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Modeling the evolution of system technology performance when component and system technology performances interact: Commensalism and amensalism

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ABSTRACT

The interaction between technologies critically determines technology evolution. Commensalism and amensalism are two common relationships between component and system technologies but have attracted scant research attention. In both the relationships, the component technology performance is unaffected by the system technology performance. However, as the component technology performance improves, the system technology performance is enhanced in commensalism but inhibited in amensalism. We model commensalism and amensalism and predict the evolution of system technology performance using Lotka-Volterra equations. In these two scenarios, we decouple the equations and derive the general analytic solution for system technology performance. We also deduce the corresponding solutions for cases where the component technology performance follows a logistic function or simple exponential growth. The solutions consider the impact on system technology performance of changes in component technology performance and enable us to predict the future performance evolution of system technology. We demonstrate the prediction accuracy of our model through an empirical study of the concrete skyscraper technology. We also interpret the parameters in Lotka-Volterra equations and explore strategies to boost system technology performance. The analytic solutions and parameter interpretations allow practitioners and policy makers to use our model as a strategic management tool for their future work.

1. Introduction

Technology evolution describes variation in technology performance over time. It critically determines the destinies of industries and firms (Lee and Nakicenovic, 1988; Utterback, 1996). We broadly define technology to include hardware (e.g., aircraft, automobile, laptop) and software (e.g., know-how, human knowledge, programs) (Grübler, 1998). Technology performance can be measured by technical parameters such as speed, capacity, and efficiency or combined parameters such as capacity per unit cost.

Researchers have used different mathematical functional forms to develop descriptive models and empirically illustrate them using technology evolution data. Technology performance forecasts are typically made by extrapolating data on past performance through these models. However, several functional form models for technology performance forecasting exist. Practitioners often have to go through tedious procedures to select an appropriate model for their problem (Meade and Islam, 1998; Young, 1993). Moreover, most of parameters in these models lack physical meaning or interpretation. The models often are best fitting curves rather than descriptors of causality. In other words, many models assume that technology evolution is not affected by external or internal factors. These models do not identify what factors shape future technology performance and how firms can change it. Importantly, most technology performance models consider a technology in isolation and not as interconnected with other technologies.

In practice, however, similar to an ecosystem, technologies interact with one another during their development. For example steel technology interacts with bridge technology and central processing unit (CPU) technology interacts with computer technology as they evolve. The underlying interactions among technologies facilitate their evolution, potentially leading to innovations. Two technologies can interact in different ways. A summary of the possible modes of interaction between two technologies based on community ecology theory (Sandén and Hillman, 2011) appears in Table 1.

When using an ecosystem analogy in technology interaction, competition has a clear interpretation as two technologies vie for adoption. For example, in the evolution of audio recording technologies, the 78 rpm record was supplanted by the long playing (LP) record which

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Table 1
Two-technology (two-species) interaction modes.

Mode of interaction	Technology 1	Technology 2	General nature of interaction
Competition	−	−	Both technologies inhibit each other
Symbiosis	+	+	Both technologies favor each other
Neutralism	0	0	Neither technology affects the other
Parasitism (and predation)	−	+	Technology 2 is benefited, Technology 1 is inhibited
Commensalism	0	+	Technology 2 is benefited, Technology 1 is unaffected
Amensalism	0	−	Technology 2 is inhibited, Technology 1 is unaffected

gave way to the cassette, which was replaced by the CD, followed by digital streaming technology of music storage and playback. We can model this technology evolution using a competitive model of existing and replacement technologies.

Besides competing with each other, two technologies may also interact with each other in tandem. A system technology is often supported by one (or more) component technologies. For example, the computer (system) has a symbiotic relationship with the hard drive (component). Computer hard drive capacity limit has grown from megabytes to terabytes over a fifty-year period. This change in hard drive technology supported the boom in computer technology. At the same time, the fast development of computer technology also facilitated improvements in hard drive performance.

Both competition and symbiosis have been researched (e.g. Fisher and Pry, 1971; Marchetti and Nakicenovic, 1979; Pistorius, 1994). Furthermore, neutralism does not involve technology interaction whereas parasitism (and predation) is more likely in community ecology rather than in technology evolution.

However, commensalism and amensalism are two common relationships between technologies in the real world, yet they have received only scant attention in the literature. Component technology (Technology 1 in Table 1) has either a beneficial or a detrimental effect on system technology (Technology 2 in Table 1), but it is typically not affected by system technology. Commensalism or amensalism can occur when one component technology serves a diverse set of system technologies, leading to system technologies having a negligible impact on the evolution of that component technology. For example, the technical performance (e.g., length, load capacity) of a modern bridge (system) relies on advances in steel (component) technology. Improved steel properties (e.g., strength, ductility) can lead to better bridge performance, but the evolution of bridge technology has little impact on the development of steel technology because steel also supports and interacts in the ecosystems of many other system technologies (e.g., automobile, ship). In this case, the bridge has a commensalism relationship with steel. Similarly, an amensalism relationship exists between a CPU and a laptop. The development of the CPU makes this component more compact, inducing more unwanted heat in the CPU area. The thermal dissipation performance of a laptop system is weakened by the rapid development of the CPU component, prompting a whole system redesign.

In this paper, we model technology commensalism and amensalism and predict system technology evolution using Lotka-Volterra equations. Because system technology development has a negligible influence on component technology in commensalism and amensalism, we are able to decouple and reduce the Lotka-Volterra equations to a single first-order linear ordinary differential equation. The solution of the reduced Lotka-Volterra equations enables us to predict the future evolution of a system technology from historical performance data on system and component technologies. Thus, we contribute to the interactive technologies' evolution literature by proposing new models for commensalism and amensalism and empirically demonstrating the models with strong predictions and implications for managers and policy makers.

The rest of the paper is organized as follows. In Section 2, we review related literature. We develop the models and describe the procedure for solving the reduced Lotka-Volterra equations and derive the general solution for system technology performance in Section 3. In Section 4, we analyze the logistic growth function and the simple exponential growth function as representative component technology evolution curves and derive the corresponding solutions for system technology performance. We discuss strategies to boost system technology performance through simulation results in Section 5. In Section 6, we demonstrate the model through an empirical application in which we develop predictions for concrete skyscraper technology using the previously developed solutions. We discuss the implications of our model for managers and policy makers in Section 7. We close with conclusions and suggestions for future research.

2. Related literature

Previous research in this area has focused on technology competition and substitution through different models (e.g., Fisher and Pry, 1971; Marchetti and Nakicenovic, 1979). Pistorius and Utterback (1997) argue that interactions between technologies should be viewed broadly through three major modes: pure competition, symbiosis, and predator-prey. Borrowing from community ecology (Odum and Barrett, 2005), Sandén and Hillman (2011) extend the modes of technology interaction to six based on the types of interactions between two species (Table 1).

First suggested by Pistorius and Utterback (1997), Lotka-Volterra equations can be used to study the interaction between two technologies. Lotka-Volterra equations are:

$$\frac{dN}{dt} = A_n N - B_n N^2 \pm C_{nm} NM \tag{1}$$

$$\frac{dM}{dt} = A_m M - B_m M^2 \pm C_{mn} MN \tag{2}$$

where $N(t)$ and $M(t)$ denote performance measures of the two technologies m and n, respectively. The derivatives $\mathrm{d}N/\mathrm{d}t$ and $\mathrm{d}M/\mathrm{d}t$ represent the performance change rates of the two technologies. A, B, and C are constants.

Lotka-Volterra equations were first introduced by Vito Volterra in the early 20th century to model population changes of sharks and food fish in the Adriatic Sea. The model has been expanded and successfully applied in the fields of demography and ecology during the last century (Porter et al., 1991). Prior research has examined the mathematical characteristics of Lotka-Volterra equations (Bazykin, 1998; Goh, 1976). The Lotka-Volterra model includes a technology interaction term and is powerful to fit Logistic, Gompertz, Bass, Non-Symmetrical Responding Logistic (NSRL) and Sharif-Kabir curves (Bhargava, 1989; Morris and Pratt, 2003). Unfortunately, analytic solutions of Lotka-Volterra equations are not available yet. Numerical methods have to be applied for solving the equations, making predictive explorations of technology interactions cumbersome.

Modis introduced the same six interaction modes between products or firms before Sandén and Hillman (2011) did for technology interaction (Modis, 1997). Product sales commensalism phenomenon is illustrated by add-ons and accessories sales. For example, the more the