

Understanding Patterns of Technology Evolution: An Ecosystem Perspective

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Abstract. Understanding the dynamics of technology evolution—whether for the purposes of forecasting new product or technology infrastructure developments, or identifying the basis for future digital convergence in the global market—is a key challenge for innovators, senior managers, and policymakers. This research provides an overview of a new *ecosystem model of technology evolution*, the purpose of which is to structure these kinds of assessments and suggest reusable analysis structures to ensure that total environment of technological innovation is considered. We use examples from the end-user computing context and the electronics industry to identify five patterns of technology evolution that commonly occur. We also develop a state diagram-based approach to demonstrate the cyclical nature of technology evolution. Finally, we illustrate our findings using a case study on digital music technologies.

Keywords: Business technologies, digital music industry, ecosystem model, evolutionary patterns, management of technology, technology ecosystem, technology evolution.

1. Introduction

In this bustling world of technological change, managers often find themselves overwhelmed by the number of choices that are available when making technology-related decisions. Whether a manager must make a decision regarding new product development, technology infrastructure investment, or marketing and production strategy, the current environment of business technologies can be a complex place. Most managers will readily admit that it is difficult, if not impossible to accurately predict future technological advances. Nevertheless, senior managers in the most successful firms in today's fast-paced, "on-demand" world should understand the nature of technological change and evolution. They should know enough to be able to create reasonably accurate forecasts, and take advantage of high value technology investments and emerging market opportunities to maintain or grow their market shares.

To date, there has been extensive research done on the nature of innovation and technological change. This research provides many theories that help senior managers to interpret how technological evolution works. It also offers them many useful methods for making effective technology forecasts. (See [12] and [22] for examples.) However, a key insight often missing in the prior research is that individual technologies usually 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 and development of a given technology as a whole. Adomavicius et al. [1] proposed a new *ecosystem model of technology evolution* for understanding the dynamic nature of technological evolution. In this paper, we will build on this prior work and present common patterns of technology evolution using examples from the end-user computing and electronics industry. We also propose a new means of representing and analyzing technology evolution using a *state diagram approach*. Our approach is based on the common *evolutionary patterns* that can be identified to occur within typical technology ecosystems, and that are of interest in a variety of real world settings in which effective management of technology is an important challenge. We believe that the exploration of these kinds of new ideas holds out significant potential for improving senior managers' understanding of how technologies evolve in the presence of a variety of environmental forces.

The remainder of the paper proceeds as follows. Section 2 briefly reviews the main concepts on which our ecosystem model of technology evolution is founded. Section 3 outlines the paths of influence that occur across technologies within an ecosystem. Section 4 identifies common patterns of technology evolution that can be observed in the real world, based on the paths of influence that we have presented. Section 5 follows with a description of our new method for modeling temporal changes in the ecosystem using a state diagram approach. We also illustrate its application and the insights that it creates with a case study on the digital music industry. Section 6 concludes with an overview of our contributions, the limitations of the present work, and recommendations for future research directions.

2. Background: Technology Ecosystem Model

Business researchers have begun to adopt a biological ecosystem model in the analysis of business relationships and strategic decision making [6, 7, 8]. Iansiti and Levien [7] define a business ecosystem framework which argues that industrial systems made up of relationships between firms can be modeled as loosely coupled systems and networks. Additionally, they define "shared fate" and "collective behavior" within an ecosystem to emphasize

the importance of recognizing the interdependent nature of firm relationships. Managers and academics are coming to recognize the value of the ecological metaphor for understanding the complex network of business relationships within and across industries [5]. For example, Quaadgras [13] used network modeling techniques to define the RFID business ecosystem and predict firm participation.

While it is evident that the ecological analogy is proving to be important in business literature, there has been a lack of analytical tools that provide value to practitioners. Additionally, previous research incorporating the ecosystem model has focused on industrial ecosystems and relationships between firms. Our research applies the biological ecosystem analogy to the task of understanding the dynamic nature of technology evolution. We specifically focus on developing analytical methods and tools that provide insights to managers and technology practitioners.

The term *technology ecosystem* is appropriate because it emphasizes the inherently organic nature of technology development and innovation that is often absent in standard forecasting and analytical methods. In a word, changes and transformations in technology are as much a product of the environment for innovation, as they are due to technological progress in general. The traditional notion of an ecosystem in biological sciences describes 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). Within the ecosystem, the evolution of one species affects and is affected by the evolution of other species. In the environment of business technologies, there are many factors that influence the evolution and development of a specific technology. By considering the technology ecosystem as an interrelated set of technologies and environmental forces, a manager can more successfully identify factors that may impact innovation, development, and adoption of new technologies—and ultimately the success of the business activities that use the innovations.

In the biological sciences, ecosystems are composed of a *population of organisms* (including enemies, such as predators and parasites), a *set of resources*, and *external environmental forces*. In today's world, technologies coexist in an environment that can be modeled based on the biological ecosystem analogy that considers populations of technologies which contain overlapping hierarchies and many interdependent relationships. The ecosystem model for technology evolution is a conceptual model that is the result of an extensive review of technology forecasting and evolution literature. It integrates the strengths of many modeling methods in economics and organizational theory. The model builds

on the concept of the *population perspective* [18] from evolutionary economics. In this perspective, technologies are assigned values based on technical and service characteristics and are grouped into populations based on a distance metric in characteristic space. Over time these populations change form as technologies evolve with the populations. The conceptual model also builds on hierarchical models of technology evolution, most notably by Rosenkopf and Nerkar [15]. In this model three levels of the hierarchy are typically considered, *component* level technologies combine to form *product* level technologies and products are then combined to form a *system of use*. Co-evolution of technologies in this model occurs both within levels and across levels in the hierarchy [2, 3].

For example, our view of an ecosystem of personal computer technologies would include the PCs themselves, as well as the components (hard disk drives, processors), competing technologies (laptops), and peripheral or collaborating technologies (printers, software, scanners). Additionally, 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 in order to add value to the system of use. The hierarchal nature of technologies within a population leads to the identification of 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. Specifically, we identify three roles that technologies can play within an ecosystem: *component*, *product* and *application*, and *support and infrastructure*.

The *component role* describes technologies when they are used as components in more complex technologies. For example, there are several technologies that act as components for the personal computer: microprocessors, RAM chips, hard disk drives, etc. When a technology acts as a component, a 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, consider the hard disk drive. It acts as a component in PCs, MP3 players, and many other devices. However, the hard disk drive also has a set of component technologies itself, including DC spindle motors, actuators, and platters.

The *product and application role* describes technologies when they are built up from a set of components, and are designed to perform a specific set of functions or satisfy a specific set of needs. When acting in this role, the technology is associated with a specific application or use. 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, in a digital music technology ecosystem an MP3 player plays a product role because it is composed of several components and is designed to provide a specific service to its user: storing and playing digital music files. Additionally, MP3 players can compete with related technologies, such as CD players, and satellite radio devices.

The *support and infrastructure role* describes technologies when they 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 another more complex 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. In this example, a printer acts as a supporting technology for the PC, and the PC in turn acts as a supporting technology for the printer.

In addition to roles, the ecosystem model should include external environmental forces on the evolutionary outcomes of technologies. Specifically, three major types of external environmental forces can influence the state of a technology ecosystem: 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 government may mandate that all automobiles in the US must come equipped with global positioning system (GPS) tracking devices for safety reasons. This mandate would in turn have an impact on the GPS and automotive technology ecosystems by driving new innovations to meet government regulations. The concepts of social forces is based the *social constructivism in technology* perspective which 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 [4].

Technical forces represent pressures and needs for technological change formed by technical barriers and opportunities. Theories from evolutionary economics propose 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. In other words, it is part of human nature to invent and the

ongoing processes of research and knowledge discovery ultimately lead to new technological innovations. In his review of evolutionary economics, Nelson [11] introduces the *theory of cumulative technology* which serves as the basis for our conceptualization of technical forces.

Economic forces are captured by market dynamics and the demand for new products and technologies. For example, as the demand for mobile phones increased more resources were allocated for further technological development in the cellular phone ecosystem. In contrast, as the demand for VCRs decreased, continued efforts to innovate and develop the technologies within that ecosystem decreased as well. The concept of economic forces is based on Mokyr's [10] model of technology evolution that considers market pressures as a driver of the selection and adoption of new technologies.

It is apparent that the general view of an ecosystem can be very complex, with technologies playing multiple roles and having multiple relationships. In practice, however, a manager is interested in the analysis of a specific set of technologies in a specific context. A *specific ecosystem view* is defined by identifying the technologies and their roles that are relevant to the analysis at hand [1]. Using the technology ecosystem model, an 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).

3. Paths of Influence in the Technology Ecosystem

Technology-related decisions and forecasting tasks are predictive in nature. The decision to invest in a new technology or develop a new technology product requires the manager to identify a goal or desired future state. Since technologies change over time, any practical model of technological evolution must consider the *temporal aspects* of such change. To represent the influence that current technologies have on future technologies, the technology ecosystem model defines *paths of influence* [1].

Paths of influence occur within or across the component, product and application, and support and infrastructure technology layers within the ecosystem and they describe relationships among these technology layers over time. Technological evolution and development is complex and can take many paths through the layers within a technology ecosystem. Therefore, paths of influence are possible from any of the current states to any of the future states of the technology layers within an ecosystem.

For example, the current component technologies can potentially influence the development of new product technologies, representing a specific path of influence: Component Layer (C) → Product/Application Layer* (P*). The asterisk (*) is used to indicate a future state of a technology layer in the ecosystem, and we use C, P, I as abbreviations for component layer, product and application layer, and support and infrastructure layer, respectively. Layers without an asterisk represent current states in the ecosystem.

Paths of influence represent the influence one technology layer has on another in the evolution of a set of technologies in the ecosystem. For example, the success of the DVD player has helped drive the development of new DVD component technologies equipment. These include recordable DVD ROMs, multi-layer DVD ROMs, and new blue-ray technologies (P→C*). Similarly, the evolution of infrastructure technologies can drive the development of new product technologies. For example, the wide cellular phone network provides infrastructure for new phone services and applications such as text messaging and picture mail (I→P*). For the purposes of this paper we adopt the 3x3 matrix that classifies the paths of influence as shown in Table 1. For more detail on paths of influence, see Adomavicius et al. [1].

4. Patterns of Technology Evolution

Sahal [17] defines an analytical framework for understanding patterns of technological evolution. The author identifies several specific patterns, including invention, innovation, and diffusion, and recognizes that technology development follows an evolutionary process. Additionally, the author notes that the temporal evolution of any system that is subject to a collection of random changes is characterized, in general, by prolonged oscillations. Therefore, the existence of recurring fluctuations in innovation and technology evolution should

be expected. Worlton [21] investigates the recent evolution of high-performance computing and identifies patterns of technological change. Specifically, he notes that technological change typically occurs in four stages: invention, innovation, diffusion, and change of scale. Additionally, Rosenberg [14, p. 74] shows that "technological forces exist which may lead to cyclical behavior in certain industries, where major innovations come to substitute for on another sequentially in time." Building on these ideas of technological evolutionary patterns and cycles of innovation, we apply our ecosystem model and the concept of paths of influence to demonstrate how these patterns and cycles can be mapped over time.

As discussed in the previous section and in Adomavicius et al. [1], each cell in Table 1 represents a possible path of influence in the technology ecosystem. Over time technologies evolve, some new technologies are introduced, and some existing technologies die out. An ecosystem's form and content change as well as the patterns of evolution occurring within the ecosystem. One advantage of the ecosystem model and the 3x3 matrix of paths of influence is that patterns of evolution can be identified and analyzed. At any given point in time, any collection of paths of influence can be at work in the ecosystem. However, it is advantageous to the manager to identify common patterns of evolution that occur in a technology ecosystem as it matures. Below we describe five examples of technology evolution patterns that are based on paths of influence and match our observations of real world instances of technology evolution and development. Table 1 acts as a template for Figures 1 through 5, which illustrate the evolutionary patterns as *collections* of the paths of influence occurring in the technology ecosystem at a given time.

Table 1. Paths of Influence in a Technology Ecosystem

	COMPONENT FUTURE STATE (C*)	PRODUCT FUTURE STATE (P*)	INFRASTRUCTURE FUTURE STATE (I*)
COMPONENT PRESENT STATE (C)	Component Evolution Examples: microprocessors and Moore's Law, digital camera mega-pixels.	Design and Compilation Examples: digital camera, MP3 players, PCs	Standards and Infrastructure Development Examples: XML, RFID
PRODUCT PRESENT STATE (P)	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
INFRASTRUCTURE PRESENT STATE (I)	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

Product Development. The first common pattern of technology evolution describes the initial stages of the evolution of a particular product technology. In this pattern the ecosystem may exhibit many different product and component technologies, as designs are being developed and accepted. We call this pattern of technology evolution *product development* because the primary paths of influence at work in the ecosystem deal with the impacts of new technology components and products on each other. (See Figure 1.)

Figure 1. Product Development

	C*	P*	I*
C			
P			
I			

For example, the introduction of the first personal digital assistants (PDAs), such as the Apple Newton and the Palm Pilot, required the simultaneous development of products, the PDAs themselves ($P \rightarrow P^*$), and components, microprocessors, micro hard disk drives, touch screens, etc. ($C \rightarrow C^*$). In this scenario, no initial infrastructure technologies specifically designed to support the PDA were in place and the pattern of evolution focused primarily on the refinement of the product and component technologies. Component technologies are developed or refined to meet the requirements of new products ($P \rightarrow C^*$) and, similarly, product designs are modified and refined based on the available components ($C \rightarrow P^*$).

Product and Infrastructure Alignment. The second common pattern of technology evolution, *product and infrastructure alignment*, is similar to the first except in that in this scenario a set of infrastructure technologies already exists. (See Figure 2). Infrastructure technologies play an important role in a technology ecosystem – they provide incentives for the ongoing use and adoption of product technologies.

By their definition, however, infrastructure technologies support product technologies and thus require the existence (or planned existence) of the product and application technologies they support. The common mode of technological evolution is the development of new products to leverage that infrastructure and the refinement of the infrastructure technologies to support product technologies. For example, the expansion of global communications and the growing interconnected reach of the Internet 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 complex storage

issues of the Internet. Another example is Google’s GMail. As of June 2005, Google’s new email system, Gmail (gmail.google.com), is offering subscribers over 2 GB of space for personal email storage and utilizes a search engine technique for mail organization. This signals a new trend for free online storage and storage products in terms of the software functionality additions that they are offering [9]. These products will likely evolve to manage large amounts of data across the Internet using intelligent storage technologies ($P \rightarrow P^*$).

Figure 2. Product and Infrastructure Alignment

	C*	P*	I*
C			
P			
I			

The research currently being conducted by the PlanetLab project (www.planet-lab.org) 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 [16] ($I \rightarrow I^*$). PlanetLab is implementing “smart” nodes to increase the intelligence of the Internet and increase its usability ($P \rightarrow I^*$, $I \rightarrow P^*$). Smart nodes will allow users to access files and desktops anywhere they have Internet access regardless of location. In this pattern, the interplay between infrastructure and product technologies is the driving force for technology evolution.

Feed-Forward Evolution. The next two common patterns of technology evolution describe purely cross-level co-evolution and primarily occur during the ongoing maturation of a technology ecosystem. The paths of influence in the upper right section represent the *feed-forward paths of influence*. In each case, evolution of current technologies impact technologies at higher levels of the technology hierarchy in the future state. (See Figure 3).

For example, the introduction of an evolved component technology can drive evolution of the technologies that will use this new component. When new components are combined to create a new product, this path of influence reflects the process of design and compilation.

Figure 3. Feed-Forward Evolution

	C*	P*	I*
C			
P			
I			

For example, the development of color LCDs, high capacity solid state storage devices, and CMOS sensors for image capture provided the component technology enhancements necessary to create a digital camera product technology ($C \rightarrow P^*$). Another feed-forward path of influence occurs as components become standardized, and support and infrastructure technologies emerge that leverage those standards. Radio frequency identification technology (RFID) has existed since the early 1990's; however, until recently there have been very few standards for RFID sensors and readers. New standards foster interoperability and spark the development of new supporting technologies ($C \rightarrow I^*$). Similarly, diffusion and adoption paths of influence occur when a technology in the product layer becomes widely adopted. This provides motivation for the development of infrastructure technologies. For example, the widespread diffusion of digital cameras has resulted in the placement of self-service photo printing kiosks in many grocery stores ($P \rightarrow I^*$).

Feed-Back Evolution. The paths of influence in the lower left section refer to *feed-back* paths of influence in technology evolution. (See Figure 4). Often the use of a technology impacts the development and evolution of the technologies it depends on. For instance, as product layer technologies evolve, advancements in component technologies are often necessary to realize a new design.

Figure 4. Feed-Back Evolution

	C*	P*	I*
C			
P			
I			

The increasingly important requirement for copyright protection and security in digital goods requires advancements in the basic digital encryption technologies, such as watermarking and time-decay mechanisms ($P \rightarrow C^*$). Similarly, the growth and development of support and infrastructure layer technologies can easily impact component layer technologies. For example, the development of many new internet component technologies such as Dynamic HTML or Active Server Pages (ASP) resulted from the continuous growth of the World Wide Web ($I \rightarrow C^*$). Also, once a support or infrastructure technology is in place, it provides opportunities for a new product technology to leverage the services and facilities it provides. The widespread adoption of instant messaging paved the way for new products and applications, such as video conferencing, file transfer, and online game software, leveraging the existing infrastructure ($I \rightarrow P^*$).

Incremental Evolution. Finally, *incremental evolutionary patterns* within a technology ecosystem signal stability and

within-level co-evolution. The diagonal in Figure 5 represents incremental innovations and includes the continuous development and refinement of technologies within each role.

Figure 5. Incremental Evolution

	C*	P*	I*
C			
P			
I			

For example, Moore's Law explains that processing power of integrated chips will double approximately every 18 months and ongoing research and development continues to uphold this law ($C \rightarrow C^*$). Similarly, incremental product evolution occurs as existing products are integrated or new features are added to improve on design and create new products. Camera phones are an example of the integration of two existing technologies (digital cameras and mobile phones) to create new product ($P \rightarrow P^*$). The same ideas hold for incremental support and infrastructure evolution. Technologies in this role can evolve over time as the products they support also evolve. The mobile phone network is a supporting technology that has grown in size and evolved to provide new services as cellular phone adoption continued to grow ($I \rightarrow I^*$). Therefore, incremental evolution represents steady-state evolution and can occur at any point in the evolutionary life cycle of a technology ecosystem.

We further note that the evolutionary patterns in a given ecosystem may differ slightly from those described above. It is possible that only some of the paths of influence in a given pattern act at a given time. For example, the incremental evolutionary pattern may exhibit only $C \rightarrow C^*$ and $P \rightarrow P^*$ (but not $I \rightarrow I^*$) paths of influence at a given time. The paths of influence included in each of the five patterns discussed above identify the likely evolutionary forces acting within each pattern.

5. Technology Evolution Cycles

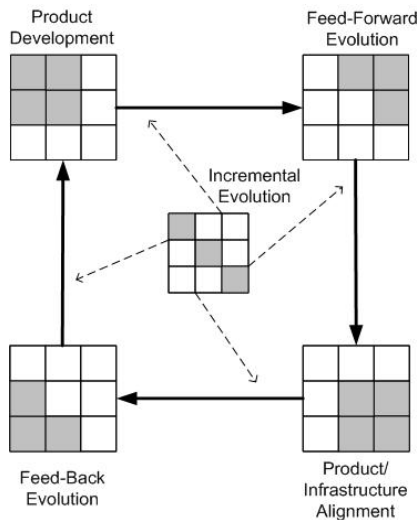
Although identifying patterns of evolution in the technology ecosystem provides additional insights for managers making technology-related decisions, a more significant contribution of the technology ecosystem model is its ability to provide a systematic approach for describing the temporal changes in the ecosystem using these evolutionary patterns.

5.1. State Diagram Analysis

We use *state diagrams* to describe the behavior of a system. Simplified state diagrams represent the evolution of technologies in the digital music industry by identifying the transitions from one common evolutionary pattern to another as time passes.

It has been shown that innovation typically occurs in specific stages [17, 21] and in cycles [14, 21], and new innovations typically replace existing ones [14]. Using the five common patterns of technology evolution identified in the previous section to outline the stages of innovation, we describe technology evolution as cyclical process through a state diagram where the ecosystem transitions through each of the evolutionary patterns.

Figure 6. Evolutionary Pattern Cycle



At the beginning of an evolutionary cycle, initial product development forces are typically at work and new product and component technologies are introduced and refined. Once initial product and component technologies become stable, the feed-forward process of evolution builds on these initial technologies and new product and infrastructure technologies emerge. As the ecosystem matures, infrastructure must evolve and stabilize to support the continued development of new product technologies. At this point product/infrastructure patterns of technology evolution take control. The component technologies must then respond to the newly stable products and infrastructure and a feed-back evolutionary process results. Finally, the ecosystem reaches a steady state in which stable incremental evolution continues until a new initial product development disrupts the stability and begins a new cycle. Figure 6 illustrates the evolutionary pattern cycle. As previously noted, incremental evolution can occur at any point within the cycle as indicated in Figure 6.

5.2. State Diagram Analysis of Digital Music Industry

To illustrate this cyclical nature of technology evolution, we provide an analysis of the evolution of digital music technologies. We will show that, in its young life, the digital music ecosystem has already passed through at least two of these evolutionary cycles.

The demand for digitally-formatted music files,

players, and services has grown steadily over the past five years. In fact, a new digital music market has developed with many technological innovations and rapid consumer adoption. Since it was originally patented in Germany in 1989, the MP3 audio compression format has had quite an impact on the traditional music industry. 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 February 1999, Sub Pop Records became the first label to begin releasing music in the MP3 format. Since then, the introduction of mass storage digital music players and online digital music retailers has transformed the music business.

Table 2. Timeline of Digital Music Technologies

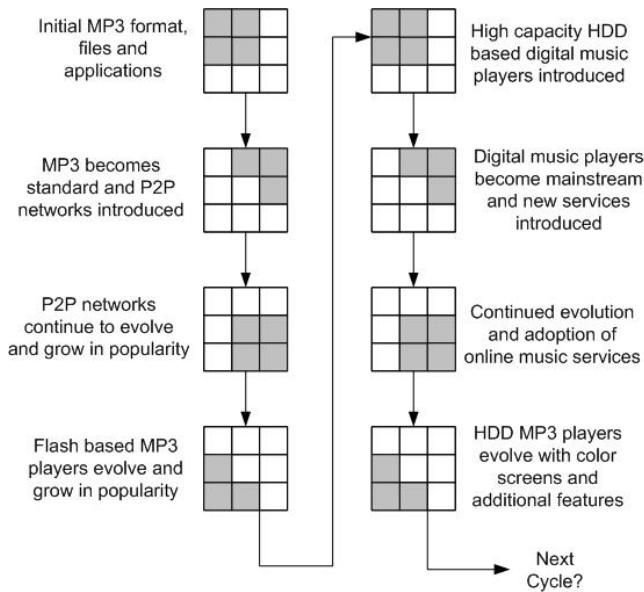
YEAR	EVENT
1989	German MP3 patent
1996	US MP3 patent
1998	First portable MP3 player (32 MB)
Feb 1999	Sub Pop distributes MP3 music
May 1999	Napster founded
May 2000	Transactional watermarking developed
Jan 2001	Apple iTunes music applications released
Jul 2001	Napster injunction
Oct 2001	10 GB Apple iPod introduced
Mar 2002	20 GB iPod for PC introduced
Apr 2003	40 GB iPod introduced
Oct 2003	Dell DJ introduced iTunes online music store opens
Sep 2004	MSN online music store opens
May 2005	Yahoo online music store opens

We use the evolution of digital music technologies to demonstrate the effectiveness of identifying transitions between common evolutionary patterns in technology ecosystems. The digital music technology ecosystem provides an appropriate case study for this analysis because it includes many different component, product, and infrastructure technologies, most of which were introduced within the past 15 years. The music industry is highly dynamic and complex and provides an interesting context for exploring technology evolution. Table 2 provides a brief timeline of the evolution of digital music technologies.

Figure 7 depicts two evolutionary cycles of digital music technologies. The first cycle of digital music technology evolution starts with the introduction of the MP3 compression format and software applications for playing MP3-encoded music files. The birth period of the digital music industry is characterized primarily by the initial product development pattern of technology evolution, where component technologies (such as the MP3 compression format) and product technologies (digital music software such as WinAmp) were being refined as

they gained more attention. Activities in this era included the refinement of the MP3 format by integrating it into MPEG-1 in 1992 and MPEG-2 in 1994. Once the MP3 standard had reached a reasonable level of adoption, feed-forward patterns of technology evolution took over as new product and infrastructure technologies were introduced based on the MP3 encryption format. The first portable MP3 player, the 32MB MPMAN device from Eiger Labs, was released in the summer of 1998 [20], and P2P networks were introduced with Napster's inception in May of 1999. Both technologies emerged because of the popularity of the MP3 compression format.

Figure 7. Digital Music Technology Evolution Cycles



As popularity increased for the technologies in the digital music ecosystem, additional infrastructure technologies were developed, including further refinement of P2P networks and the introduction of new MP3 standards, such as Microsoft's WMA and Apple's AAC. As a result of the continued growth in popularity of digital music products and technologies, feed-back patterns of technology evolution took hold as new components and products, such as higher capacity flash storage based players, were developed. At this point technologies had somewhat of a steady state, with the majority of MP3 players being flash storage based and virtually all MP3 file distribution occurring over P2P networks.

A second evolutionary cycle began when innovations in components, such as high capacity micro hard disk drives, led to the initial product development of hard disk drive-based MP3 players, such as the Apple iPod and the Creative Nomad Jukebox. These new HDD-based players sparked feed-forward patterns of evolution that resulted in the introduction and adoption of new online music services, such as iTunes and Napster 2.0, as well as a slew of accessories for portable MP3 players, such as FM

transmitters and voice recorders. With the presence of multiple online music providers and portable MP3 players, technology evolution has become focused on the alignment of infrastructure and product technologies. The wide adoption of the new second generation of digital music technologies led to feed-back patterns that included introduction of new products using new components such as color LCD screens.

The digital music technology ecosystem will likely hold steady in a state of incremental evolution until the next series of radical product and component innovations result in the beginning of a new cycle. Based on the recent introduction of MP3 enabled mobile phones from Motorola and Sony/Ericsson [19], it is likely that the next cycle of technology evolution in the music industry will begin as new components and products are introduced, resulting in the converge of multiple handheld computing devices (PDAs, cellular phones, MP3 players, digital cameras). The ecosystem view allows the manager to track, model, and analyze these types of evolutionary patterns and cycles, and better understand the dynamic nature of technology evolution.

Figure 8 provides an alternative representation of the cyclical nature of evolution in digital music industry using paths of influence to represent transitions between states. The nodes in Figure 8 represent the collection of component (C), product (P), and infrastructure (I) technologies at each time in the evolutionary process. The edges between nodes represent the paths of influence as outlined in Section 3 of this paper. Finally, the evolutionary patterns are represented by the set of edges between each time period. Dashed edges represent incremental evolution which can occur at any point within the cycle.

6. Summary and Future Work

In this paper we review the main concepts of the technology ecosystem model and outline the paths of influence that occur among technologies within an ecosystem. Using the ecosystem model and the notion of paths of influence we present an approach to analyze the changes in technologies over time by identifying the commonly occurring patterns of technology evolution. We use a state diagram-based approach for modeling temporal changes in the ecosystem, and we illustrate its application and the insights that it creates with a case study on the digital music industry.

The proposed approach for representing evolutionary patterns provides insights for visualizing and analyzing complex relationships between multiple technologies in a technology ecosystem. The advantage of the proposed approach is that it is intuitive and not difficult to comprehend. It provides managers with an additional tool for supporting decision-making tasks involving new technologies and innovation; it also allows managers to

think more systematically about the complex dynamics at play in the evolution of interrelated technologies by providing the ability to identify and recognize prototypical evolutionary patterns (rather than isolated paths of influence) in a given ecosystem.

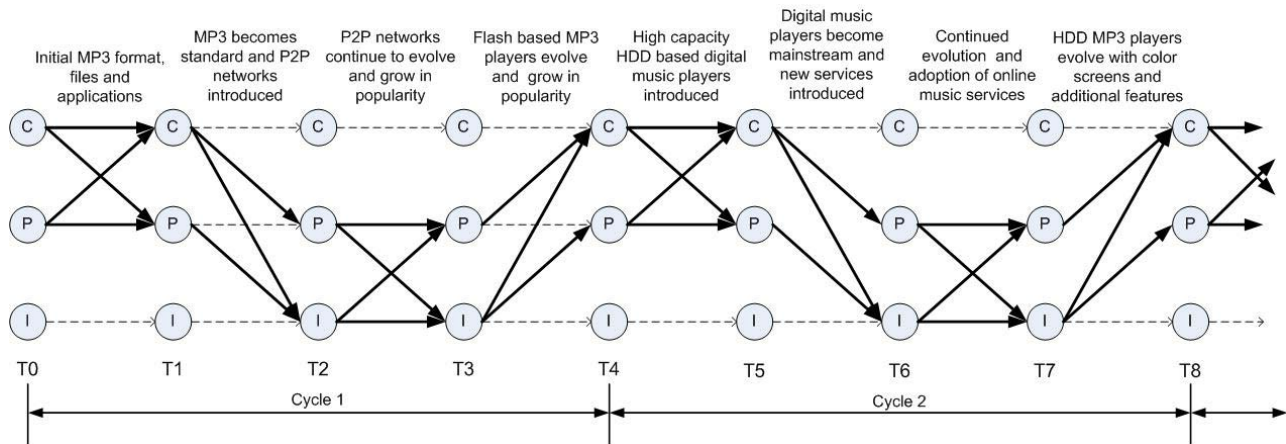
Aside from the benefits mentioned earlier, the proposed approach also presents some potential challenges. For example, one challenge for an analyst using this model would be to define the boundaries of an ecosystem. This may prove to be a difficult task, especially in highly complex information systems and high-tech industries. Ecosystems may extend indefinitely as the analyst considers extensive series of relationships between technologies. Another possible challenge is the classification of technology roles within an ecosystem. In other words, as ecosystems become more complex (e.g., product technologies might be viewed as components for some other technologies), the analyst may find that it is difficult to assign only one specific role (component, product, or infrastructure) to a given technology.

In our future work we are planning to further refine the evolutionary patterns and investigate their various temporal

relationships and characteristics (e.g., the length of evolutionary cycles). We plan to validate our approach further by applying it to a number of other technology ecosystems and garnering feedback from practicing technology managers. In addition, we suggested in the paper that the model should include three possible classes of environmental forces: social and governmental, economic, and technical. A natural next step for this research stream is to further develop these concepts and explore the causes and effects of external environmental forces and their relationships with technology roles and evolutionary patterns. Furthermore, our current model focuses on the technologies themselves and not on the firms or the agents behind the technologies. We plan to extend the ecosystem view to capture these agents and consider their impact on the patterns of technology evolution.

We also plan to investigate how this approach can be integrated with or complemented by other techniques for managing innovation in the areas of new product development, technology forecasting, technology marketing, and technology investment.

Figure 8. Digital Music Technology Paths of Influence



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