

# Technology roles and paths of influence in an ecosystem model of technology evolution

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**Abstract** We propose a new conceptual model for understanding technology evolution that highlights dynamic and highly interdependent relationships among multiple technologies. We argue that, instead of considering technologies in isolation, technology evolution is best viewed as a dynamic system or *ecosystem* that includes a variety of interrelated technologies. 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 each others' evolution. We also classify types of interactions between technology roles, which we term *paths of influence*. We demonstrate the use of our proposed model through examples of wireless networking (Wi-Fi) technologies and a business mini-case on the digital music industry.

**Keywords** Ecological perspective · Environmental analysis · Innovations · Paths of influence · Technology

analysis · Technology ecosystem · Technology evolution · Technology roles

## 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 technology 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 technology forecasting and evolution. We review a variety of relevant perspectives and propose a new conceptual model of technology evolution that incorporates and integrates key concepts from the prior literature and offers new ideas as well.

Prior research has developed many perspectives on technology evolution, such as punctuated equilibrium [24, 44], technology diffusion and IT waves [3–5], multi-level effects [22, 35, 36, 41], and hierarchical evolution and modularity [1, 2, 9, 34]. We propose a new framework that shows how linkages between technological innovations in three separate but interdependent technology roles shape the evolution of technology systems and individual technologies. We improve on current methods by introducing a systematic technique for representing and classifying evolutionary pathways within a system of interrelated technologies.

A key point in our research is that individual technologies cannot be considered in isolation in the analysis of innovation and technology evolution.

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Instead, it is necessary to consider a system of inter-related technologies and the interdependent technological advances that influence evolution. Building on concepts from three streams of literature, we use the metaphor of a *technology ecosystem* to build a framework for analyzing technology evolution using *paths of influence* to represent relationships between technologies over time. First, the *population approach to technology evolution* from evolutionary economics and other models of industrial and technology ecosystems provide the perspective of viewing multiple interrelated technologies as a population whose characteristics and members change over time [38]. Second, the *technology and product hierarchy approach* to technology evolution identifies specific levels of technologies and the modes of co-evolution both across and within these levels [34]. Finally, research on *technology trajectories* [14] and *patterns of innovation* provides some initial concepts for representing relationships between technologies over time. Our framework uses a technology ecosystem perspective 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. We define major constructs of this framework, including three specific roles that technologies play within an ecosystem: the *component* role, the *product and application* role, and the *support and infrastructure* role.

The technology ecosystem metaphor suits our model well because of its parallels to the traditional notion of an ecosystem, which is a habitat for a variety of different, yet related, species that co-exist and influence each others' development and survival. Our model builds on this metaphor to describe the interrelated set of technologies, the roles they play, and the relationships they exhibit, which impact innovation, development, and adoption. The strength of such a 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 firms use this new model of technology evolution in managerial settings to analyze the technological developments relevant to their specific strategic objectives?

We demonstrate the usefulness of our model by analyzing technological innovations in wireless networking technologies and the digital music industry.

The article is organized as follows. Section 2 provides an overview of relevant prior research from which our framework is developed. Section 3 outlines our framework and defines the main theoretical constructs of our subsequent analysis. Here and later in the article, we use digital wireless network technologies (Wi-Fi) to illustrate our ideas. Section 4 expands the theoretical framework to incorporate the temporal aspect of technology evolution. Section 5 presents an application of the framework through a detailed case study on technology evolution in the digital music industry. Section 6 discusses the limitations of our model as well as potential extensions and future work and also provides concluding remarks.

## 2 Relevant technology evolution perspectives

According to Ziman [46], technological innovations in an industry are so interrelated that one might describe them as occurring in an *ecological system of co-evolving artifacts*. We use the term *technology* as defined by Dictionary.com: the application of science especially to industrial or commercial objectives. We focus on *tangible technological artifacts*, that is, technological objects produced through human conception, including physical objects, digital objects (e.g., software), processes, and configurations (designs). We use the term *technology evolution* to refer to the change of technology over time, including the development of new technologies and the refinement of existing technologies. The biological definition of evolution is not completely analogous to our discussion of the evolution of technologies. Biological evolution assumes blind (or natural, random) drivers for selection and variation, whereas technological change is thought to be fueled by the planned process of design [46]. We build on concepts from three streams of prior research to construct our conceptual model. In the remainder of this section we review this literature.

### 2.1 The system and population approach to technology evolution

There are numerous technology forecasting methods—from analytical extrapolation of trends to expert panel discussions (see [15, 33] for examples). Forecasting technological evolution is complex and difficult since many factors impact the development of a

technology and it is nearly impossible to accurately capture the influence of them all. Therefore, to represent the complex, dynamic, and interdependent nature of technology evolution, a system view of technologies and their relationships is necessary.

The idea of a technology (or industrial) ecosystem has been used in previous research to describe relationships between technologies and organizations. For example, Iansiti and Levien [18, 19] define a *business ecosystem* based on the “shared fate” and “collective behavior” of a set of related firms. This model emphasizes the need to consider multiple sources of influence (e.g., multiple firms and organizations) for strategic purposes. Similarly, Rosenkopf and Tushman [35, 36] have used a system view to analyze interorganizational relationships and investigate the co-evolution of technology and organizations. Additionally, many other researchers have suggested that individual technologies cannot be analyzed in isolation. Dosi’s *technology paradigms* [14], Nelson and Winter’s *technology regime* [30], and Sood and Tellis’ *platform innovation* [42] level of analysis all reinforce the importance of viewing technologies as a system in evolutionary analysis.

To develop a comprehensive view of technology evolution, we must also consider the *population perspective* from research in evolutionary economics on technological change. Saviotti [38] describes the key concepts of the *evolutionary approach* to economics by summarizing relevant literature across economics, organizational science, and biology. (For a review of evolutionary economics, see [29, 30]). 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 the 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: competition, commensalism, and predation [25, p. 5]. In economics, these interactions can translate into various forms of competition and collaboration between firms [38]. For example, Metcalfe and Gibbons [26] define *innovation competition* as technological differences between firms that result in continuous change in the economic performance of firms. Finally, an evolutionary approach typically also considers the influence of external environments on evolutionary outcomes.

By considering interrelated sets of technologies, the population approach to technology evolution supports the ecosystem view. Saviotti and Metcalfe [39] 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* [40] focuses on the importance of acknowledging the variance and differences in properties among members of a population.<sup>1</sup> With respect to technological evolution, analysis using the population perspective considers a population of technologies represented as a “cloud of points” in characteristics space [38]. Over time, the properties of technology populations can change, for example, population density can change, a single population may fragment, and separate populations may converge.

## 2.2 Hierarchies and roles in technology evolution

The ecosystem view and population perspective provide 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 [45] and hierarchies [9]. In fact, several studies have considered the interdependent relationships among evolving components of complex technologies (see [16, 17, 44] for examples).

Rosenkopf and Nerkar [34] 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 of use. 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 co-evolve within each level of the hierarchy (*within-level co-evolution*) and evolution at any level can impact evolution across other levels of the hierarchy (*cross-level co-evolution*).

Tushman and Rosenkopf [45] 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 co-evolution of components. Cross-level co-evolution is more closely related to ideas in biology. One such idea is

<sup>1</sup> The *population perspective* is the opposite of the *typological perspective* often used in the biological sciences, which states that a given species can be adequately represented by the properties of the average or representative individual within the species.

*downward causation* from Campbell [7, 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 technology evolution, consider that an old PC design may become obsolete or be replaced with a new one, and thus drive the obsolescence or new innovation of the components it used. A related concept is *whole-part co-evolutionary competition* [8, 34]. Applied to technology evolution, it suggests that selection among variants at one level of a technology hierarchy can conflict with selection at other levels.

Finally, in discussions of innovation and product design, Baldwin and Clark [1, 2] have shown that, as products and technologies have evolved, firms have become increasingly dependent on the use of modules to handle the increasing complexity. Modules are subsystems of product components that provide firms more flexibility in product design and manufacturing. Designing new products in the age of modularity requires the development of architecture, interfaces, and standards, which create an intuitive hierarchical framework for understanding relationships between various technologies and levels of hierarchy within a product system.

### 2.3 Technology trajectories and patterns of innovation

A review of the technology evolution literature would not be complete without a discussion of techniques and theories for representing the evolutionary paths technologies take as they change over time. Dosi introduced the *technology trajectory* [14] to represent the movement of multidimensional tradeoffs among the technological variables within a technology paradigm. These tradeoffs define a cluster of possible technological outcomes bounded by the technology paradigm. Dierickx and Cool [13] interpret technology trajectories as the series of path-dependent experiences that track with the evolution of a technology. Also, in their study of Formula 1 racing technology evolution, Jenkins and Steven [20] define technology trajectories as the thread connecting one technological experience to another over time.

Expanding on trajectories, other scholars have formulated general patterns of innovation to represent modes of technology evolution. Sahal [37] argues that innovation processes are governed by a common system of evolution leading to the formation of specific patterns of innovation. These patterns guide subsequent

technological developments, thus creating *technological avenues* of innovation. Similarly, Kash and Rycraft [21] argue that technologies evolve by moving along a path or trajectory embedded in a technology community, which results in three common types of innovation: incremental, transitional, and transformational. Within the population perspective, Saviotti [38] proposes five basic processes or patterns in a model of technology evolution: birth, death, incremental innovation, technology transfer and diffusion, and emergence of new technological populations. Moreover, Baldwin and Clark [2] argue that in the age of modularity specific design rules govern patterns of innovation. These rules act through six *operators of modularity* that result in innovations through the following module actions: *splitting* (one module into multiple), *substituting* (replacing one module with another), *excluding* (removing a module from a design), *augmenting* (adding new modules), *inverting* (rearranging modules), and *porting* (applying a module in a new context).

### 2.4 Gaps and opportunities

We build on the diverse set of ideas presented above to develop a conceptual framework for representing evolution within an ecosystem-based view of technology. Our effort is focused on providing value to industry analysts, experts, and managers, who may use this framework in real-world settings to analyze technological developments relevant to their strategic objectives. We attempt to fill the following three specific gaps in previous research.

First, it is clear that different technologies can play different roles within technology ecosystems. While some research has incorporated hierarchical levels [9, 34], very little research has dealt with specific definitions of technological roles within a system of technologies. We define three general roles technologies can play and provide a methodology for identifying technologies in these roles.

Second, concepts of technological systems, paradigms, and regimes emphasize the need to consider sets of technologies together in the analysis of innovation and evolution; however, defining this set is quite subjective. For example, a *technological paradigm* [14] refers to a set of procedures, “relative” problems, and the common body of knowledge needed for the solution. Similarly, Kash and Rycraft [21] base the system on a “technological community,” and Podolny and Stuart [32] represent relationships between technologies as “common threads of knowledge” or “technological commonalities.” Though these representations of relationships are sufficient for theory development and

high-level analysis, they provide little value to managers attempting to apply these models in decision-making situations. What managers need is a framework to model relationships between specific technologies. Our framework fills this gap by defining a set of co-evolutionary relationships among technologies that can be explored to analyze different evolutionary paths.

Finally, the level of analysis in many models of technology evolution is either unclear or varying. Most include firms and the economic environment within the system of technology evolution. We focus on tangible technological artifacts and try to avoid incorporating firms and economic indicators in order to emphasize specific technological relationships. Therefore, our model uses technology classes, like desktop PCs, as the level of analysis rather than firm-specific technology models, like the Dell XPS 600 gaming PC, to eliminate confounding firm-level factors, such as marketing effort and brand. It also provides the flexibility for an analyst to choose the granularity of technology class that is most appropriate for the analysis at hand. This includes choosing a more general class of portable devices for playing recorded music versus the more specific class of disk-based MP3 players.

### 3 Modeling the technology ecosystem

In this section we describe the main concepts of our model for analyzing technology evolution developed by deriving insights and integrating the ideas from prior research.

#### 3.1 Defining the ecosystem view

The population perspective provides a conceptual view of multiple related technologies that exist as a single population. In the model presented by Saviotti [38], a population consists of specific technologies (e.g., PC models) that are similar, based on their technical and service characteristics. We build upon the population perspective and include not only similar technologies, but also other related technologies. We also use the hierarchical concepts from Rosenkopf and Nerkar [34] to identify the structure of related technologies. Our view of an ecosystem of PC technologies includes the PCs, as well as the competing technologies (e.g., laptops and personal digital assistants or PDAs), components (e.g., hard disk drives, processors), and supporting technologies (e.g., Internet technologies, printers, software, scanners).

The ecosystem of all related technologies can be complex, with technologies playing multiple roles and

having multiple relationships. In practice, however, an analyst is typically interested in performing a specific analysis of a specific set of technologies. Podolny and Stuart introduced the concept of the *technological niche* [32]. It includes a focal innovation, the innovations on which the focal innovation builds, the innovations that build upon the focal innovation, and the technological ties among the innovations within the niche. We build on this by proposing a *specific ecosystem view* to identify the technologies and their roles that are relevant for the analysis at hand.

More specifically, an analyst using our approach will choose a *focal technology* (i.e., the technology that the analyst is most interested in) and a *context of use* for identifying the most relevant view of the ecosystem.<sup>2</sup> A *context* is a specific application, use, or capability of the focal technology under consideration. Different ecosystem views can be produced based on the focal technology (e.g., laptops) in different contexts (e.g., laptops as gaming devices, business productivity devices, and mobile communication devices). Using our framework, an analyst can identify the technologies immediately related to the focal technology within a given context based on three *roles* that technologies play in an ecosystem.

#### 3.2 Technology roles

The focal technology and the context of use provide the starting point and the scope of a specific ecosystem view. In an ecosystem, there are three roles that technologies play based on their relationships to the focal technology within a given context of use: *component*, *product and application*, and *support and infrastructure*.

The *product and application role* includes the focal technology and other technologies in direct competition with the focal technology in a given context. For example, if an analyst chooses a laptop computer as a focal technology in the video-gaming context, other technologies in the product and application role would include desktop computers, video game consoles (e.g., Microsoft Xbox or Sony Playstation), and handheld devices providing similar capabilities to users.

The *component role* technologies are identified as necessary for the product and application set of technologies to perform their functions in the given context of use. So, although there are many technologies that may act as components for the laptop computer, certain components are necessary in the video-gaming

<sup>2</sup> As mentioned earlier, we focus on analyzing the relationships between technology classes. For simplicity, we will use the general term *technology* instead of *technology class*.

context (e.g., microprocessors, RAM, display screen, video card, network card, hard disk drives), whereas others are not (e.g., parallel printer ports, zip drives).

The *support and infrastructure role* identifies technologies that add value to the performance or use of the product and application role technologies within the given context. The distinction between the component role and the support and infrastructure role is that components are typically part of the physical structure of product and application technologies and are necessary for them to perform in a given context of use. Support and infrastructure technologies add value to the technologies they support by creating a system of use [34], but are not required for product and application technologies to perform in the given context. For example, a printer is not physically necessary for the design and use of a PC. However, it supports the PC's functionality in many contexts, and together they provide additional value and services to their users. While some supporting technologies act as enabling infrastructure (e.g., the Ethernet), others act as peripherals (e.g., the printer). However, our proposed framework emphasizes specific views of technology evolution based on analysts' perspectives. Since such perspectives generate focused identification of the ecosystem for a given analyst, both peripheral and infrastructure technologies act in a supporting role for the product and application technologies. Therefore, we combine these roles for simplicity in our analysis.

### 3.3 Identifying the technology ecosystem

We next present a set of steps to help an analyst identify a specific view of a technology ecosystem, which consists of the various technologies that are related to the focal technology in a chosen context. As an example, we focus on a hypothetical case involving a product analyst in a laptop manufacturing firm who wishes to understand the relationships among the technologies used for providing wireless networking and communication capabilities to the laptop computer.

- Step 1 (Identification of focal technology and context).

The analyst should choose a focal technology, 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 laptop computer) with a context related to a specific application for that product (e.g., wireless communication and networking capabilities).

- Step 2 (Identification of competing technologies). The analyst should next identify any other classes of technologies that compete directly with the focal technology in the given context. For example, desktop computers, personal digital assistants, and wireless handheld gaming systems (e.g., Sony PSP) may all be classes of technologies competing with the focal technology by providing similar wireless functionality.

- Step 3 (Identification of component technologies). The analyst should next identify the various technologies that are used as components in the focal technology and its competing technologies in the chosen context. In the current example, this role includes technologies such as processors, RAM, wireless integrated chipsets, Bluetooth adapters, and Wi-Fi 802.11g network interface cards.

- Step 4 (Identification of support and infrastructure technologies).

Finally, the analyst should identify the various technologies that support the focal technology and/or its competitors and increase value to the user by forming a system of use. In the current example, this set of technologies may include wireless enabled printers, wireless web cameras, wireless routers, Bluetooth peripherals, etc.

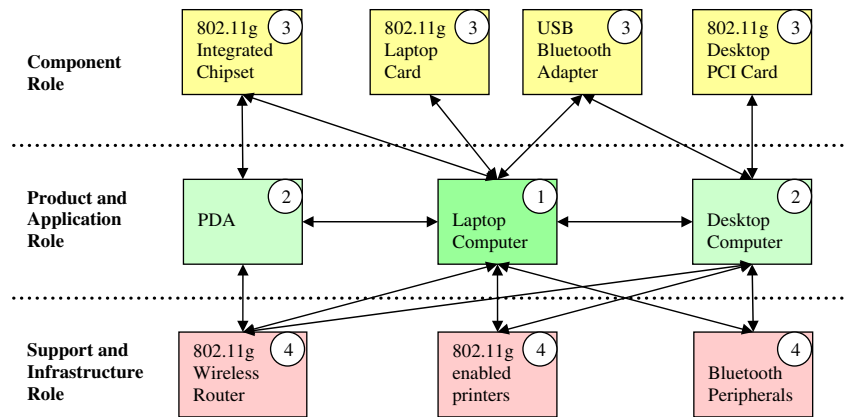
The steps above provide a view of an ecosystem that is centered on the focal technology and pertains to a given context. Following this process, an analyst can reliably produce a view that identifies technologies in the three basic roles as well as the key relationships among these technologies. This serves as a starting point for identifying potential interactions (see Fig. 1).

The numbers in Fig. 1 correspond to the process steps described above. This process provides the first level of analysis (i.e., it considers the focal technology and technologies *immediately* related to it). This ecosystem view can be expanded to consider additional levels of analysis (e.g., the underlying components of components of the focal technology, other technologies for which the product and application set act as components, products that at the same time act as infrastructure to other technologies, and many others). Hereafter, we analyze an ecosystem view at this first level of analysis and further explore how technologies in this ecosystem can affect each other over time.

## 4 Classifying technology innovations with paths of influence

We earlier reviewed several perspectives on *patterns* of technological progress including technology trajectories

**Fig. 1** Specific technology ecosystem view for laptop wireless networking



[13, 14, 20], technological avenues [37], and various patterns of innovation [2, 21, 38]. We build on this research and extend our analytical framework to include the temporal aspect of technology evolution.

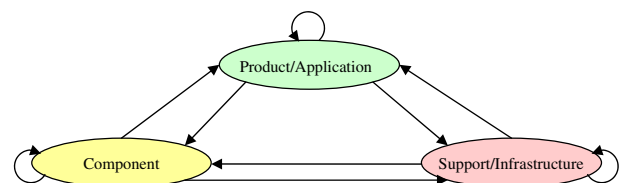
To incorporate changes over time, we model interactions between the technology roles. By acting in a specific role, technologies influence evolution of other technologies through relationships established by the structure of an ecosystem. For instance, a component technology can evolve into a newer version, which can drive product innovations and the development and deployment of new support and infrastructure technologies. Each technology in an ecosystem can potentially influence the evolution of other technologies in the same role as well as the technologies in the other two roles. Figure 2 depicts these interactions.

Success of products based on focal technologies can spur innovations in the component technologies as well as in infrastructure and support technologies. As an example, consider the specific ecosystem view discussed earlier, which had laptop computers as a focal technology and the wireless networking capabilities as the context.<sup>3</sup> The demand for laptop PCs, 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 802.11 g components, and eventually to long-distance WiMAX components [43]. 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 adapters (network cards), to laptops with integrated 802.11b and 802.11 g chipsets (e.g., Intel Centrino technology). Similarly, supporting technologies such as low-cost, wide-coverage Wi-Fi base

stations, Wi-Fi enabled peripherals (wireless printers and web cameras) and new encryption technologies (Wired Equivalent Privacy and Wi-Fi Protected Access) have evolved alongside the component and product technologies. The success of wireless technologies and the growth of wireless networks are additional drivers in the continuing development of wireless technology. Figure 3 depicts interactions that occurred in the evolution of technologies within this ecosystem. It also shows that innovations within the wireless PC ecosystem are interdependent and influence technologies within and across the technology roles.

#### 4.1 Defining nine paths of influence

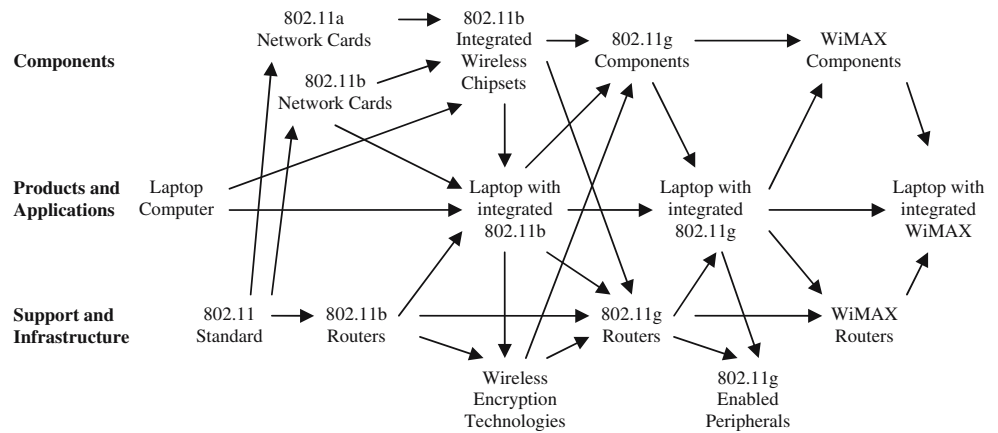
To represent the interactions outlined in Figs. 2 and 3, we define paths of influence within a technology ecosystem. Generally, we say that there is a *path of influence* between technology *X* and technology *Y* whenever technology *X* has influenced the development of technology *Y*. Paths of influence occur within or across technology roles within the ecosystem and describe relationships between technology roles over time. Below we present our classification of nine paths of influence. This classification integrates and extends several ideas from prior literature including downward causation [7], leading components and core subsystems [45], whole-part co-evolutionary competition [8], cross-level and within-level co-evolution [34], and operators of modularity [2].



**Fig. 2** Temporal interactions among technology roles

<sup>3</sup> For a brief history of the IEEE Wi-Fi 802.11 standard, see the Intel case study “Intel and 802.11” at [www.intel.com/standards/case/case\\_802\\_11.htm](http://www.intel.com/standards/case/case_802_11.htm).

**Fig. 3** Temporal interactions among Laptop-related Wi-Fi technologies



Let C, P, and I denote the present state of technologies in the *component role*, *product and application role*, and *support and infrastructure role*, respectively. Let C\*, P\*, and I\* denote the future states of technologies in these roles. Nine paths of influence are possible between the technologies in any of the current states (C, P, I) and the technologies in any of the future states (C\*, P\*, I\*). Thus, technology evolution can follow many paths within a technology ecosystem. For instance, the current component technologies (C) can potentially influence the development of new product technologies (P\*), representing a specific path of influence  $C \rightarrow P^*$ .

We classify the nine paths into three groups according to the resulting innovation. Paths from the current state of any role to the future state of the component role (C\*) are *component-oriented paths of influence*. Similarly, paths that end with P\* are *product-oriented paths of influence*, and paths that end with I\* are *infrastructure-oriented paths of influence* (see Fig. 4).

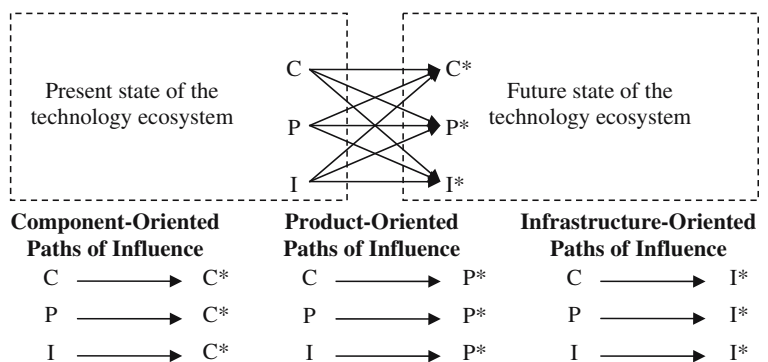
Our representation of the nine paths of influence between the technology roles provides a systematic way to classify the temporal impacts that technological innovations have on each other within a technology ecosystem. We next explore each path of influence in detail, and use examples from different ecosystems to demonstrate the wide applicability of our approach.

## 4.2 Component-oriented paths of influence

### 4.2.1 Component integration and evolution ( $C \rightarrow C^*$ )

As component technologies are used in product and application technologies, resources are invested in continued development and, therefore, a natural evolution results. Similar to Baldwin and Clark’s *operators of modularity* [2], current component technologies may evolve into new component technologies when two components become integrated into one, one component is split into multiple components, or a component is augmented or ported into a new form. 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 the power consumption of integrated circuits will decrease exponentially over time. Due to the continued resource investment in research and development, these laws have held true and microprocessor performance has steadily evolved over time (e.g., the dual core processors represent new configurations built on earlier component designs). We have seen similar improvements in digital camera mega-pixel resolution and in the battery life of mobile phones. In the case of this path, existing components often provide a strong

**Fig. 4** Nine paths of influence between technology roles in a technology ecosystem



foothold for the innovations that result in next generation components.

#### 4.2.2 *Product-driven component development* ( $P \rightarrow C^*$ )

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.

#### 4.2.3 *Infrastructure-driven component development* ( $I \rightarrow C^*$ )

The expansion and development of infrastructure and supporting technologies can also drive component technology innovations. For example, the expansion of the Internet and World Wide Web led to advancements in the underlying personal computer component technologies, such as advanced network cards, software components such as dynamic HTML (DHTML) and XML support in browsers, various networking and communications software, 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

#### 4.3.1 *Design and compilation* ( $C \rightarrow P^*$ )

Product technology innovations often develop through the unique combination of component technologies and design processes. For example, digital cameras combine core component technologies, such as image sensors, color capture equipment, storage devices, lenses, and battery technologies. Similarly, PDAs

combine component technologies such as microprocessors, communication devices, and touch screens. Engineers and designers must understand the available component technologies to successfully design new products. Thus, the available component technologies can shape the design process and impact the outcome of product and application technologies.

#### 4.3.2 *Product integration and evolution* ( $P \rightarrow P^*$ )

Similar to Component Integration and Evolution ( $C \rightarrow C^*$ ), product and application technologies can be integrated to create new products, separated into multiple product technologies, or augmented to include new features, versions, or designs. For example, within a digital music ecosystem, two distinct product technologies—a CD player and an MP3 player—have been integrated resulting in a single device that can play both regular audio CDs and the CDs with MP3 files on them. Also, 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. Interactions between product technologies from different ecosystems are also possible—camera phones are a product technology that integrates a cell phone with a digital camera, resulting in a potential overlap of the two previously distinct ecosystems.

#### 4.3.3 *Infrastructure-leveraging product development* ( $I \rightarrow P^*$ )

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 supporting infrastructure for the introduction of new technologies, products, and services distributed through the instant messaging client (e.g., games, downloads, and file transfers). Similarly, the diffusion of mobile phones and wireless networks provides opportunities for new products and services, such as video mail and text messaging.

### 4.4 Infrastructure-oriented paths of influence

#### 4.4.1 *Standards and infrastructure development* ( $C \rightarrow I^*$ )

New component technologies can give rise to new standards thus facilitating the creation of new infrastructure and supporting technologies. For example,

XML by itself can be viewed as a component technology. However, when industry leaders and government bodies agree to use XML-based standards for describing data, the resulting standards represent a support technology. Selecting a set of component technologies as a standard can create the infrastructure to support future products, applications, and services. The use of radio frequency identification (RFID) tags is another example. RFID tags are a component technology in many contexts. However, when an industry leader like Wal-Mart announces that all of its suppliers must comply with RFID-based supply chain management, new support and infrastructure technologies develop [12]. Business alliances or consortia may decide to adopt a component technology as a standard 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. As an example, a standardized electronic medical record specification will promote easier data transfer among healthcare systems in the United States medical system.

#### 4.4.2 Diffusion and adoption ( $P \rightarrow I^*$ )

Products and applications that lead to infrastructure and support 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 Office Suite, in turn, has become a widespread support technology for PCs. Another example comes from the rapid adoption of digital cameras and the emergence of supporting

technologies, such as digital photo-editing software, affordable photo-quality color printers, and self-service digital photo printing kiosks.

#### 4.4.3 Support integration and evolution ( $I \rightarrow I^*$ )

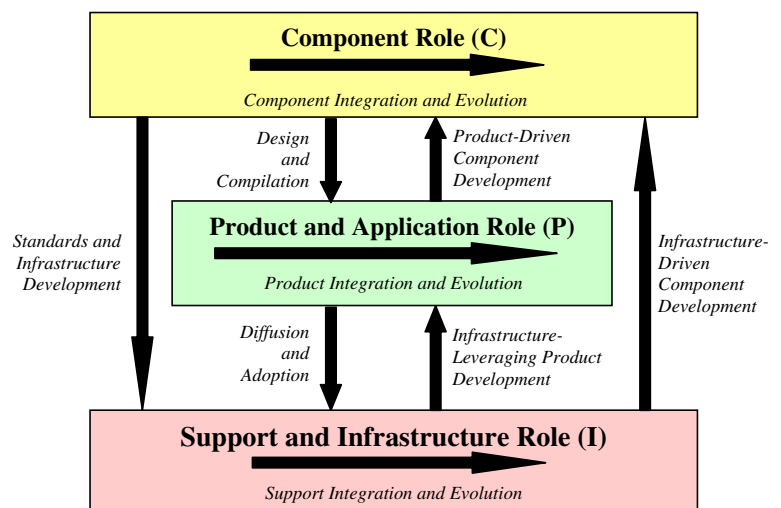
While the development and evolution of support and infrastructure technologies primarily comes in response to adoption and diffusion of product and application technologies, natural evolution also takes place. Similar to the ( $P \rightarrow P^*$ ) and ( $C \rightarrow C^*$ ) paths of influence discussed previously, support technologies can be split into multiple technologies, integrated from multiple technologies, or augmented to create new variations based on prior technologies. For example, cell phone networks have grown in size over the past twenty years to provide wider coverage areas and new services for users. Another example of a continuously evolving support technology is the expansion of the Internet. As more users log on, new technologies are needed to support effective communications, control costs, and improve telecommunications capabilities.

#### 4.5 Paths of influence: summary and wireless networking case

One of the major contributions of our ecosystem model of technology evolution is a classification of influences that lead to technological innovations. Furthermore, we combine the paths of influence defined above with the framework outlined earlier to represent our conceptual ecosystem view of technology evolution (see Fig. 5).

The effectiveness of the ecosystem-based model lies in its ability to capture the dynamic nature of

**Fig. 5** Paths of influence and technology roles: a conceptual diagram



technology evolution. Our model provides structure for understanding the dynamics between technologies in various roles within an ecosystem.

Let’s look again at the case study of wireless networking capabilities for laptop computers. As we noted before, technology evolution and innovation processes are complex and include a combination of influences (i.e., the development of a new technology or improvements to an existing technology may be triggered by multiple paths of influence). For example, development of second-generation wireless devices, such as 802.11b network interface cards and laptops with integrated wireless chipsets, was influenced by technologies in all three roles (see Fig. 3).

Using the classification of paths of influence, we can better interpret the different interactions occurring in the evolution of this ecosystem. For example, many new component technologies related to wireless networking capabilities for laptops have evolved. The 802.11 standard, originally developed in 1990, provided the initial influence for developing the first 802.11a and b laptop adapters ( $I \rightarrow C^*$ ), and the next generation 802.11 g adapters were built off of these initial components ( $C \rightarrow C^*$ ). Eventually the widespread use of these adapters in laptops resulted in the development of integrated wireless chipset components ( $P \rightarrow C^*$ ).

Similarly, we can classify influences on product technology evolution. For example, the development of the new integrated wireless chipsets led to the introduction of the first laptops utilizing them ( $C \rightarrow P^*$ ), and the success of these laptops led to an upgrade in the product technology to include the latest 802.11 g chipsets and wireless security features ( $P \rightarrow P^*$ ). Additionally, competing technologies, such as PDAs, leveraged the wireless networking infrastructure and included wireless capabilities themselves ( $I \rightarrow P^*$ ).

Finally, the influences on the support and infrastructure technologies can also be identified. The evolution of component technologies led to the refinement of the 802.11 standard to include the 802.11 g classification ( $C \rightarrow I^*$ ). New peripherals, such as Wi-Fi printers, web cameras, and media streaming routers, were developed as more and more laptop and desktop PCs came enabled with wireless networking capabilities ( $P \rightarrow I^*$ ). And the supporting technologies, such as 802.11 routers, have kept pace with the ecosystem evolving from supporting 802.11b to supporting 802.11b and 802.11g with increased range ( $I \rightarrow I^*$ ). Table 1 provides a structured summary of these paths of influence.

### 5 Model application: an analysis of the digital music industry

We have illustrated our framework with examples based on the laptop-related Wi-Fi technology ecosystem. We now provide a more comprehensive demonstration of the analysis approach that our ecosystem model of technology evolution facilitates by focusing on the digital music industry.

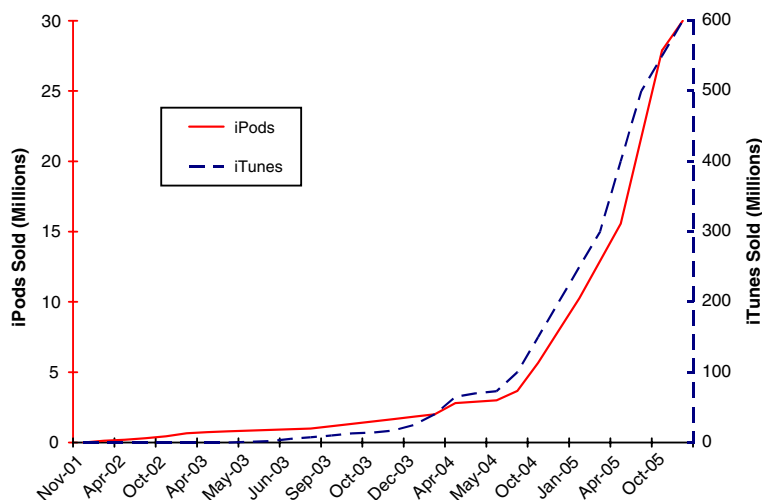
#### 5.1 Background of the digital music industry

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 [6]. The digital music industry involves multiple players: artists, record labels, Inter-

**Table 1** Paths of influence: examples from laptop wireless networking case

Component-oriented paths of influence $C^*$	Product-oriented paths of influence $P^*$	Infrastructure-oriented paths of influence $I^*$
<i>C Component integration and evolution</i> Evolution from 802.11 b to 802.11 g adapter cards	<i>Design and compilation</i> Introduction of first 802.11 b integrated laptops	<i>Standards and infra-structure development</i> 802.11 g standards and routers
<i>P Product-driven component development</i> Development of 802.11 g integrated chipsets	<i>Product integration and evolution</i> Laptops upgraded to integrated 802.11 b/g chipsets	<i>Diffusion and adoption</i> 802.11 b/g-enabled peripherals such as wireless printers and Web cams
<i>I Infrastructure-driven component development</i> 802.11a/b standards led to initial production of 802.11a/b components	<i>Infrastructure-leveraging product development</i> PDAs with built in 802.11 b/g capabilities	<i>Support integration and evolution</i> Accelerated 802.11 b/g routers, development of 128 bit WEP encryption

**Fig. 6** Sales of iPods and iTunes, 2001–2005



net 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 continue to evolve quickly in the digital music industry. Consider the Apple iPod MP3 player. The first incarnation of the iPod was sold 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. Among the latest developments, in the fall of 2005 Apple released iPods that support video playback and updated the iTunes store to provide video downloads for purchase. Figure 6 depicts the rapid adoption of Apple iPods and the use of the iTunes music service. Note that as consumers continued to adopt the iPod player, the supporting music service, iTunes, grew in popularity. As sales of iPods reached 1.5 million, the sales of iTunes began to increase rapidly.

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 analyst working for a portable digital music player manufacturer must consider the ecosystem of technologies related to digital music playback and distribution when making strategic decisions. One potentially important question for analysis would be: 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 provides the interpretative structure for exploring this question.

## 5.2 Step-by-Step identification of the elements in the ecosystem

### 5.2.1 Step 1 (Identification of focal technology and context of use)

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 iPods and iTunes sales. Following our four step process, an analyst working for a MP3 player manufacturer can identify a specific ecosystem view. First, the analyst must identify a focal technology. An obvious choice is the hard disk drive-based portable MP3 player.<sup>4</sup> Next, she must identify the context of the specific ecosystem. Since hard disk drive-based MP3 players are designed for a specific purpose, the natural choice for the context relates to that purpose: playback and distribution of digital music.

<sup>4</sup> 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.

5.2.2 Step 2 (Identification of competing technologies)

In the product role, there are multiple classes of technologies that compete with the hard disk drive-based MP3 player for the purpose of digital music playback and distribution, such as flash storage-based players (as made by Apple, Creative, Rio, iRiver, and Sony), PDAs with MP3 playback capabilities, and more traditional portable music devices such as CD players and mini-disc players.

5.2.3 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.

5.2.4 Step 4 (Identification of support and infrastructure technologies)

Finally, in the support and infrastructure role, digital music files and streaming audio have given consumers a new music format, and the online digital music retailers (e.g., Apple iTunes, Sony Connect, and Microsoft's MSN Music) support digital music players and the consumers who use them, by providing

complementary products and services. As another example, Griffin Technology produces an entire product line of accessories that include FM transmitters, voice recorders, and car chargers, which specifically provide support for the Apple iPod and other MP3 players. Additionally, several digital music file standards have developed as players in the music industry have created specific support networks for their products. 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 classifies the component, product, and support technologies in this specific ecosystem view of the digital music industry.

5.3 Analyzing the paths of influence

Besides identifying the technologies within the ecosystem, the analyst must also consider the relationships between them. It is apparent that the success of MP3 player technologies is having an impact on other technologies within 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 available through iTunes) 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 [23].

Component and support technologies helped shape the current digital music market and provide

**Table 2** The digital music technology ecosystem: roles and technologies

Roles	Example technologies
Component (C)	Hard disk drives Solid-state (flash media) storage MP3 compression format (encoders and decoders) Small electronics components Interface designs and software Encryption technologies (Microsoft Janus, watermarking)
Product and Application (P)	HDD digital audio players (Apple iPod, Creative Zen, Dell DJ) Flash storage-based digital audio Players (Apple iPod Nano, Creative MuVo) PDAs with MP3 playback (Dell Axim X5, Palm Treo) Traditional portable music players (CD Walkman, minidisk player)
Infrastructure and support (I)	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, etc.) Standards (AAC, WMA, RealAudio) Accessories (Griffin Technology)

opportunities for digital music products. The simultaneous development and adoption of peer-to-peer networks and the encoding and decoding technologies for the MP3 format ( $C \rightarrow I^*$  and  $I \rightarrow C^*$ ) helped to fuel their joint success and, in turn, the development of the first portable MP3 players ( $I \rightarrow P^*$  and  $C \rightarrow P^*$ ). 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 ( $P \rightarrow I^*$ ), and has promoted research and development of better encryption, storage, and interface technologies ( $P \rightarrow C^*$ ). At all three levels of the ecosystem, we see the occurrence of continuous incremental evolution. At the product level, new designs of digital music players are being released ( $P \rightarrow P^*$ ). At the infrastructure level, online music stores and P2P services are providing new and innovative services ( $I \rightarrow I^*$ ). And at the component layer, underlying technologies such as storage and encryption have been evolving and becoming less expensive ( $C \rightarrow C^*$ ). Table 3 organizes some of the paths of influence in this ecosystem and provides additional examples.

#### 5.4 Insights and opportunities

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

Looking at Table 3 again and considering recent developments of technologies within the digital music ecosystem, an analyst should be able to identify 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. For example, the increasing capacity and decreasing physical size of hard-disk drives and processors provided opportunities for larger capacity MP3 players with more sophisticated operating systems. Similarly, the evolution of LCD screen and multimedia chipset technologies provided opportunities for new playback capabilities. Thus, it is reasonable to have anticipated the development of Apple’s latest incarnation of the iPod, the iPod Video, which leverages all of these component technology advancements.

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, large capacity storage, and support for digital photos suggest an opportunity for an MP3 player to be integrated with a digital camera. Similarly, many of the components used in MP3 players are also used in mobile phones. Therefore, it was a natural progression for mobile phones to provide MP3 playback capabilities. In fact, Motorola recently released a phone (the ROKR) that provides support for the iTunes music store and file format [11] and Apple announced in January 2007 that it plans to release iPhone, an MP3 player/cell phone/digital camera/internet device hybrid.

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 understand the changes

**Table 3** Paths of influence in the digital music ecosystem

Component-oriented paths of influence $C^*$	Product-oriented paths of influence $P^*$	Infrastructure-oriented paths of influence $I^*$
<i>C Component integration and evolution</i> Steady evolution of storage devices development, LCD screens, rechargeable batteries	<i>Design and compilation</i> New color display and steadily increasing capacity in MP3 players	<i>Standards and infrastructure development</i> Development of multiple audio file formats: MP3, AAC, WMA, RAM
<i>P Product-driven component development</i> MP3 player adoption has driven development of component technologies, like iPod click-wheel	<i>Product integration and evolution</i> Cell phones playing digital music, integration of digital photos with MP3 players	<i>Diffusion and adoption</i> MP3 accessory development such as FM transmitters and voice recorders
<i>I Infrastructure-driven component development</i> P2P networks have driven new requirements for encryption technologies	<i>Infrastructure-leveraging product development</i> Development of MP3 players that work with multiple digital music providers	<i>Support integration and evolution</i> Revised digital rights management rules, new services at online music sellers (e.g., album art downloads)

occurring in the evolution of this technology context. This allows analysts to focus on specific issues while considering the many factors within the ecosystem.

### 6 Conclusions and directions for future research

This article offers a number of contributions. We presented a model for understanding technology evolution through the lens of a technology ecosystem. We discussed the technology ecosystem and the roles technologies can play within 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 paths of influence, which provides structure around the highly dynamic system of temporal relationships between technology roles. We also identified relationships and issues related to the ecosystem model of technology evolution that will provide structure for future research. In addition, we illustrated the analytical utility and efficacy of our approach in the context of digital music-related technologies, as well as laptop-related wireless communication technologies. These provided a means to gauge the validity of our constructs and analysis process.

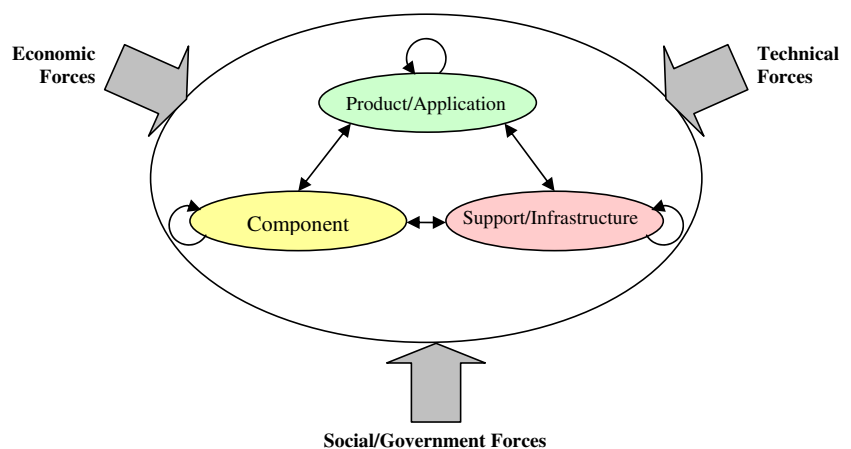
Our model offers a clearly defined process for identifying a technology ecosystem that leads to a structured view of interrelated technologies in a given context and provides a starting point for analysis and discussion. Senior managers who are making decisions regarding technology investment, product development, product positioning, and marketing must consider the dynamic set of relationships between multiple technologies in an ecosystem. The technology ecosystem model provides a vehicle for structuring the analyst’s interpretations and for communicating these interpretations to others.

This model is a first step in a line of technological evolution research that focuses on the complexity of interrelated systems of technologies. As part of the future work, this model can be extended to address a richer set of research questions, as discussed below.

*What are the influences and characteristics of external environmental forces?*

An ecosystem model of technology evolution should also include external environmental forces and their effects on technological change. Let us briefly discuss three major types of external environmental forces: social and governmental forces, technical forces, and economic 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 [10]. Additionally, concepts such as the *national system of innovation* [38, p. 188] and Pavitt’s *taxonomy of innovations* [31] suggest that different industrial sectors and even nations have some greater competitive advantage for developing new technologies within a given ecosystem. *Technical forces* represent pressures and needs for technological change formed by technical barriers and opportunities. In his review of evolutionary economics, Nelson introduces the *theory of cumulative technology* [29]. It 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. Murray [28] argues that science and technology evolve together through a co-mingling of networks of scientific and technological researchers and professionals.

**Fig. 7** Technology ecosystem with external forces



*Economic forces* are captured by market dynamics and the demand for new products and technologies. For example, Mokyr's [27] model of technology evolution considers market pressures as a driver of new technology selection and adoption.

These external forces are complex and important in the shaping of technological evolution. In fact, each of the external forces may be acting at any given time, and discerning the specific effects of each will definitely be a difficult task. In Fig. 7, we update our previous figure of the technology ecosystem (Fig. 2) to include these external forces, and highlight the need for future research to understand their true effects.

*How does an analyst, using our proposed framework, define the boundaries of an ecosystem?*

The specific ecosystem view can be expanded to consider additional levels of analysis (e.g., the components of components of the focal technology). Analyzing such ecosystems may prove to be a difficult task though, 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. We believe that it will be fruitful to develop some new modeling elements in our framework to represent technology role shifts over time and derive meaning from them relative to the larger changes in technology evolution that are occurring.

*What are the characteristics of the nine paths of influence?*

Another research direction is to identify specific 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. We also seek to understand how specific relationships between technologies within an ecosystem affect the outcome of technology evolution. In addition, we recognize that ecosystems and technologies within different industries will behave differently. Therefore, we plan to

refine our model further by working with experts in specific context areas, such as digital music or RFID.

*What role do firms and other economic agents in the marketplace play in this model?*

Our current model focuses only on the technologies themselves and not on the firms or the agents behind the technologies. We plan to extend the ecosystem view to represent these agents and their impact on technology evolution.

Pursuing some of these extensions will further advance technology evolution research, eventually leading towards the development of predictive capabilities for applications in technology forecasting and new product development. The novel concepts related to the ecosystem-based view constitute a significant step towards this goal.

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## 7 Appendix Key terms and definitions

Term	Definition
Evolutionary approach	A view for modeling economic systems in terms of evolutionary concepts such as variation and selection
Paths of influence	Representations of the specific types of influence technologies can have on each other within and across technology roles 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 (Saviotti 1996)
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 (Rosenkopf and Nerkar 1999)

## Appendix continued

Term	Definition
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-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
Technology trajectories	The series of path dependent experiences that track with the evolution of a technology (Dois 1982, Dierickx and Cool 1989) or the thread connecting one technological experience to another across levels of analysis (Jenkins and Steven 2001)

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