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Standard-Scape: An Agent-based Model of Competition in Markets with Network Externalities (05-105)

Judy K. Frels, James A. Reggia, and Debra Heisler

How Firm Advertising Affects Employees' Trust, Organizational Identification, and Customer Focus (05-106)

Mary Wolfinbarger and Mary C. Gilly

Handling Missing Values in Marketing Data: A Comparison of Techniques (05-107)

James Lemieux and Leigh McAlister

Mapping the Domain of Subjective Value in Negotiation (05-108)

Jared R. Curhan, Hillary Anger Elfenbein, and Heng Xu

Consumer Testimonials as Self-Generated Advertisements: Evaluative Reconstruction Following Product Usage (05-109)

Terence A. Shimp, Stacy L. Wood, and Laura Smarandescu

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Standard-Scape: An Agent-based Model of Competition in Markets with Network Externalities

Judy K. Frels, James A. Reggia, and Debra Heisler

In network markets, it becomes critical for firms to "tip" the market in their direction. Before undertaking aggressive strategies such as penetration pricing, however, firms should determine just how important network externalities are to their customers.

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Report Summary

Some products, particularly those in the information technology market, become more valuable and useful to consumers when the number of other consumers using the product increases. For example, as more and more people purchased VHS videocassette recorders, their value to consumers increased and that of Sony's incompatible Betamax declined. In such network markets a company may adopt strategies, sometimes counter to strategies for other markets, to ensure that its products become the prevailing standard.

In this study, Frels, Reggia, and Heisler examine the evolution of network markets through a computer simulation using agent-based modeling (based on data derived from a study of cellphone plans offered to college students). Two firms battled for market dominance by using strategies based on target market share and price cuts. The authors studied markets in which the two companies' technologies were equally capable and in which one technology was superior to the other. They find that the importance of the network to the consumer is critical in determining the financial success of enacting network development strategies.

When two equal technologies compete in an environment in which network externalities are important to consumers, a more aggressive penetration pricing strategy leads to larger numbers of adopters and also to greater income. When one technology is inferior, a penetration pricing strategy may increase market share, but not income.

When network externalities were less important to consumers, and technologies are equally capable, aggressive network development via penetration pricing was successful from an adoption standpoint, but was always disastrous from a financial standpoint. Further, when the most aggressive strategy was countered by even the slightest price cutting on the competitor's part, both firms lost money.

The only time the inferior technology matched the superior technology in financial success was when network effects were minimal. However, success may be too positive a word to describe the situation, since both the inferior and superior technologies were forced to cut prices severely to achieve their market share goals. ■

Introduction

In many markets, particularly information technology markets, consumers gain benefits from doing what other consumers do: standardizing or adopting compatible products. Such markets are called network markets (Besen and Farrell 1994; Frels, Shervani, and Srivastava 2003) because the value that a consumer gets from a product depends on the network of other consumers associated with that product. For example, telephones and fax machines are valuable only when other people (a network) have purchased such products. The VHS version of the videocassette recorder was deemed more valuable than Sony's Betamax because, as more people purchased the VHS format, there were more people with whom one could trade videotapes and video rental stores began to carry more titles in that format. Network markets are "tippy" or "winner take all," meaning that as one product gets ahead, it becomes more attractive to the next adopter who, upon adopting it, makes it even more attractive to the next adopter. Thus, one characteristic of such markets is that often only one technical standard is likely to prevail. Because the value that the network provides can overwhelm the value provided by the technology itself, it is possible that the prevailing standard will not be the most technologically advanced.

In such markets, firms are encouraged to adopt strategies to ensure the market tips in their direction rather than their competitor's. In our research, we examined the efficacy of strategies recommended in network markets. Strategies appropriate in network markets often run counter to strategies recommended in non-network markets. Because network markets show increasing returns to adoption, it becomes critical for a firm to gain an early lead in adoption (Besen and Farrell 1994). Thus, in such a market, it may be worthwhile to pursue strategies that do not immediately enhance revenue under the assumption that greater revenue can be captured once the market has tipped in the firm's direction. Examples of suggested strategies for network markets include penetration pricing, signaling, product improvements, preannouncements, licensing the technology to additional producers, and support for developing complementary products (Besen and Farrell 1994; Hill 1997).

Our research uses agent-based models. In his book *Micromotives and Macrobehavior* (1978), Schelling proposed that much could be learned about aggregate human behavior by examining preferences and behaviors at the individual level. His early models provided startling results on social structure formation, but were constrained by the computational limits of the time. As computational power has increased and become more widely available, we have seen the emergence of computer-simulated multi-agent models (Ferber 1999; Liu 2001; Weiss 1999). In multi-agent models, individuals (called agents) and their environment are given characteristics and rules by which they are created, live, consume, interact, and die. This bottom-up approach is based on developing realistic yet simple decision rules for each type of agent and allowing their behavior to evolve over time. Surprisingly, despite the simplicity of the rules, one often finds that the behavior emerging from the overall system is complex and difficult to foresee.

In an artificial world we call "Standard-Scape," our agents represented adopters (individual consumers or firms) who chose between two incompatible technological products (A or B) and whose goal is to maximize their utility (Frels, Heisler, and Reggia 2003). We also modeled technology sponsor agents representing firms competing in a market with network externalities where the firms vied to achieve a dominant market share and then recoup their investment in gaining that share. Each technology sponsor firm had a cost of goods sold, and we tracked the revenue each firm obtained from the agents adopting its products. If, through various strategies, the technology sponsor agents depleted the capital they had gained from adoptions, the technology sponsors went out of business.

Why would a manager be interested in simulated models of consumer and firm actions? We believe there are several reasons. First, our models included multiple populations—consumers and technology providers. Such a model is difficult to examine empirically, requiring multiple populations to be sampled simultaneously and then analyzed in a single model. Developing analytical models that include multiple populations has been intractable, discouraging economists from using mathematics to address the interdependencies among the networks. Our models represent the complete product ecosystem and allow consumers and firms to react to one another.

Second, we show the emergent characteristics of the markets over time. Surveying these populations longitudinally would require a significant commitment of time and capital. And while formal mathematical economics models often demonstrate that multiple equilibria are possible (e.g., Katz and Shapiro 1985, 1986; Farrell and Saloner 1986), they do not address the many market situations occurring before the equilibria are reached, where strategic action by firms may alter the path to equilibrium. With the methodology we propose, intermediate stages in the market evolution can be witnessed by the researcher, but more importantly, by the technology sponsor agents within the model who may choose to take strategic action to alter the path. The system is dynamic, and thus, the opportunity to examine the evolution of the marketplace is an important one.

Third, using the methodology described below, we did not rely on top-down or extraneous coordination devices such as common knowledge assumptions or imposed market equilibrium constraints (Tesfatsion 2002). We designated initial starting conditions and initial rule sets for agents, but no subsequent intervention from the modeler was required or permitted. Thus, we did not externally impose market-clearing prices or other coordination devices. The market evolves independently, based on the rules designed for each agent type.

The marriage of agent-based modeling and network markets is ideal. Traditional game theory models of such markets necessarily exclude many of the players, oversimplify their decision processes, or fail to model their impact on one another. Axelrod (1997), a leading game theory researcher has noted the benefits of simulation: "Simulation is necessary because the interactions of adaptive agents typically lead to nonlinear effects that are not amenable to the deductive tools of formal mathematics" (p. 6).

Network Development Strategies

Many strategies are recommended by economists to develop the networks associated with a product. These can be grouped based on their focus on one of three networks: user network, complements network, or producer network.

Strategies suggested that target the user network include penetration and predatory pricing (Farrell and Saloner 1986; Besen and Farrell 1994; Katz and Shapiro 1994), preannouncing products or upgrades (Farrell and Saloner 1986; Besen and Farrell 1994), investing in reputation (Katz and Shapiro 1994), and making sunk investments that commit to the network and can be seen by consumers (Katz and Shapiro 1994).

Strategies associated with the complements network are also suggested. These include strategies ranging from attracting suppliers of complements by licensing the interface to the core technology to providing conversion or development support to building adapters to existing complementary goods (Besen and Farrell 1994; Hill 1997). These strategies may also include contracting out the development of complements to ensure a timely development of this network (Katz and Shapiro 1994).

Finally, strategies tied to the producer network are also suggested. These include persuading other manufacturers to adopt a technological standard (Besen and Farrell 1994) or licensing a product for cloning (Connor 1995). However, when firms are asymmetric in market power, the stronger firm may benefit by resisting compatibility through assertion of intellectual property rights and by changing its technologies frequently to avoid free riding by follower firms (Besen and Farrell 1994).

In our simulations, we examined penetration pricing targeted at the user market for several reasons. First, penetration pricing is the most common strategy recommended for the purpose of growing the user network in an environment where network externalities exist (Katz and Shapiro 1985, 1994; Besen and Farrell 1994, Farrell and Saloner 1986). Further, although penetration pricing affects revenue and profit, it does not involve a direct cost outlay. Thus, it is modeled with greater external validity than other strategies suggested in network market research.

Penetration pricing, although widely cited as a desirable strategy in network markets, is not well defined. As Tellis (1986) defines it: "Penetration pricing and experience curve pricing attempt to exploit scale or experience economies, respectively, by currently pricing below competitors in the same market and thus, driving them out . . . Other essentials for penetration pricing are price sensitivity on the part of some consumers and the threat of competitive entry" (p. 151-2). However, when strategists and researchers discuss penetration pricing, they often include some of the intent that would definitionally be better suited under predatory pricing. Tellis defines predatory pricing "as a strategy of pricing low to hold out competition with the sole objective of establishing monopolistic conditions and subsequently raising price; this practice is illegal under Section 2 of the Sherman Act and the Robinson-Patman Act of 1936" (Tellis 1986, p. 151). When researchers discuss penetration pricing, they often implicitly include the intent to drive the competitor out of the market (as stated in the definition of penetration pricing above) and then establishing monopolistic conditions and raising the price, as stated in the definition of predatory pricing.

Our pricing strategy rule followed this practice of combining these two pricing definitions to generate the following rules:

- When a firm has a market share it does not deem sustainable, it lowers its price to gain further market share.
- When a firm has a market share that it deems dominant and overall market penetration by all providers is significant, it raises its price to recoup earlier revenue forgone by price cutting and to take advantage of its near monopolistic situation (Farrell and Saloner 1986).

Hypotheses

Besen and Farrell (1994) describe the situation many firms face in the marketplace that we studied: two technology sponsors with incompatible technologies competing to become the industry standard. Under such circumstances, they recommend several strategies for success, one of which is to develop an early lead in the installed base. This is judged to be particularly useful when the users' adoption decision is visible to other users and thus can influence the decision of later adopters. One recommended method of achieving this early lead in adopters is through penetration pricing. Thus, we propose,

H1a: Technology sponsors that enact penetration pricing strategies will gain more adopters than will technology sponsors that do not enact penetration pricing strategies.

H1b: Technology sponsors that enact penetration pricing strategies will gain greater income than will technology sponsors that do not enact penetration pricing strategies.

We were also interested in studying the possibility that an inferior technology may gain a dominant market share in a network market (Arthur 1989). Although this has been debated in the economics literature (Arthur 1989; Lebowitz and Margolis 1990, 1995), empirical evidence is scant (for an exception, see Frels, Shervani, Srivastava 2003). We constructed simulations in which one technology can deliver only 80% of the capability of the other. We suggest that through penetration pricing, an inferior technology can indeed dominate a market. Thus,

H2: When using penetration pricing strategies, inferior technologies can gain more adopters than superior technologies.

However, we wanted not only to explore an inferior technology's ability to dominate from a market share perspective, but also to investigate its ability to profit from its gains in share. The link between market share and profitability has generally been considered to exist and to be positive (Buzzell and Gale 1987; Szymanski, Bharadwaj, and Varadarajan 1993; Hellofs and Jacobson 1999). However, the wisdom of pursuing market share for market share's sake and market share's positive relationship to profitability has been questioned by others (Slywotzky and Morrison 2001; Nagle and Holden 2002). The staying power of Apple Computer (even before the introduction of the iPod) has shown that market share alone is not the only determinant of success. We posit that penetration pricing strategies enacted to gain market share may have deleterious effects on the financial health of the firm. Thus,

H3: When using penetration pricing strategies, inferior technologies will gain less net income than superior technologies.

Methodology

Our initial version of Standard-Scape was a modified and extended version of a multi-agent simulation environment developed to investigate situations in which communication evolves between initially noncommunicating agents (Reggia et al. 2001). This simulator supported a 60 x 60 cellular space in which different classes of agents moved and interacted with the environment and other agents. The simulator was very flexible and had numerous parameters (e.g., number of agents present, size of cellular world, distance over which agents interacted, agents' memory capacity, agents' decision making, etc.) Agents had a limited "internal model" of their environment, and their behavior was governed by a finite-state automata model.

To initiate simulations, 600 agents were randomly placed in the grid, no more than one to a spot, for the duration of the simulation. In each time period (a month in this setting), agents sought to adopt a product (A or B) that maximized the agents' utility, calculated using a multi-attribute model (Fishbein and Ajzen 1975) described below. Adopting a product created network externalities (as well as switching costs) that then influenced agents' future utility functions. We modeled a multi-period adoption scenario because such repeated adoption is common in business settings in which continued investment in technology is often required to meet the needs of employees or customers (Frels, Shervani, and Srivastava 2003).

Consumer agents' adoption decision

The structure of our consumer agents' utility function was based on a multi-attribute model (Fishbein and Ajzen 1975) reflecting the standalone technological value of the product, the price of the product, the network of users associated with the product, the consumer's expectations of the future size of the network (Besen and Farrell 1994), and the agents' switching costs (Burnham, Frels, and Mahajan 2003). In the notation below, *p* designates a particular product and *i* designates an individual consumer agent. All weights ($w1_i$–$w5_i$) in the equation below are positive and sum to 100.

$$Utility_{pi} = w1_i(Tech_p) - w2_i(Price_p) + w3_i(Network_{pi}) + w4_i(Expect_{pi}) + w5_i(Investment_{pi})$$

where

$Tech_p$ represents the performance rating of each of the two technologies A and B.

$Price_p$ represents the price of each of the two technologies A and B.

$Network_{pi}$ is calculated as ln(number of neighbors who have bought product p)/ln(total number of neighbors)

$Expect_{pi}$ represents agent-specific expectations about the future size of the user network for products A and B (Besen and Farrell 1994).

$Investment_{pi}$ represents the investments an agent has made in product A or B to date or their switching costs.

At each time tick (conceptualized as a month), each simulated consumer agent attempted to purchase the technology with the greatest utility provided that:

- The consumer agent had sufficient capital.
- The utility of the chosen product was greater than the reservation utility of $Threshold_i$. This represented the amount of utility above and beyond the price that a product must provide in order to bring the consumer to action and purchase a product rather than choosing "no choice" as a preferred option.

Further, when the product that maximized the consumer's utility was determined, that product was adopted with only 85% probability; 15% of the time, the consumer agent would not buy the product even though the utility surpassed the threshold and had sufficient capital. This accounted for events outside the model (Arthur 1989).

One other aspect of the consumer adoption decision provided a stochastic element. The expectations regarding the future size of the product networks ($Expect_{pi}$) were randomly assigned to each agent. These values were updated through the duration of the run to reflect the market evolution. Upon creation, each agent was set to change its expectation every 1 to 12 time ticks. This number was randomly generated and fixed for that agent throughout the run. When it was time to change its expectation, the agent updated that expectation based on which technology the majority of its neighbors bought at the last time tick. The expectations were modified by a random number between 0 and 1. The expectation for the technology with the larger market share went up by a fraction, while the expectation for its competitor went down by a fraction. The expectations had a minimum of 0 and a maximum of 100.

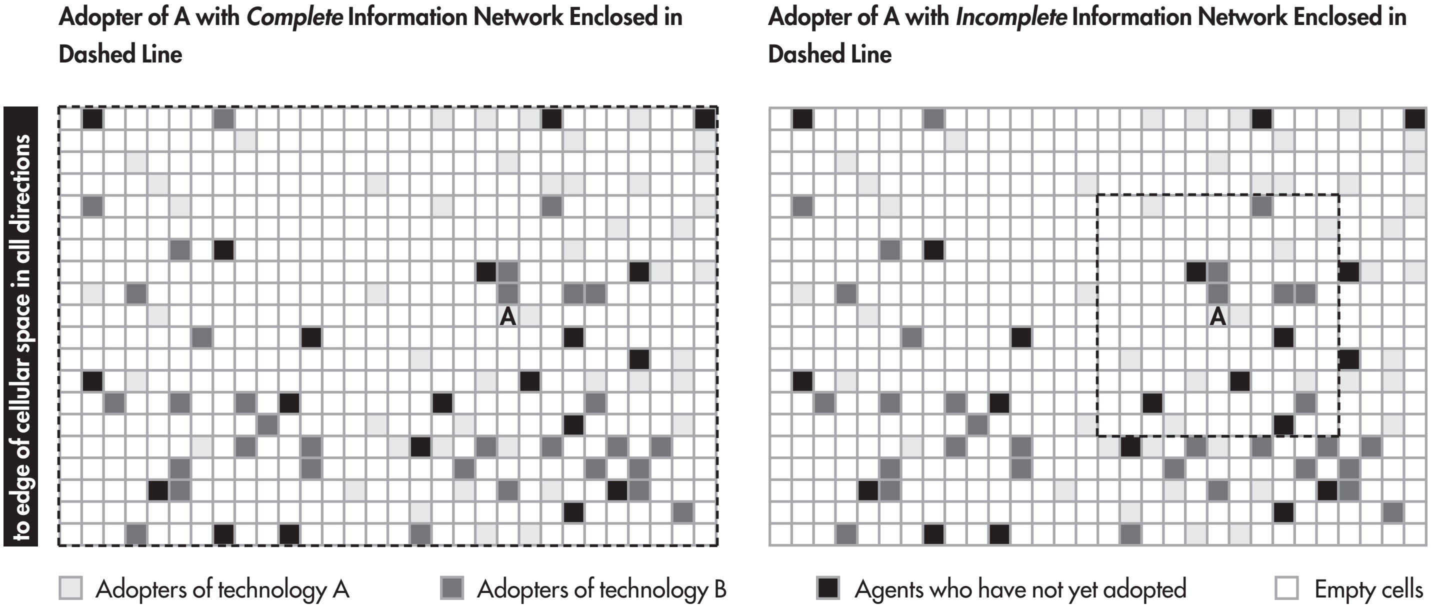
Agents operated in two different information environments. In the environment of complete information or global vision, each agent could see what all 599 other agents in the Standard-Scape adopted. In the incomplete information or local vision environment, consumer agents did not have information about what every other agent was doing; they had information about only the agents in the 120 locations surrounding them (their neighbors). The average number of neighbors for each agent in this scenario was 18.2. Figure 1 depicts a segment of Standard-Scape.

Empirical basis for simulated agents

The weight or importance associated with each attribute in the consumer's utility function was based on empirical data gathered in a choice-based conjoint study. This provided our agents a basis in actual consumers and thus with greater external validity.

Experimental Design. Our conjoint study gave subjects multiple cellphone plans that offered a new feature: "push to talk." Cellphones and "push to talk" were chosen for several reasons. First, they were technology-based products with which our subjects, undergraduate students, would be familiar. Second, given the timing of the research, the "push to talk" feature was recently marketed to consumers and specifically teens. Hence, we believed they would have some familiarity with the function, but the function would not yet be widely diffused. However, to ensure that each subject had at least a basic understanding of the feature, information on the feature was provided to all subjects. Third, the "push to talk" feature added a network externality element to cellphones that did not exist otherwise. Users must be on the same network or use the same service provider in order to use

Figure 1
A Segment of Standard-Scape



this function. This was emphasized in the task as outlined below.

Choice conjoint was used because it mirrored more closely the task of our agents in Standard-Scape and because it has been shown to more closely model actual choice contexts (Orme 2001). Providing the "none" option more clearly reflected realistic choices in the world and the choices our simulated agents had in Standard-Scape. Further, use of the "none" option allowed us to capture information on each subject's relative reservation utility or threshold.

The profiles presented varied on five attributes, reflecting the five elements simulated in the utility equation. The first attribute, technology, was defined as the reliability and quality of the service. This had three levels represented by 2.5 stars, 3.5 stars, and 4.5 stars. The second attribute, the price of the service, was set at $29.99, $39.99, or $49.99. The third attribute, the network, was defined as the number of people in the subject's circle of friends who use the same service and, thus, with whom one would be able to use the "push to talk" feature. The three levels of this attribute were "Nobody you know uses this service," "About half of your friends use this service" and "Pretty much all your friends use this service." The fourth attribute was the future success expected from this cellphone provider. The three levels of this attribute were represented as experts' expectations for the long-term survivability of the service provider. Specifically, the low level was represented as "Experts say the future prospects of this service provider are shaky, at best," mid-level as "Experts are undecided about the future prospects of this service provider," and the high level as "Experts believe this service provider will continue to provide the service in the future." Finally, switching costs were described as "The trouble it would be for you to switch to this service provider." This attribute had only two levels and was operationalized as "Keep your same phone number and transfer all contact information" and "Requires new cellphone number and you cannot transfer your saved numbers."

Procedure. The experiment was administered via computer using Sawtooth Software CBC System (Orme 2001). Subjects, using a computer in a behavioral lab, were presented with three screens instructing them to imagine that they were choosing a new cellphone service provider that offered the "push to talk" feature. The attributes were explained, and the subjects were given two practice choice sets, each with two options and the "none" option. They were then informed that the actual experiment was beginning and reminded of the attributes' meanings. Subjects had 20 choice tasks, each composed of 3 full-profile product descriptions along with the opportunity to select "I would choose none of the services shown." The profiles were generated randomly for each subject using Sawtooth Software CBC System (Orme 2001), which provides approximately random orthogonal designs, with each subject given a unique set of questions. Subjects indicated their preference for one of the three profiles or the "none" option by clicking on the box containing the profile. Subjects could return to previous screens by clicking "previous." Following the 20 choice tasks, subjects answered questions regarding their ownership and use of cellphones as well as basic demographic questions.

The 141 participants were drawn from a large mid-Atlantic undergraduate marketing course and were offered extra credit for participating. The choice data were transformed into individual importance weights for each attribute by using the hierarchical Bayes package from Sawtooth Software. By including the "none" option, we were also able to obtain a unique threshold for each subject to use in the simulation. The weights and thresholds used for each of the 600 agents in the simulation were randomly sampled, with replacement, from these 141 actual consumers.

Calibration of the Empirical Agent Data. In order to draw conclusions from projections based on our empirically-based agents, we needed to calibrate the simulations with actual adoptions witnessed in this group of subjects. To do this, we modeled adoption of traditional cellphones. The conjoint experiment was immediately followed by a series of questions, including one about whether the subject owned a cellphone. The results indicated that 82.6% of the subjects owned a cellphone (9.4% of all subjects owned a cellphone with the "push to talk" feature, 8% of the subjects did not own a cellphone, and 2.2% were considering purchase.) Early simulations achieved market penetration rates of only 3% to 8%, far from the number of subjects who reported owning cellphones in our study. Thus, we calibrated the threshold of the agents, and to further focus the study on the network effects, we increased the relative weight of the network. The network weight was doubled, and then all 5 weights were readjusted to sum to 100% again. Using a base price of 50, we adjusted the threshold of the agents downward by 10% of the original threshold until we could achieve market penetration rates of approximately 80% to 85%, mirroring the number of subjects who stated they owned cellphones. This occurred at 40% of the original threshold.

Thus, threshold values were fixed in our simulation, but we used both the original network weights (minimal network) and the increased network weights (augmented network) as a two-level factor in our experimental design.

Technology sponsor agents

Each competing technology was controlled by a technology sponsor agent. These sponsor agents were able to take action every three time periods (i.e., once per quarter) and react to the market penetration they observe in the marketplace. Each technology sponsor agent, one for technology A and one for technology B, had two internal variables: MktShareTrigger, which describes the market share this sponsor agent wanted to achieve when at least 80% of the market had been penetrated, and PricingFactor, which describes the percentage by which the sponsor raised or lowered the price of the technology. Further, the technology sponsor agents could observe the market share they and their competitors achieved, as well as overall market penetration. (We calculated market share as the number of agents who bought into a particular technology as a percentage of all agents who purchased either technology; market penetration was the proportion of agents, of

Table 1
Penetration Pricing Strategies Tested

	Penetration Pricing Factor	
Market Share Trigger	**20%**	**50%**
65%	Itchy but weak trigger finger (IWTF)	Most aggressive
20%	Least aggressive	Desperation

all possible agents, who bought either technology.)

In each time period, consumer agents were endowed with a certain amount of capital ($100) that they were able to spend on technology A or B or save for future spending, depending on their utility function. If they purchased a product, an amount of capital equal to the price of the product (set by the technology sponsor agents) was transferred to the technology sponsor agent as payment. The technology sponsor agents amassed capital by a simple calculation of revenue (payments) minus the cost of goods sold ($25 for each item). Sponsor agents accumulated capital as long as they sold at a price above their costs. Sponsor agents may sell below their cost, but could only operate for 36 time periods (i.e., 36 months, 3 years, or 12 quarters) with negative capital. After 36 time periods with negative capital, technology sponsor agents exited the market (i.e., went out of business).

The sponsor agents' primary goal was to stay in business. Thus, the first step in executing the pricing rule was to check cumulative capital and, if it was negative, the sponsor agent raised its price by PricingFactor. If cumulative income was positive, the sponsor firms proceeded with the pricing rule.

When the market penetration was low (less than 80%), considered low market penetration, the technology sponsor lowered its price by the PricingFactor in order to attract more buyers. If the market penetration was high (over 80%), the technology sponsor did one of three things based on its current market share and its MktShareTrigger. When the sponsor's market share was between 20% and its desired market share (MktShareTrigger), the technology sponsor lowered its price by the PricingFactor; the technology sponsor believed it still had a chance to achieve the dominant market, so it fought. When the sponsor's market share was above its desired market share, the technology sponsor raised its price by the PricingFactor; it "won" and raised its price to recoup its earlier investment in obtaining this market share. When the sponsor's market share fell below 20%, the technology sponsor did nothing in order to keep its loyal customers.

The technology sponsor had to worry not only about market penetration and market share, but also about its income and accumulated capital so that it would not go out of business. The technology sponsor agents were only allowed to have a negative accumulated capital for 36 ticks or 3 years, at which time the sponsor went out of business regardless of the number of agents buying its product.

At the end of each third time period, the technology sponsors followed the procedure outlined above. Each sponsor agent could not see the new price of the other's technology until the next time the technology sponsors acted, so in effect the two technology sponsor agents acted simultaneously. The adopter agents did not see the effects of the price change until the beginning of the next time step.

Experimental design of simulations

Our simulations were run in a 5 (pricing strategies) x 2 (vision of agents) x 2 (importance of network) experimental design. We developed a menu of pricing strategies (MktShareTrigger and PricingFactor) to be enacted by the inferior technology. In all cases except the most basic runs (described below), the inferior technology enacted one of the strategies and the superior technology enacted the least aggressive strategy. We then examined the effectiveness of these

Table 2

Competition after Five Years between Equal Technologies When One Technology Performs Most Aggressive Strategy

		Mean Income 30 runs		Mean Agents Adopting 30 runs		Out of Business Frequency	
		Most Aggressive	No Action or Least Aggressive	Most Aggressive	No Action or Least Aggressive	Most Aggressive	No Action or Least Aggressive
		Column A	Column B	Column C	Column D	Column E	Column F
Part A: Augmented Network—Network More Important to Consumers							
Most aggressive competes with no action							
	Incomplete information	176,690.83**	87,245.00**	477.23**	9.60**	0	0
	Complete information	242,237.70**	117,545.00**	470.43**	17.83**	0	0
Most aggressive competes with least aggressive							
	Incomplete information	171,085.07**	61,056.07**	422.87**	61.50**	0	0
	Complete information	221,688.47**	70,149.93**	397.60**	93.97**	0	0
Part B: Minimal Network—Network Less Important to Consumers							
Most aggressive competes with no action							
	Incomplete information	–21,306.77**	121,205.00**	444.70**	20.13**	0	0
	Complete information	–11,984.30**	155,970.00**	433.13**	27.73**	0	0
Most aggressive competes with least aggressive							
	Incomplete information	–16,880.47	–40,261.20	290.53**	170.57**	0	0
	Complete information	–8,606.80	–19,237.40	238.53	233.17	1	0

**Columns A and B or columns C and D significantly different $p < .05$

strategies in market share and income gained. Market share triggers for price cuts ranged from 20% to 65%, and penetration pricing factors ranged from 20% to 50% (Table 1). In the most aggressive strategy, the technology sponsor cut price by 50% when its market share dropped below 65%. In the least aggressive strategy, the technology sponsor agent cut price by 20% when its market share dropped below 20%. In the "itchy but weak trigger finger" (IWTF) strategy, the technology sponsor was quick to cut prices (below 65% market share) but by a modest amount (20%). In the desperation strategy, the technology sponsor waited to cut prices until the market share dropped below 20% but, at that point, cut them significantly (50%).

The vision of the agents determined the amount of the information they had about other agents' adoption decisions. The amount of information was either incomplete (vision was five cells in all directions or the nearest 120 neighboring cells) or complete (vision was global, so the agent could see the entire Standard-Scape or all 599 other agents in the 3,600 cells of the simulation). The importance of the network factor in the consumer agent's utility function reflected the use of either the minimal network numbers revealed in the conjoint study or the augmented network values calculated to achieve adoption rates consistent with rates revealed by the study.

Results

Hypothesis testing

Our first hypothesis concerned the efficacy of penetration pricing strategies. Table 2, Part A

Table 3

Competition Between an Inferior Technology and Superior Technology over Five Years

(Inferior technology enacting multiple penetration pricing strategies; superior technology enacting least aggressive strategy)

		Mean Income 30 runs		Mean Agents Adopting 30 runs		Out of Business Frequency	
		Inferior Column A	**Superior** Column B	**Inferior** Column C	**Superior** Column D	**Inferior** Column E	**Superior** Column F
Base Strategy							
Minimal network	_Incomplete information_	207,500.00**	518,640.00**	45.77**	120.97**	0	0
	Complete information	255,170.00**	725,845.00**	54.73**	167.13**	0	0
Augmented network	_Incomplete information_	210,290.00**	904,935.00**	47.40**	216.60**	0	0
	Complete information	154,632.50**	1,365,855.00**	29.43**	320.57**	0	0
Least Aggressive Strategy							
Minimal network	_Incomplete information_	_–8,401.93**_	_–69,052.27 **_	89.30**	375.50**	0	0
	Complete information	_–5,581.80**_	_–29,281.77 **_	95.53**	385.30**	0	0
Augmented network	_Incomplete information_	18,020.97**	207,037.60**	74.10**	405.03**	0	0
	Complete information	7,483.83**	381,535.17**	_215.33_	_271.97_	0	0
Desperation Strategy							
Minimal network	_Incomplete information_	_12,748.10**_	_–85,832.93**_	68.43**	384.73**	2	0
	Complete information	_24,221.87**_	_–58,686.60**_	120.17**	348.90**	0	0
Augmented network	_Incomplete information_	24,227.20**	166,148.33**	194.27**	289.13**	0	0
	Complete information	84,223.40**	236,725.80**	_280.73**_	_202.37**_	0	0
Itchy Weak Trigger Finger Strategy							
Minimal network	_Incomplete information_	_–6,116.30**_	_–79,690.77**_	77.53**	389.27**	0	0
	Complete information	_–17,199.60_	_–17,501.47_	129.17**	352.27**	0	0
Augmented network	_Incomplete information_	–3,389.40**	254,383.17**	92.40**	391.07**	0	0
	Complete information	–14,393.80**	395,621.90**	_310.17**_	_182.47**_	0	0
Most Aggressive Strategy							
Minimal network	_Incomplete information_	_15,566.17**_	_–81,372.97**_	36.80**	416.00**	3	0
	Complete information	_22,756.13**_	_–56,427.47**_	151.30**	316.80**	1	0
Augmented network	_Incomplete information_	–3,040.47**	180,200.30**	_272.73_	_207.57_	0	0
	Complete information	68,370.27**	208,440.27**	_334.70**_	_149.47**_	0	0

** = $p < .05$; italics emphasize cells where inferior technology outperforms or matches the superior technology.

summarizes our results. We see that when two equal technologies compete in an environment in which network externalities are important to consumers, a more aggressive penetration pricing strategy leads to larger numbers of adopters (supporting H1a) and also to greater income (supporting H1b). This is true both when agents had complete information about what others are adopting (vision was global) and when they had incomplete information regarding other agents' adoption decisions (vision was local). Even when met with meager price cutting by the competition, this most aggressive penetration pricing strategy proved

Table 4

Competition Between an Inferior Technology and Superior Technology over Sixteen Years, Eight Months

(Inferior technology enacting multiple penetration pricing strategies; superior technology enacting least aggressive strategy)

		Mean Income 30 runs		**Mean Agents Adopting 30 runs**		**Out of Business Frequency**	
		Inferior Column A	**Superior** Column B	**Inferior** Column C	**Superior** Column D	**Inferior** Column E	**Superior** Column F
Base Strategy							
Minimal network	*Incomplete information*	671,840.00**	1,856,290.00**	42.17**	131.90**	0	0
	Complete information	755,735.00**	2,614,397.50**	40.73**	190.67**	0	0
Augmented network	*Incomplete information*	701,185.00**	3,293,865.00**	47.00**	233.63**	0	0
	Complete information	388,100.00**	4,836,962.50**	15.93**	342.93**	0	0
Least Aggressive Strategy							
Minimal network	*Incomplete information*	*1,939.93*	*−947.90*	42.53**	215.70**	24	15
	Complete information	*2,618.27*	*664.13*	59.53**	386.70**	19	4
Augmented network	*Incomplete information*	33,667.10**	864,110.67**	35.97**	446.40**	19	0
	Complete information	178,884.87**	102,624.80**	*197.63*	*280.37*	11	0
Desperation Strategy							
Minimal network	*Incomplete information*	*−16,817.93**	*−1,207.83**	*294.40***	*97.53***	5	23
	Complete information	*922.77*	*1,993.80*	*273.17*	*172.07*	5	17
Augmented network	*Incomplete information*	43,511.00**	665,261.00**	*204.77*	*276.50*	0	0
	Complete information	303,008.83**	602,327.43**	*260.93*	*220.03*	0	0
Itchy Weak Trigger Finger Strategy							
Minimal network	*Incomplete information*	*−402.40*	*3,909.17*	15.13**	215.57**	29	16
	Complete information	*0.00*	*4,905.90*	0.00**	405.40**	30	4
Augmented network	*Incomplete information*	72.87**	961,828.13**	1.73**	477.67**	29	0
	Complete information	263,859.30**	977,108.83**	*200.47*	*280.10*	13	0
Most Aggressive Strategy							
Minimal network	*Incomplete information*	−17,720.93**	3,841.90**	*269.70*	*153.77*	10	20
	Complete information	−14,557.60**	2,329.00**	*275.40*	*175.60*	9	17
Augmented network	*Incomplete information*	50,478.10**	550,618.53**	*279.20**	*199.10**	1	0
	Complete information	*343,291.33*	*385,346.13*	*320.10***	*165.30***	1	0

* = $p < .10$; ** = $p < .05$; italics emphasize cells where inferior technology outperforms or matches the superior technology.

successful both financially and from a market share standpoint.

This can be contrasted with the outcomes when the network was less important in the consumer agents' utility function (see Table 2, Part B). In these cases, the aggressive network development strategy was mostly successful from an adoption standpoint, but was always disastrous from a financial standpoint. Further, when the most aggressive strategy was countered by even the slightest price cutting on the competitor's part (column B), both firms lost money. Thus, we find support for H1a, but only partial support for H1b.

Table 5

Comparison of Strategy Results within Each Technology Sponsor Agent after Five Years

	Income		Agents Adopting	
	Inferior	**Superior**	**Inferior**	**Superior**
Base (b)	206,898.13^{l,d,i,m}	878,818.75^{l,d,i,m}	44.33^{l,d,i,m}	206.32^{l,d,i,m}
Least aggressive (l)	2,880.27^{b,d,m}	122,559.68^{b,d,m}	118.57^{b,d,m}	359.45^{b,d,m}
Desperation (d)	36,355.14^{b,l,i}	64,588.65^{b,l,i}	165.90^{b,l}	306.28^{b,l}
IWTF (i)	–10,274.78^{b,d,m}	138,203.21^{b,d,m}	152.32^{b,m}	328.77^{b,m}
Most aggressive (m)	25,913.02^{b,l,i}	62,710.03^{b,l,i}	198.88^{b,l,i}	272.46^{b,l,i}

Superscripts indicate a result that is significantly different from that achieved by this same technology sponsor when the inferior technology enacted other strategies. For example, in the first column, row IWTF, the superscript "b, d, m" next to "–10,274.74" indicates that the inferior technology earns significantly less money using the IWTF strategy than it does using the base (b), desperation (d), and most aggressive (m) strategy. However, the amount earned in the IWTR does not differ significantly from that earned in the least aggressive (l) strategy. In all simulations here, the superior technology used the default (least aggressive) strategy.

We see little support for H2 in the data (see Table 3, columns C and D). Regardless of the extreme penetration-pricing strategy, we see only five instances where the inferior technology gained as many or more adopters than the superior technology. These all occurred when the network was augmented and, in four of five instances, when agents had complete information about other agents, both allowing for the greatest impact of network externalities. Even when we ran the simulations for 200 time periods (Table 4, columns C and D), the inferior technology had no greater chance of overtaking the superior technology in terms of the number of agents adopting. Thus, we see virtually no support for H2.

We do find partial support for H3. Data for testing H3 is presented in Table 3, columns A and B. When the inferior technology undertook any penetration pricing strategy and the network importance was minimal, the inferior technology, on average, earned as much income as (one instance) or more than (seven instances) the superior technology. However, when the network weights were augmented, the superior technology again dominated the inferior in terms of income achieved. The pattern of these results held when we allowed the simulations to run for 200 time periods (Table 4, columns A and B).

Which strategy is most successful?

Both technology sponsors were most financially successful when both pursued no penetration pricing at all (Table 5 and Figure 2). On average, the superior technology achieved greater income in the base case than with any pricing strategy (mean $878,818.75), as did the inferior (mean $206,898.13). However, both sponsors saw significantly fewer agents adopting in the base scenario compared to all other strategies, an average of 44.33 adopters for the inferior technology and an average of 206.32 adopters for the superior sponsor (see Table 5 and Figure 3). The inferior technology obtained the greatest number of agents adopting by using the most aggressive strategy (198.88). The superior technology gained the most agents when the inferior technology employed the least aggressive (mean 359.45) or IWTF (mean 328.77) strategy.

Which strategy is most perilous?

By tick 60, the superior technology sponsor never went out of business (Table 3, columns E and F). The inferior technology sponsor agent went out of business twice when using the desperation strategy, both when the vision was small and the network less important; thus network effects had the least opportunity to influence the purchase decision. It also went out of business four times when using the most ag-

Figure 2
Income for Strategies over Five Years

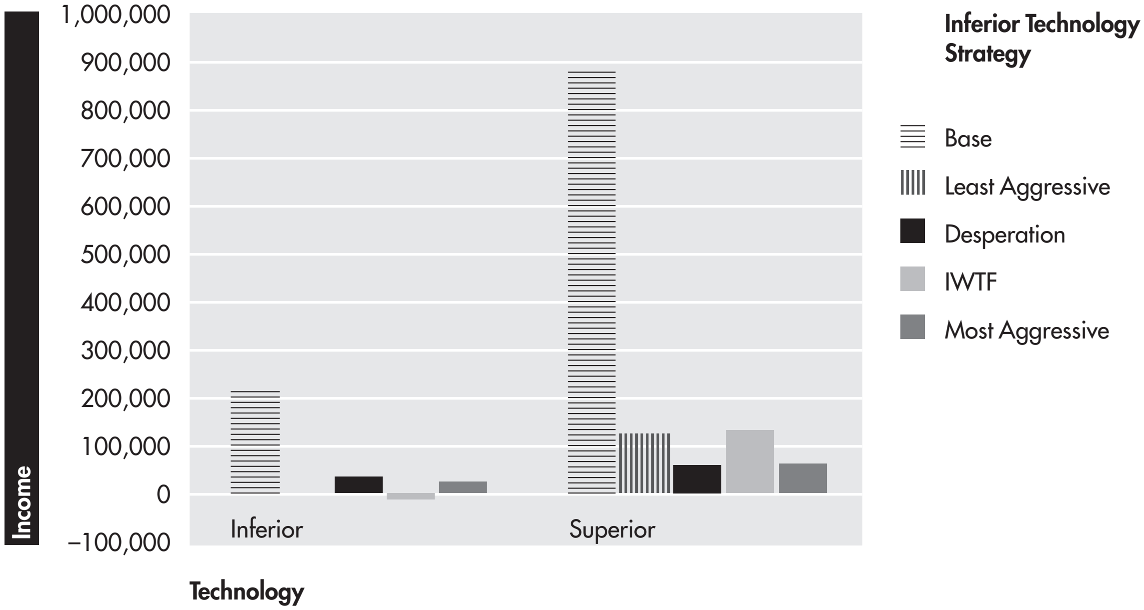
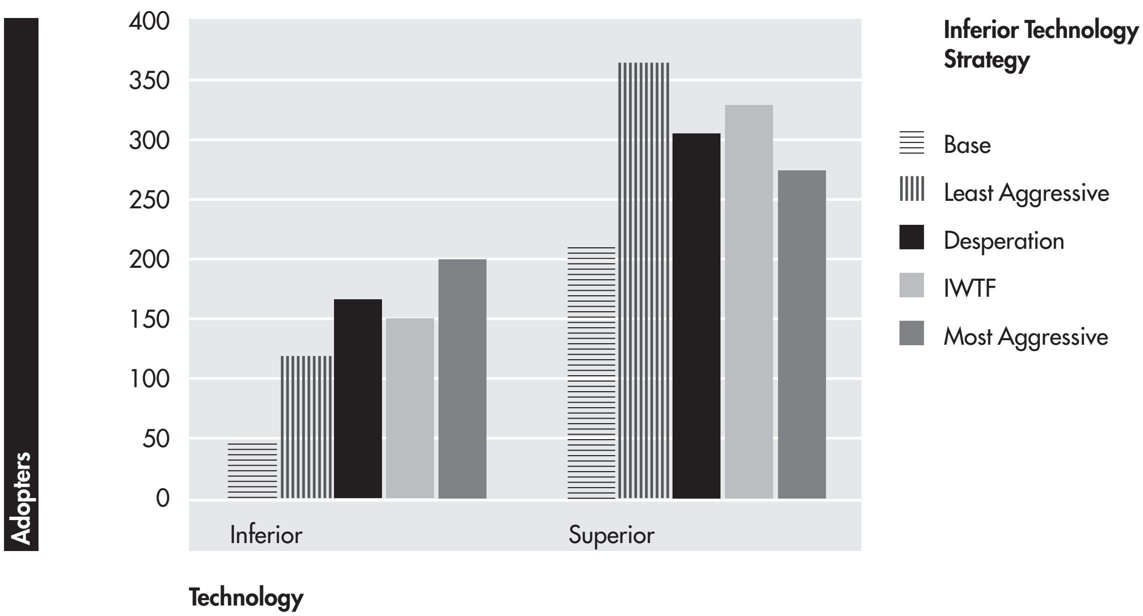


Figure 3
Adopters for Strategies over Five Years



gressive strategy, all when the network was less important.

When we allowed the simulation to continue for 200 time periods, we saw sponsors going out of business more frequently (Table 4, columns E and F). The least aggressive and the IWTF strategies seemed most prone to putting the inferior technology sponsor out of business. Both strategies involved price cuts of only 20%. In contrast, the superior technology appeared to be most likely to go out of business when the inferior technology sponsor adopted the desperation or most aggressive penetration pricing strategy. Both strategies involved price cuts of 50%.

Discussion

We believe our results suggest three areas for discussion. First, the importance of the network to consumers is crucial in determining the success of penetration pricing strategies. Our results illustrate the dramatic difference in results achieved when the importance of the network was augmented in the consumers' utility function versus when it was not. Thus, misinterpreting the relevance of network externalities to a firm's potential market and, thus, misapplying network development strategies may lead to successful market share development but may also lead to disastrous financial results. Also, when technologies are symmetric and a firm has lost the market share battle, little is gained by even mild price cutting. Those consumers concerned with network externalities are unlikely to switch to a nondominant standard due to a minor price decrease. The consumer base purchasing the loser's product is likely to be loyal to that product, and the greater margin that can be achieved from that base, the greater financial success the firm will have. This has been Apple Computer's strategy for some time.

Second, when the technologies are asymmetric, an inferior technology sponsor enacting a penetration pricing strategy may occasionally achieve market share success, but that success is not necessarily tied to financial success. When network externalities are important to consumers and when consumers have complete information about other consumers' choices, it is possible for the inferior technology to gain significantly greater market share than the superior. However, even when the inferior sponsor wins the market share battle, financial rewards do not follow. In fact, the only time the inferior technology can match the superior technology sponsor's financial success is when consumers care much less about the network, and in these cases, success may be too positive a word to describe the situation. When the network effects were minimal, we found that both the inferior and superior technologies were forced to cut prices severely to achieve their market share goals. In the least aggressive and the IWTF strategies, the average price for the inferior technology at tick 60 was far below that of the superior technology, although both were below the cost of goods sold. However, the superior technology had a much larger number of adopters than the inferior, and each sale below cost dragged the superior provider further into debt. Thus, for these two strategies, both firms had negative income but the superior's income was below the inferior's. For the desperation and the most aggressive strategies, the ultimate prices at tick 60 were comparable and typically just above cost of goods sold, but, again, because the superior technology had far more adopters than did the inferior, each dip into negative income pricing had a much larger overall effect on ultimate net income. Exacerbating this, because the superior technology sponsor practiced the least aggressive strategy as its default, when it did begin to raise prices to recoup lost revenue, its price was raised slowly rather than at the more rapid rates of the most aggressive and desperation strategies. When the time frame was expanded to 200 time periods (just over 16 years), we saw the same pattern of results.

Third, in our simulations, no penetration pricing at all brought the greatest financial reward to the sponsor agents, although it achieved very low market penetration. It is possible that this result is an artifact of the manner in which we implemented the pricing rule. Thus, it is more fruitful to compare the outcomes of different strategies to one another, given that they were all implemented with the same biases, whether known or unknown. Within the strategies, those with larger price cuts (most aggressive and desperation) led to the largest number of adopters for the inferior technology. These also were the most successful strategies from a financial standpoint. These same strategies, enacted by the inferior technology sponsor, were also most damaging to the superior technology's financial and market share position. Thus, they point to the value of true penetration pricing rather than modest price cuts in a network market.

Conclusion

Network markets are ideally suited for modeling with agent-based simulation. The nonlinearity of market evolution with positive feedback loops can be easily modeled using agent-based models. Further, the nondeterministic nature of the models allowed us to explore multiple outcomes that evolve from the same starting point.

In these simulations, we explored two technology sponsor agents operating in markets with varying degrees of network externalities. These agents practiced different penetration pricing strategies, and we examined the market share and income achieved. Our consumer agents' utility functions were based on empirical consumer choice data, providing greater external validity to our conclusions.

Our findings underscore the importance to managers of understanding the consumers' utility function and avoiding implementing network development strategies when network effects are not important to the consumer. We also find that, once penetration pricing strategy is enacted, it is more effective to be aggressive rather than timid. Finally, we find that it may be possible for an inferior technology to dominate via penetration pricing and that, in such a case, the more aggressive the price cuts, the more financially attractive the outcome. However, it is also important to note that no penetration pricing at all resulted in the greatest financial reward to both firms, whether inferior or superior.

Future research should include additional elements of network effects, such as quality or compatibility, and other networks such as the complements or producer networks (Frels, Shervani, and Srivastava 2003). Future studies might also consider additional network development strategies such as licensing to a low-cost provider and preannouncement of product up-grades, as well as product upgrades themselves. ■

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