINITION
Evolutionary Approach	A view for modeling economic systems in terms of evolutionary concepts such as variation and selection.
Technology Ecosystem	A system of interrelated technologies that influence each other's evolution and development. A specific technology ecosystem view is defined around a focal technology in a given context.
Technology Evolution	The change in technology structure over time, including the development of new technologies and the refinement of existing technologies.
Technology Roles	The influential roles that a technology can play with respect to other technologies in a given technology ecosystem. These include the component, product and application, and support and infrastructure roles.
Technology Layers	In a specific ecosystem view, technologies playing the same role with respect to the focal technology are grouped as a technology layer.
Technology-Shaping Forces	External environmental forces that can influence the development and evolution of a technology or technology ecosystem. These include social and governmental forces, technical forces, and economic forces.
Paths of Influence	Representations of the specific types of influence technologies can have on each other within and across technology layers over time.
Population Perspective	An evolutionary approach from economics that provides the perspective of viewing multiple interrelated technologies as a single population characterized by technical and service characteristics.
Product Hierarchy Approach	An evolutionary approach that considers hierarchical layers within a group of technologies. In this view, products are comprised of components and are coordinated into systems of use.

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