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UNDERSTANDING EVOLUTION IN TECHNOLOGY ECOSYSTEMS

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The current technological environment is becoming increasingly complex, and managers are faced with new challenges related to technology forecasting, technology investment and adoption, and new product development. The *technology ecosystem model* provides a principled approach to understanding evolution of technology artifacts and environment by taking into account the interdependent nature of related technologies.

UNDERSTANDING TODAY'S DYNAMIC TECHNOLOGY ENVIRONMENT

The current environment of business technology can be a complex place to navigate for senior managers making decisions about new product development, technology investment, and technology planning. Many industry analysts recognize that it is difficult, if not impossible, to accurately predict future technological advances. However, successful managers and entrepreneurs in today's fast-paced, on-demand world have to understand the nature of technological change and evolution in order to accurately forecast and take advantage of investment and market opportunities. For example, there is no doubt that the VoIP industry presents huge technology investment opportunities – the VoIP equipment market is forecast to reach $8.5 billion by 2008 (Frost and Sullivan 2005). However, converging technology capabilities in this industry are making it challenging to know how VoIP will evolve, which further emphasizes the financial importance of accurate technology forecasts.

There has been extensive research on the nature of innovation and technological change which provides many theories of technological evolution and numerous methods for technological forecasting. (See Porter et al. 1991 and Ziman 2000 for examples.) A critique of these models, however, is that in discussions of innovation and technology evolution, technologies are often considered individually. Instead, we argue, it is necessary to consider a system of interrelated technologies and environmental factors that influence the evolution and development of a given technology. We propose a *technology ecosystem model* for understanding the dynamic nature of technological evolution. The model is designed to help analysts identify the important relationships between multiple technologies that potentially affect their business decisions. The model outlines three specific *roles* technologies can play within an ecosystem and nine *paths of influence* that describe the types of impact technology roles can have on one another. Examples throughout the article illustrate various aspects of the model.

TECHNOLOGY AS AN ECOSYSTEM

The term *technology ecosystem* emphasizes the organic nature of technological development that is often absent in forecasting and analytical methods. In the biological sciences, ecosystems are composed of a population of organisms, a set or resources, and external environmental forces. Similarly, technologies coexist in an environment containing *populations of technologies* organized as *overlapping hierarchies* with many *interdependent relationships* (Adomavicius et al. 2007). By considering a technology ecosystem, a manager can more successfully identify factors that may impact innovation, development, and adoption of new technologies.

Technology Roles

We identify three specific roles that technologies can play within an ecosystem: (1) *component*, (2) *product and application*, and (3) *support and infrastructure*. By acting through these roles, classes of technologies influence the evolution and development of each other.

The *component role* describes technologies when they are used as components in more complex technologies. For example, RAM chips, microprocessors, hard disk drives act as components for the personal computer (PC). When a technology acts as a component, a more complex technology depends on that 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, the hard disk drive (HDD) acts as a component in PCs, digital audio players (DAPs), and many other devices, but it also has a set of component technologies itself, including DC spindle motors, actuators, and platters.

The *product and application role* describes technologies comprised of a set of components and 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 and competes with other technologies in this role. For example, in a digital music technology ecosystem a DAP plays a product and application role because it is designed to store and play digital music files, is composed of several components, and competes with related technologies, such as CD players and satellite radio devices.

The *support and infrastructure role* describes technologies that work in 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 these 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.

Identification of a Specific Ecosystem View

The general view of an ecosystem can be very complex, with technologies playing multiple roles and having multiple relationships. In practice, however, an industry expert 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. In particular, the analyst can specify a *focal technology* and a *context of use* for that technology, and then identify the technologies immediately related to the focal technology within the given context. For example, consider a product manager in a PC manufacturing firm assigned with the task of determining the necessary storage capabilities for a new model of PC. We outline four steps the analyst can follow to identify a specific ecosystem view in Figure 1.

Figure 1. Identifying an Ecosystem View

Step 1 (Identification of Focal Technology and Context of Use). The analyst selects a focal technology, or a starting point for mapping out the ecosystem, and a specific context of use. A natural choice is the product produced by her company (e.g., a PC) with a context related to a specific business decision (e.g., storage capabilities).

Step 2 (Identification of Product/Application Technologies). The analyst identifies any other types of technologies that compete with the focal technology to provide the same service or functionality within the given context. With the focal technology, these correspond to technologies playing the product and application role. For example, laptop computers, personal digital assistants (e.g., Palm Pilot devices), and servers may all be classes of technologies competing with the focal class in the given context.

Step 3 (Identification of Component Technologies). The analyst identifies technologies that are used as components in the product and application role technologies. This set of technologies plays the component role with respect to the focal technology.

Step 4 (Identification of Support/Infrastructure Technologies). The analyst identifies technologies that work with the product and application role technologies to increase value to the end user. These technologies play the support and infrastructure role with respect to the focal technology.

In a specific ecosystem view, a *technology layer* is defined by a set of technologies playing the same role with respect to the focal technology. By following the process above, the analyst will be able to reliably produce a view that captures the three basic layers of relationships for the focal technology and provides a starting point for identifying potential interactions in the ecosystem. Table 1 is a list of potential technologies within the specific ecosystem discussed above.

Table 1. Roles in the Personal Computer Storage Technology Ecosystem

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

Figure 2. A Technology Ecosystem Relative to a Focal Technology

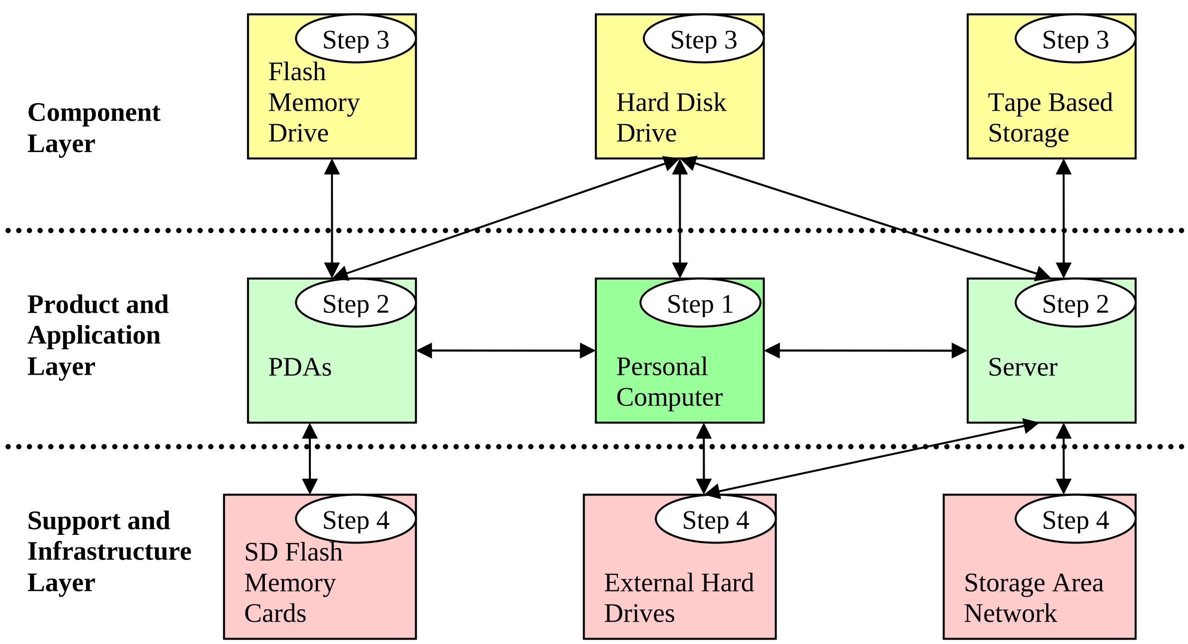


Figure 2 provides a graphical view of the *first level* of analysis: it considers the focal technology and technologies immediately related to it. If necessary, the ecosystem view could be expanded to consider additional levels of analysis, such as the components of components of the focal technology. Also, in the current example we focus on generic technology classes; however, the analyst could identify specific technologies by manufacturer and incorporate a firm-level competitive analysis into the ecosystem. For example, Dell could consider one of its PC models as the focal technology and then identify specific competing models. A clear benefit of modeling in this manner is that the analyst has the ability to decide the level of detail captured by the ecosystem view. In the hands of a domain expert, the technology ecosystem view could be a powerful tool for discovering relationships and opportunities.

RELATIONSHIPS AND INFLUENCE: INCORPORATING THE TEMPORAL ASPECT

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 impact that current technologies have on future technologies, we define *paths of influence* within a technology ecosystem. Specifically, paths of influence occur between technologies in a current state of the ecosystem and technologies in a future state of the ecosystem. Technologies are organized into roles, and a path of influence captures the effect of technologies in a specific role of the current ecosystem state on technologies in a specific role in the future ecosystem state (Adomavicius et al. 2007). Therefore, paths of influence occur within or across the technology layers and describe relationships between technology roles over time in the ecosystem. For example, the current component technologies may influence the development of new product technologies, representing a specific path of influence Component Role → Product and Application Role* (or C→P*).[1] The underlying causal mechanisms behind paths of influence are based on the fact that technological innovation by nature builds on the state of the art. Any advancement in a component technology, such as increased HDD capacity, immediately provides opportunities for the development of new products that use the new component (C→P*). Conversely, the success of a product technology indicates that there is a demand for the functionality this product provides and, in turn, sparks innovation to improve the product in its next generation, which is embodied by the development of improved components (P→C*). This suggests that innovations in a technology both drive and leverage innovations in other related technologies. Therefore, paths of influence can exist between any technology role

[1] We use the asterisk (*) to indicate a future state of a technology layer in the ecosystem, and we use C, P, I as abbreviations for component role, product and application role, and support and infrastructure role respectively. Current states in the ecosystem are represented as layers without an asterisk.

in the current state and any role in the future state of an ecosystem. Table 2 classifies the nine paths of influence in a 3×3 matrix, each cell representing a different path.

Table 2. Paths of Influence: Characteristics and Examples

	Component Future State (C*)	**Product Future State (P*)**	**Infrastructure Future State (I*)**
Component Present State (C)	**Component Evolution** New components improve on the past generation of components *Example*: Microprocessors obeying Moore's Law	**Design and Compilation** A new product is designed using existing components *Example*: PCs that use dual core processors	**Standards and Infrastructure Development** New infrastructure technologies developed to leverage existing components *Example*: P2P networks developing around the mp3 file format.
Product Present State (P)	**Product-Driven Component Development** Product success drives need for next generation components *Example*: Decreasing size of HDDs for personal devices	**Product Integration and Evolution** A new product is created by combining existing products and new products improve on past generation of products *Example*: Integrating cell phone with digital camera	**Diffusion and Adoption** Product success drives need for infrastructure to support/enhance product use *Example*: Development of photo-quality laser printers for home use
Infra-structure Present State (I)	**Infrastructure-Driven Component Development** New components developed that better operate in existing infrastructure *Example*: Microprocessors with integrated 802.11b/g chipsets for wireless networking	**Infrastructure-Leveraging Product Development** New products developed that leverage existing infrastructure *Example*: Instant messaging applications developed for communication over Internet	**Support Evolution** New infrastructure improves on past generation of infrastructure *Example*: Growth of mobile cellular phone network and 3G upgrades

This classification offers interesting insights into how technologies evolve. For example, some technological innovations represent the continuous development and refinement of technologies within the same role. (See paths C→C*, P→P*, I→I*.) For instance, 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 (Service, 2005). 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 integration of two existing technologies to create new product.

Other technological innovations represent the impact of current technologies on the next generation of products and infrastructure that use or work with them. (See paths C→P*, P→I*, C→I*.) The introduction of the next generation component technology can drive evolution of the technologies that will use this new component. For example, the evolution of high capacity micro HDDs has enabled the development of many popular DAPs, such as the iPod.

Alternatively, components can become standardized, and new support and infrastructure technologies emerge that leverage those standards. For example, P2P networks evolved as a result of the increased use of the MPEG-1 Audio Layer 3 (MP3) audio compression format, which made it easier to share music files over the Internet. Similarly, a diffusion and adoption path of influence can occur when a product technology becomes widespread, which provides motivation for the development of new infrastructure technologies. For example, the widespread adoption of digital cameras for personal use has led to the introduction of affordable photo-quality printers.

Often the use of a technology impacts the development and evolution of technologies on which it depends. (See paths P→C*, I→C*, I→P*.) For instance, as product role technologies evolve, advances in component technologies are often necessary to realize a new design. The growth in popularity of DAPs and other personal digital devices has sparked the development of smaller components, such as high capacity micro-HDDs. Also, once a support or infrastructure technology is in place, it provides opportunities for new product technologies to leverage its services and facilities. For example, the rapid expansion of the internet and quick adoption of broadband has driven the development of applications, such as instant messaging, that leverage this infrastructure. Additionally, the growth and development of support and infrastructure role technologies can spark further innovation in component role technologies. For example, the widespread adoption of wireless networking technologies led to the development of microprocessors with integrated 802.11b/g chipsets and the next generation of wireless networking products using new 802.11n and Wi-Max standards.

In concert with the technology roles, paths of influence provide structure to capture the dynamic and complex nature of technology evolution. Since the development of a new technology or improvements to an existing technology may be triggered by one or more paths of influence, identifying these paths can also provide the analyst with tangible opportunities for technology investment and product development. Specifically, the ecosystem model of technology evolution allows the analyst to identify 1) the current state of the technology ecosystem using the technology roles construct and 2) the causal mechanisms that lead to transitions between states of the ecosystem using the paths of influence construct. Additionally, by monitoring the states and transitions of a specific ecosystem over time, the analyst can identify recurring patterns or trends in state transitions, which may provide predictive implications and insights on the timing and release of new technologies.

CASE STUDY: EVOLUTIONARY PATTERNS OF INTELLIGENT STORAGE

There are many potential settings in which it is possible to use the framework provided by the ecosystem model and resulting paths of influence, such as DVD technologies, protection mechanisms for information goods, the changing capabilities of RFID tags, and the rapidly changing functionality of digital camera technologies. We next describe an application of the framework to an evolving technological paradigm – *intelligent storage*.

Background on Data Storage Technologies

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

By adopting the ecosystem view of technology evolution, a manufacturer can identify the component, product and application, and infrastructure and support technologies related to the PC (the focal technology) in the context of storage as outlined previously. (See Table 1.) The manufacturer can also identify examples of the types of innovations that have emerged or have the potential to emerge in the data storage industry. Raw storage technologies include HDDs, tape, and optical storage. We think of these as component role technologies, since they provide the technological foundations for products and applications in the data storage industry. However, to become useful in the industry, these raw storage technologies must be integrated with other technologies to form storage products that satisfy specific storage needs. Product role technologies that compete with the focal technologies include electronic devices that use storage components (e.g., PCs, PDAs), in addition to specifically designed storage servers and devices.

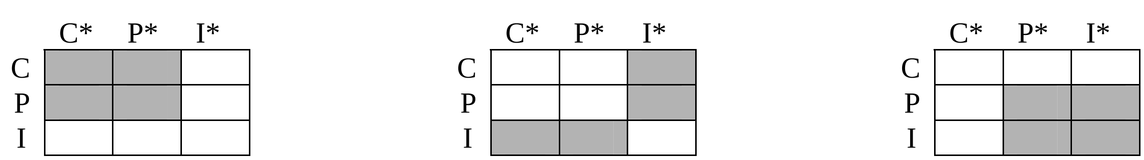
Furthermore, today's storage systems include connectivity and maintenance functionalities that support the need for highly usable data storage. As storage systems have evolved, so too have the infrastructure technologies that support the widespread use of these systems. For example, many specific protocols have been developed to provide consistency in storage system operation. The Network File System (NFS) and the Common Internet File System (CIFS) have become standard network protocols for storage system communication. Similarly, as communication technologies (e.g., Ethernet LAN and TCP/IP) have become more widely adopted, networked storage systems (e.g., storage area networks or SANs and network attached storage or NAS) have also become more commonly used.

From Data Storage to Intelligent Storage Technologies

A recent trend in the data storage industry is the development of *intelligent storage technologies*. Intelligent storage will impact component, product, and infrastructure technologies within the data storage ecosystem and is likely to become the new focus of the industry. Intelligent storage technologies are aware of resources and data objects (and their content), can dynamically manage them, and have the potential to learn new tasks as requirements change (DISC 2004). We can identify paths of influence that may impact the development of specific *intelligent* technologies in the storage ecosystem in three key areas: a) devices, b) systems and networks, and c) the Internet and global applications. Based on the paths of influence prevalent in these three areas of development, the manufacturer will be able to identify three corresponding patterns of technological innovations. (See Figure 3.)

In the development of intelligent devices, the manufacturer is likely to see simultaneous component evolution and the design of new products and applications (Figure 3a). As intelligent systems and networks evolve, they will incorporate new component and product technologies to provide the support infrastructure for the emerging storage needs (Figure 3b). Additionally, the Internet will continue to become more intelligent (as evidenced by the latest developments in Web search, Web services, and semantic Web technologies) and provide the supporting infrastructure technologies for global and distributed applications (Figure 3c). Below we provide specific examples to illustrate and explore these evolutionary patterns.

Figure 3. Evolutionary Patterns in the Intelligent Storage Technologies Ecosystem



(a) Intelligent storage devices

(b) Intelligent storage systems/networks

(c) Intelligent Internet and global applications

Examples of the Evolutionary Patterns of Intelligent Storage Technologies

First, we can embed intelligence into devices by using object and attribute-based storage techniques and providing support for specific file types. These techniques use advanced file systems to provide smarter and faster searches as compared to the current *de facto* standard hierarchical file systems. For example, Microsoft's next generation file system WinFS is an attribute-based relational system that will be available as an add-on for their next operating system release Windows Vista (Montalbano 2005). It is likely that storage component technologies, such as HDDs for PCs, will evolve to support and improve on this intelligence (C→C*). Similarly, based on the emergence and success of small mobile personal electronic devices, such as MP3 players and PDAs, one might have predicted a greater demand for storage devices that are high in capacity, smaller in size, and extremely stable (C→P*, P→C*). These personal devices may have specific storage application needs based on the type of data being stored. Storage technologies, such as high capacity micro drives and solid-state storage, will likely evolve as components and provide intelligent support for small electronic devices (C→C*). Smart personal media devices that utilize attribute-based storage techniques also could evolve to meet consumer media management requirements (C→P*, P→P*). For example, personal digital media devices can potentially incorporate storage components that manage large photo and video collections based on attributes such as the location of a recording or the subject.

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

Third, the expansion of global communications and the growing reach of the Internet also provide opportunities for storage technology evolution. As Internet users' storage requirements evolve, so will the technologies that support them. Storage device manufacturers may develop smart products, applications, and supporting technologies to manage the complex storage issues of the Internet. The latest generation of online email systems provides a good example. Both Google's Gmail (gmail.google.com) and Microsoft's Windows Live Mail offer subscribers over two gigabytes of space for personal email storage as well as innovative new email search functionality.

Based on the preceding analysis, an analyst might predict a new trend for free online storage and storage products. These products will evolve to manage large amounts of data across the Internet using intelligent storage technologies (P→P*) and advanced search methods. The current research 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 (I→I*) (Roush 2003). PlanetLab is implementing smart nodes to increase the intelligence of the Internet and increase its usability (P→I*, I→P*). Smart nodes allow users to access files and desktops anywhere they have Internet access regardless of location.

By identifying the important technologies and relationships within the data storage ecosystem, manufacturers can create the structure necessary for understanding the evolving data storage industry. In the above example, we showed how this approach can help to analyze the evolution of intelligent storage technologies and to discuss opportunities for new products, components, and services that would use and support such technologies.

CONCLUSION

To make good decisions about technology forecasting, technology investment and adoption, and new product development, the ability to analyze the set of interrelated technologies as a system is crucial. Analyzing each technology in isolation is usually not as effective. The ecosystem view provides analysts with a tool for dissecting the interplay among the multiple factors that affect the process of technology evolution. We believe that the ideas discussed in this article will be further explored by the researchers and practitioners, which will advance our collective understanding of technology evolution.

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