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Understanding Evolution in Technology Ecosystems

THE CURRENT ENVIRONMENT of information technology can be a complex place for analysts and firms to navigate, especially when 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 firms need to understand the nature of technological change and evolution in order to accurately forecast and take advantage of investment and market opportunities. For example, although RFID has been in the news for the past decade as the potential distribution and retail "killer technology", uncertainties about its future technical capabilities, economics, standards, and potential social issues make it a wildcard for many potential adopting firms.[a] Despite the need to make sense of the complexities of the technology landscape, there is a lack of useful analytical tools. IT industry experts recognize this problem:

> *The main challenge is the dynamic nature of the whole rapidly changing IT environment [...] what we need are more formal frameworks and tools to help see more clearly the current and potential future technology landscapes. There is definitely room for improvement in developing these types of tools for managers.*[2]

There has been extensive research on the nature of innovation and there are many theories and methods for technological forecasting.[8] A critique of these models, however, is that technologies are often considered individually. With today's highly interconnected technology systems running the world's organizations, it is necessary to consider a system of interrelated technologies and factors that influence the evolution and development of one another. We propose the *technology ecosystem model* for representing the dynamic nature of technological evolution. The model is designed to help firms identify the important relationships between the multiple technologies that potentially influence their operations and strategic decisions. The model outlines the three specific *roles* that technologies can play within an ecosystem and the nine *paths of influence* that describe the types of interactions technology roles have with one another.

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*

a See, for example, the research report "Radio Frequency Identification (RFID) adoption stalls" from Computer Economics, February 2007, available online at: www.computereconomics.com/article.cfm?id=1203. Also see Waters and Rahman.[11]

hierarchies with many *interdependent relationships.*[1] By modeling technology as an ecosystem, an analyst 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 one another.

The *component role* describes technologies when they are used as subunits or subsystems of other technologies in the ecosystem. For example, RAM chips, microprocessors, and 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 instance, the hard disk drive (HDD) acts as a component in PCs, servers, 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 that interact with a user in a given technology usage context and are built from modules of component technologies. They are designed to perform a specific set of functions for its user in a specific usage context. 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 enable (or work as a peripheral to) other product technologies. Infrastructure technologies add value to the use of the product technologies they support and enable in the given ecosystem. For example, a printer is not necessary for the use of a PC, but it supports the PC's use by extending its functionality and expanding the PC's system of use, and together they provide additional value and services to their users. An example of enabling infrastructure technology is wireless networking access points, which enable the use of laptop computers and other devices with built-in 802.11 radios.

Identification of an Ecosystem. In theory, technologies could act in multiple roles and have multiple relationships, making a global technology ecosystem very complex and difficult to analyze. In practice, however, an industry expert or technology analyst is typically interested in understanding relationships within 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 a specific technology usage context. 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 and the resulting example technologies and their roles in Table 1.

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

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.

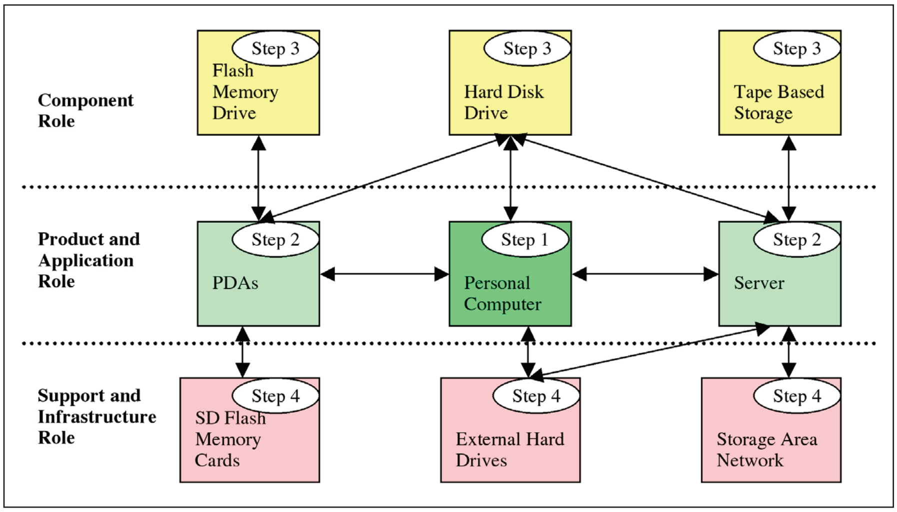
Step 3 (Identification of Component Technologies). The analyst identifies technologies that are used as components in the product and application role technologies. This set of technologies plays the component role with respect to the focal technology.

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.

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



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 decisions to invest in or develop new technology require firms to identify a goal or desired future state. Since technologies change over time, any practical model for analyzing technological change must incorporate the *temporal aspect*. To capture the temporal aspect in the technology ecosystem representation, we define *paths of influence* to describe the impact technology roles can have on one another over time. 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.[1] Therefore, paths of influence occur within or across the technology roles and describe relationships between technology roles over time. For example, 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*).[b] 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. This type of interaction is embodied by the development of improved components (P→C*). Innovations in a technology both drive and leverage innovations in other related technologies. Therefore, paths of influence can exist between any technology role 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, with examples of these interactions.

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 inte-

b We use the asterisk (*) to indicate a future state of a technology role 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 roles without an asterisk.

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:* Combining new touch screen components and hand writing recognition software to create tablet PC functionality.	**Standards and Infrastructure Development** New infrastructure technologies developed to leverage existing components *Example:* The development of IEEE 802.11 standards for wireless components.
Product Present State (P)	**Product-Driven Component Development** Product success drives need for next generation components *Example:* Decreasing size of HDDs for personal devices and increased development of higher capacity sold-state storage components	**Product Integration and Evolution** A new product is created by combining existing products and new products improve on past generation of products *Example:* Integration of mobile phones, PDAs, digital cameras, and media players to create smart phones for personal mobile computing (e.g. the iPhone).	**Diffusion and Adoption** Product success drives need for infrastructure to support/enhance product use *Example:* Development of photo-quality laser printers for home use.
Infrastructure Present State (I)	**Infrastructure-Driven Component Development** New components developed that better operate in existing infrastructure *Example:* Wireless network penetration helps drive the development of integrated wireless networking chipsets and media optimized processors.	**Infrastructure-LeveragingProduct Development** New products developed that leverage existing infrastructure *Example:* Designs of PCs and smart phones are optimized to utilize broad-band wireless services (e.g., 3G networks).	**Support Evolution** New infrastructure improves on past generation of infrastructure *Example:* Continual improvement and growth of mobile cellular phone network and 3G upgrades.

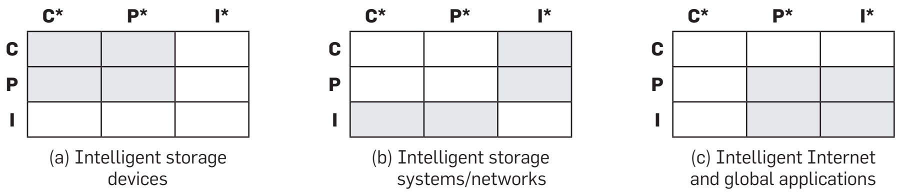
Note: Adapted from Adomavicius et al. 2008.

grated chips will double approximately every 18 months and ongoing research and development continues to uphold this law.[10] Similarly, incremental product evolution occurs as existing products are integrated or new features are added to improve on design and create new products. Smart phones for mobile computing are an example of integration of several existing technologies to create new product.

Other technological innovations represent the impact of current technologies on the next generation of products and infrastructure. (See paths C→P*, P→I*, C→I*.) For example, the evolution of component technologies, such as touch screens and high capacity micro-HDDs, has enabled the development of the latest smart phone and tablet PC products, such as the iPhone. Alternatively, components can become standardized, and new support and infrastructure technologies emerge that leverage those standards. For example, the IEEE 802.11 standards for wireless networking components provide the technological infrastructure for the Wi-Fi industry. 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 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 an 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 and optimized hardware that leverage this infrastructure. Additionally, the growth and development of infrastructure technologies can spark further innovation in component 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 WiMax standards.

Figure 3. Evolutionary Patterns in the Intelligent Storage Technologies Ecosystem



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 technology roles and (2) the causal mechanisms that lead to transitions between states of the ecosystem using paths of influence. 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 technology ecosystem framework and paths of influence. 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.[7] 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 are being increasingly treated as a strategic resource by firms[3] and the rapid increase in the storage needs of consumers for multimedia and entertainment purposes (i.e., videos, music, photos, etc.).

By adopting the ecosystem view of technology evolution, a manufacturer can identify the component, product, and infrastructure 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 drives, and optical storage systems. 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. A recent trend in the data storage industry is the development of *intelligent storage devices*. Intelligent storage will impact component, product, and infrastructure technologies within the data storage ecosystem and is likely to become the new focus of the storage 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.[4] 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, an analyst can 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.

Examples of the Evolutionary Patterns. First, intelligence can be embedded into devices by using object-based 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 (Windows Future Storage) is an attribute-based relational system that was under development as part of the Windows Longhorn operating system[c].[6] It is likely that storage component technologies, such as HDDs for PCs, will evolve to support and improve on this intelligence ($C \rightarrow C^*$). Similarly, based on the emergence and success of small mobile personal electronic devices, such as MP3 players, and smart phones, one might have predicted a greater demand for storage devices that are high in capacity, smaller in size, and extremely stable ($C \rightarrow P^*$, $P \rightarrow C^*$). 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 ($C \rightarrow C^*$). Smart personal media devices that utilize attribute-based storage techniques also could evolve to meet consumer media management requirements ($C \rightarrow P^*$, $P \rightarrow P^*$). For example, personal digital media and communication devices, such as the iPhone, could potentially incorporate storage components that manage large photo and video collections based on attributes such as the location or subject of a recording.

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.[7] 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 ($I \rightarrow C^*$, $I \rightarrow P^*$). For example, researchers an the DTC Intelligent Storage Consortium[4] at University of Minnesota are developing technologies such as network-aware tape drives[5] and parallel archival systems using object-based storage devices (www.dtc.umn.edu/disc/research.html). 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 ($P \rightarrow I^*$, $C \rightarrow I^*$). 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, similar to what is currently possible for personal computers using the Time Machine archive and recovery tool in Mac OSX Leopard (www.apple.com/macosx).

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 provide users with multiple gigabytes of storage space for personal email storage. New distributed storage technologies such as DropBox (www.getdropbox.com) and Microsoft's Windows Live FolderShare (www.foldershare.com) allow users to sync file folder contents across multiple devices and share storage with other users.

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 ($P \rightarrow P^*$) and advanced search

c Longhorn is the Windows codename for the initial development of Windows Vista and Windows server 2008. WinFS did not make it into either of the current Windows operating systems but still stands as one of the first serious attempts at a relational-based file system for commercial operating systems.

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*).[9] 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 and explore the evolution of intelligent storage technologies and to discuss opportunities for new products, components, and services that would use and support such technologies.

Conclusion

The ability to analyze the complex relationships among the technologies used by organizations today is critical for making good technology forecasts, technology investments, and technology development and adoption decisions. The technology ecosystem model presented in this article provides analysts with a tool for making sense of these complexities and helps dissect the interplay among the multiple factors that influence technological change. We believe that the ideas discussed in this article should be further explored by researchers and practitioners, which will advance our collective understanding of technology evolution. C

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