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STANDARDS COMPETITION IN THE PRESENCE OF DIGITAL CONVERSION TECHNOLOGY:

AN EMPIRICAL ANALYSIS OF THE FLASH MEMORY CARD MARKET

Abstract

Both theoretical and empirical evidence suggest that in markets with standards competition, strong network effects can make the strong grow stronger and, in some circumstances, even "tip" the market towards a single, winner-take-all standard. We theorize that in the presence of low cost conversion technologies and digital content, the tendency towards market dominance can be lessened to the point where multiple incompatible standards are viable. Our hypotheses are empirically examined in the context of the flash memory card market where both network effects and high quality conversion are present. The results show that the availability of digital converters reduces the price premium of the leading flash card formats more than of the minority formats. Therefore, producers of the non-dominant standards can be better off with the provision of conversion technology as this technology neutralizes the impact of network effects that would have otherwise been more potent. We discuss both the social and private implications of our findings.

Key words: *Network effects, standards competition, conversion technologies, flash memory, digital goods*

JEL Classifications: C12, C23, D62, L11, L15

1. Introduction

Network effects arise in many information technology (IT) markets where the value of a product or service demands interoperability. These network effects make the choice of a technology standard or platform to be an important strategic decision to both consumers and firms (Katz and Shapiro, 1985, Economides, 1996). Examples of this phenomenon include computer hardware, operating systems, application software, and, more recently, popular instant messengers and social networks. In addition to ease of communications, a widely compatible product may also give rise to longer product lifecycle, better product support and services, and a greater variety of complementary goods. In most traditional contexts, when quality and performance are similar across competing standards and consumers are increasingly aware of these compatibility benefits they are more likely to opt for a product that adopts a more popular standard, which, in turn, creates a virtuous cycle for the leading formats and helps the strong grow stronger (Shapiro and Varian, 1999). Consequently, when multiple incompatible technologies coexist, firms often have to compete *ex ante* for *ex post* market power, as once the market falls into this positive feedback loop, the growth of the leading format often becomes irreversible until it achieves market dominance. This type of market evolution has been documented in the VHS and Betamax "standards wars" (Cusumano *et al*., 1992, Park, 2004), the adoption of the DVD format (Dranove and Gandal, 2003), and the markets for U.S. desktop operating systems and office productivity software (Bresnahan, 2001).

However, as we enter a "digital era", a new and different pattern of competition seems to be emerging from several digital goods markets. Despite strong demand for compatibility, these markets do not tip towards a single standard, nor do we see a significant advantage of the incumbent over the new entrants. Witness, for example, the lack of standardization seen in markets for digital media files (Real Media, Windows Media, QuickTime, AVI, MPEG), digital photography (JPEG, GIF, TIFF, PNG), and flash memory cards (Compact Flash, SmartMedia, Secure Digital, Memory Stick, XD Picture, Multimedia).

Flash memory is a class of non-volatile, electrically rewritable memory that was introduced into the consumer electronic market in 1994[1]. With the capability to store large amounts of data in digital format, fast read/write speeds, and compact size, it has emerged as the primary storage media of various digital electronic devices such as digital cameras, digital camcorders, mobile phones, PDAs, audio players, etc. Over the past decade the flash memory market has become one of the fastest growing sectors in the IT industry. According to market research firm IDC, flash memory revenue is expected to reach $18.7 billion in 2010, up from a record $10.6 billion in 2005[2]. This growth may not be surprising given the rapid growth of the digital consumer electronics market and the heavy reliance of these digital devices on memory cards for data storage and transfer. What *is* surprising is the variety of incompatible card formats that exist in the market. In spite of apparent network effects, there are currently more than six incompatible formats and a number of variants deriving from each format. More remarkably, as depicted in Figure 1, the SmartMedia and Compact Flash formats, despite their first mover advantage (more than a 70% combined share in 2002), have both lost their once leading positions to the Secure Digital format, the current leader with a market share of 37%. The rest of the market is split by a variety of standards including: Memory Stick and Memory Stick Pro (combined 22% share), XD Picture (12% share) and Multimedia cards (5% share) with little evidence of market consolidation.

[1] http://www.sandisk.com/Oem/DocumentInfo.aspx?DocumentID=1340
[2] http://www.usatoday.com/tech/products/2006-06-04-storage-drive_x.htm

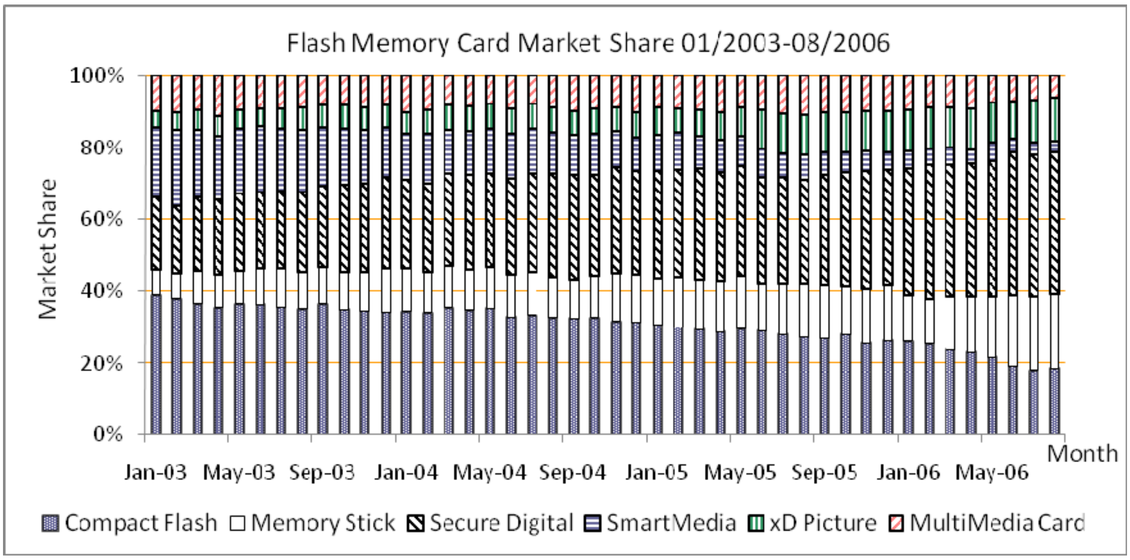

Figure 1: Flash Memory Card Monthly Market Share – January 2003 to August 2006

The characteristics of the flash memory card market imply the presence of network effects. A consumer is better off the more people who adopt a flash card format that is compatible with the ones he or she owns. A widely adopted flash card format allows users of compatible digital products to easily transfer data from one to the other (i.e. between two PDAs or from a digital camera to a digital photo printer). Furthermore, as in the case of VHS/Betamax where an increase in the market share of one type of video tape format will increase the number of studios and video tape rental stores that support this format, an increase in the demand for one type of flash memory card will increase the variety of digital products that are compatible with it, which in turn will raise demand for that type of flash memory card. However, this self-reinforcing loop is not clearly observed in the flash memory market to date. Early success does not necessarily translate into future success as the incumbent formats have been experiencing a decline in market share and new formats continue to emerge, even as the market grows. Given this distinct market outcome one may ask the questions: what distinguishes the flash memory card market from the other markets with similar characteristics? Why is there little evidence of standards convergence in a market that desires compatibility and would benefit from network effects?

In contrast to other IT Markets studied in the network effects literature, for flash memory cards, one candidate explanation involves both the digital nature of flash memory products and the associated presence of conversion technologies. Flash memory cards can store any information in digital format, which means that their contents can be transferred without loss of quality. Additionally, there is a widespread availability of inexpensive PC- and USB-based converters[3], allowing for easy conversion of data between various card formats. The existence of these conversion technologies suggests that nearly full compatibility may be achieved across different formats without compromising product performance or features (Farrell *et al*., 1992), an aspect not typically observed in other markets with network effects. For example, converting between VHS and Beta standards was costly and resulted in signal loss (Cusumano *et al*., 1992).

In this study, we analyze the flash memory market and empirically examine the role of digital converters in shaping the competition in this market. Our results suggest that in the presence of low cost conversion technologies and digital content, the probability of market dominance as driven by network effects can be lessened to the point where multiple incompatible standards are viable. We find that, in the flash memory market the increasing adoption of digital converters reduces the impact of the installed base on the product price premium, despite evidence of network effects. In particular, digital converters reduce the price premium of the leading formats *more* than they do the minority formats. The impact of network effects is less significant when there is greater adoption of digital converters.

These findings have important theoretical and managerial implications for the growing literature on network effects in IT markets. Our study is one of the first attempts in the literature to complement the analytic literature on conversion technologies in markets with standards

[3] These converters are also known as multi-format flash memory card readers that have multiple slots for different types of incompatible flash cards. Through a USB cable, consumers can read from or write to multiple flash memory cards simultaneously from a PC. Currently more than 100 models are available in the market (www.amazon.com/exec/obidos/tg/browse/-/1197398).

competition (Matutes and Regibeau, 1988, Economides, 1989, 1991a, Farrell and Saloner, 1992, Choi, 1996, 1997). Although the presence and magnitude of network effects have been empirically demonstrated in the literature (Brynjolfsson and Kemerer, 1996, Gandal, 1994, Gallaugher and Wang, 2002, Asvanund *et al*., 2004, etc), to the best of our knowledge there has not been any empirical work on newer digital goods technologies and the interaction between network effects and converters and how the market evolves in this context. Our use of market data thus contributes to the existing body of knowledge on network effects by providing unique insights into how conversion technologies affect competition in digital markets.

Our findings on the effects of conversion technologies also have important implications for both vendors and consumers. As converters become more popular, consumer perceptions of network effects decrease since compatibility can be achieved at a lower cost. Consequently, the choice of a product may rely more on other attributes, such as brand and quality attributes, than market share. Vendors' marketing and pricing strategies should adjust accordingly to account for this shift in consumer preferences. Thus, the consumer decision making process and the interaction between vendors and consumers may change significantly as a result of the introduction of converters.

Finally, from society's standpoint, the provision of a converter reduces the need to compromise between product variety and standardization, especially for markets characterized with high consumer heterogeneity. Given that there is still vast disagreement over the tradeoffs between market competitiveness and the social benefit of industry wide compatibility, our analysis contributes to the debate on standardization in IT markets by enriching the alternative choice set of such consideration.

The paper proceeds as follows: Section 2 briefly reviews the literature on network effects and conversion technologies, providing the theoretical basis for our work. Section 3 presents the conceptual model and hypotheses. In section 4, we describe the data and measures of our key variables. The econometric models and results are presented in section 5 and further discussed in section 6. Section 7 concludes the paper and suggests directions for future research.

2. Related Literature

2.1. Network effects and hedonic price models

Network effects refer to the circumstance in which the net value of the action of consuming a good (e.g., subscribing to telephone service) is affected by the number of agents taking equivalent actions (Liebowitz and Margolis, 1994). Both prior research and anecdotal evidence have suggested that, in markets with network effects, early success in accumulating a large installed base can give rise to a number of strategic advantages. In addition to the positive feedback loop generated by self-fulfilling consumer and retailer expectations, empirical research has suggested that network effects help to create switching costs to lock-in existing customers (Chen and Hitt, 2002, Zhu *et al*., 2006) and to increase the speed at which market demand grows (Economides and Himmelberg, 1995, Kauffman *et al*., 2000). Other strategic advantages include the ability to deter potential entrants (Lee *et al*., 2003, Suárez and Utterback, 1995) and the possibility to control the design interface (Conner, 1995). Moreover, given that network effects are often perceived as the consumer's valuation for a standard (Farrell and Saloner, 1985), a stream of empirical research on network effects focuses on estimating the influence of the installed base on consumer's willingness to pay for the dominant standard. Several empirical studies have found a price premium for dominant standards in markets for mainframe computers (Greenstein, 1993), IBM compatible microcomputers (Hartman, 1989), spreadsheet software (Gandal, 1994, Brynjolfsson and Kemerer, 1996), databases (Gandal, 1995) and communications equipment (Chen and Forman, 2006).

Although the above empirical studies differ in their highlighted consequences of network effects, the coefficients on their compatibility variables can all be interpreted in the same way - as an indication of the perceived value of being part of a larger network. Of particular interest is the use of hedonic regression approach in capturing this value.

The hedonic regression was first applied to IT products by Chow (1967) in estimating the annual quality-adjusted price decline in mainframe computers from 1960-1965. As a useful method to decompose consumers' consumption utility into independent valuations of different aspects of a product, hedonic regression has been widely employed in estimating the marginal benefit of products that include multiple attributes, and is particularly appealing in the empirical literature on network effects. By treating various antecedents of network effects such as installed base or learning costs as implicit features of a product, hedonic regression allows researchers to obtain estimates of the parameter measuring a consumer's willingness to adopt a standard (or the opportunity costs to switch to a different network), controlling for other intrinsic values of a product. As the choice of a flash memory card also depends on a variety of considerations other than the size of the installed base, such as brand, capacity, and speed, we adopt the hedonic model as an appropriate approach to distinguish network effects from the impacts of other factors.

2.2. Conversion technologies

An important objective of this research is to analyze the role of digital converters in influencing standards competition in markets characterized with network effects. Although the extant empirical literature has identified a variety of sources and consequences of network effects, very little attention has been devoted to the interaction between conversion technologies and technology adoption in markets characterized with standards competition. Most studies on this topic rely on either an analytic framework (Farrell and Saloner, 1992, Choi, 1996, 1997) or an historical case study (David and Bunn, 1988) to illustrate the effect of converters on technology adoption.

A major challenge of any empirical study on this topic lies in distinguishing the counteracting effects of conversion technologies on product price. In the absence of a common interface, converters enable incompatible systems to communicate with each other and hence internalize the compatibility benefits that would have been lost without converters. Consumers benefit from the provision of converters because converters can increase both product variety and the size of the network to which the consumer belongs (Matutes and Regibeau, 1988, Economides, 1989). As a result, consumers are willing to pay a higher price for the otherwise incompatible products. On the other hand, the presence of converters also reduces the expected price premium of the dominant standards as both the relative attractiveness of their products and product switching costs decrease due to a lower compatibility barrier (Farrell and Saloner, 1992). The installed base of the dominant standards may expand more slowly and competition may intensify as the intransient compatibility period extends (Choi, 1996, 1997). At the same time, new entrants are more likely to enter the market and to survive the standards war (Liu *et al.*, 2007).

Given these complicated interactions, the product price premium is not merely an indicator of the perceived value of the installed base as assumed in the classic network effects literature. A consumer's valuation of product compatibility, as measured by product price, should be further decomposed into variation due to product installed base, the adoption of conversion technologies, as well as the interaction of the two effects. Drawing upon the findings from the above literature, we develop a conceptual framework with specific hypotheses to examine the dynamics between conversion technologies and the various antecedents and outcomes of network effects.

3. Research Model and Hypotheses

Since the role of conversion technologies is of primary interest when network effects exist, identifying the presence and the magnitude of network effects is an important first step in evaluating the nature of standards competition in the flash memory card market. In the literature, network effects are most commonly evidenced by the price premium of a product format (Berndt *et al.*, 2003, Brynjolfsson and Kemerer, 1996, Gandal, 1994, 1995, Greenstein, 1993). The price premium of a product format is expected to vary positively with the size of the product's installed base. Typically, a larger installed base for a product format confers greater utility to consumers. For example, consumers of the same operating system can exchange software applications more easily with a larger number of users of the same system. Therefore, because the utility of a product increases with the installed base for the product, there will tend to be one dominant standard in the market, and the firm offering the leading market standard for the product should be able to charge a higher price for it. However, in contrast to this typical scenario, in the flash memory cards market, there is little evidence of standards convergence despite consumers' desire for product compatibility. Clearly, the literature would suggest a positive association between the size of the installed base and the flash memory card price, but it is possible that the magnitude of the positive network effects is too small to warrant a dominant firm market outcome. Regardless of magnitude, we would still expect a positive relationship between price and installed based for flash memory cards, such that:

Hypothesis 1: *the price of a flash memory card is positively associated with the size of the installed base of the same format*.

We now consider how digital converters would affect the price of flash memory cards. As discussed in Section 2, the use of digital converters can affect consumers' perceptions of product value. With digital converters, consumers of flash memory card products with incompatible formats can still exchange content with each other and thereby obtain the benefits of compatibility. Thus, digital converters can increase consumption utility across flash memory card products of different standards. This implies that greater adoption of digital converters will increase the utility (and thus the price) of flash memory cards, even if the cards are not compatible. Therefore:

Hypothesis 2: *the price of a flash memory card is positively associated with the adoption of digital converters.*

As we have noted earlier, in a market characterized by standards competition and strong network effects, typically one dominant product standard will emerge. Consumers are motivated to purchase the dominant standard to obtain the benefits of compatibility with a large installed base of other users, and the firm producing the dominant standard will therefore be able to charge a price premium for the product. However, by breaking the compatibility barrier across competing formats, digital converters can reduce the influence of the dominant standards on consumer purchase decisions. When making a technology choice, the wide presence of digital converters reduces the consumer's risk of being stranded on a new, but less popular standard, as the chances for survival of a new technology are larger when network effects are less significant. In addition, digital converters allow products with different formats to be compatible. As a result, when digital converters are present, consumers are not as motivated to purchase a dominant standard as there is less benefit from it; this lowers the producer's price premium. Following this logic, in the context of flash memory cards, a greater adoption of digital converters will especially affect the price premium of the dominant standard. Producers of flash memory card standards with a larger installed base are expected to lose more market power than those with a smaller installed base, as there is less utility from a dominant standard when converters are present. Thus, we expect that:

Hypothesis 3: *the adoption of digital converters reduces the impact of the installed base on flash memory card prices, such that the price reduction effect is stronger for standards with a larger installed base than for standards with a smaller installed base*.

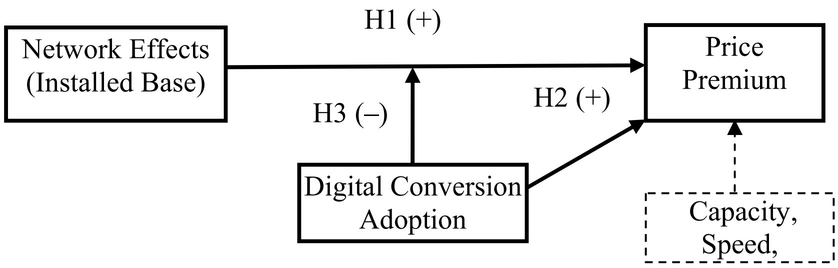

Figure 2: Research Model and Hypotheses

Figure 2 illustrates our conceptual framework for the empirical analysis, along with the predicted directions of how installed base, the adoption of digital converters, and their interaction will affect the price premium of a flash memory card.

4. Data and Measures

4.1. Sample

To test our hypotheses, we assembled a large panel dataset including data on the products and producers in the flash memory card market. The flash memory card market offers a particularly appropriate test case for our hypotheses. The market has been quite volatile since launched in 1994; different formats have emerged and competed for dominance. The co-existence of multiple formats, despite the presence of network effects and the possibility to convert data without quality loss suggest that this is a market with the potential for dynamics significantly different than those previously studied.

We selected a sample period from 2003 to 2006 for our analysis since this is a critical period in the development of the flash memory card market during which most of the current formats are present. Our primary data were generously provided by the NPD[4] research group. This data includes detailed information on the monthly retail prices and unit sales data of the major flash memory cards and digital converters sold each month by major U.S. retailers from January, 2003 to August, 2006. To supplement the NPD dataset, we also implemented a software agent which automatically retrieved flash memory card prices, sales rank and product attributes from amazon.com on a daily basis. Finally, the flash memory cards product specification data were gathered from the official associations of each flash card format.

The final dataset consists of 15,091 observations that cover all six major flash card formats and 45 major brands, with capacities ranging from 4MB to 8GB. As a result, we have a total of 706 panels[5] across 44 months. Each panel represent a format *i*, brand *j*, capacity *k* flash memory card sold during month *t*. The product level panels allow us to control for variation due to formats, capacities and brands, whereas the monthly level data allow us to control for variation due to any potential "seasonal fluctuations" (i.e., sales surge during holidays, etc.) and time trends (i.e., declining costs, etc.). The distribution of observations, broken down by formats and year, is shown in Table 1 below.

Table 1: Distribution of Flash Memory Card Observations by Card Type/Year

Card Type	**2003**	**2004**	**2005**	**2006***	**Total**	(%)
Compact Flash Card	1205	1309	1412	921	4847	(32.12%)
Memory Stick	334	453	492	343	1622	(10.75%)
Multimedia Card	317	360	453	267	1397	(9.26%)
Secure Digital Card	742	1063	1386	1251	4442	(29.43%)
Smart Media Card	583	461	387	200	1631	(10.81%)
xD Picture Card	190	264	385	313	1152	(7.63%)
Grand Total	3371	3910	4515	3295	15091	

* Note that 2006 observations only cover up to August, 2006

[4] NPD (www.npd.com) is a leading global research company. The firm provides critical consumer and retail market information based on data collected from point-of-sale (POS) terminals in major retailers across a range of outlets.
[5] Note that this is not a balanced panel due to the fact that some brands may only produce a type of flash memory cards at certain capacities and some flash memory card are discontinued after a certain period of time.

4.2. Variables

Table 2 below provides definitions of the variables used in our analysis.

Table 2: Definitions of Variables

Variable Name	**Definition**
$CardPrice_{i,j,k,t}$	deflated (in 2003 Q1 dollar) average retail price of a format ***i***, brand ***j*** and capacity ***k*** flash memory card sold during month ***t***.
$InstalledBase_{i,t}$	percentage of the cumulative sales volume (in units) of format ***i*** flash cards as of month ***t***
$ConverterAdoption_t$	Sales volume of digital converters relative to that of flash memory cards in month ***t***
Capacity	capacity (in MB) of a flash memory card
Speed	average read/write speed of a flash memory card
D_CF	dummy variable, 1 if the flash memory card is compatible with the Compact Flash format
D_MS	dummy variable, 1 if the flash memory card is compatible with the Memory Stick format
D_MMC	dummy variable, 1 if the flash memory card is compatible with the Multimedia Card format
D_SD	dummy variable, 1 if the flash memory card is compatible with the Secure Digital format
D_SM	dummy variable, 1 if the flash memory card is compatible with the SmartMedia format
D_xD	dummy variable, 1 if the flash memory card is compatible with the xD Picture Card format
D_Brand ***j***	a "make effect" dummy variable, 1 if the flash memory card is manufactured by Firm ***j*** *
D_Quarter ***q***	a seasonal effect dummy, 1 if the observation belongs to quarter ***q*** (***q***=1, 2, 3 or 4)
D_Year ***y***	a year dummy, 1 if the observation belongs to year ***y*** (***y***=2003, 2004, 2005 or 2006)

* Only brands with market share greater than 1% are selected.

The key variables for our analysis are price and the installed base of a flash memory card model, as well as the adoption level of converters. The flash memory card price, $CardPrice_{i,j,k,t}$, is computed as the deflated (in 2003 Q1 dollars) average retail price of a format *i*, brand *j*, capacity *k* flash memory cards sold during month *t*. The current installed base, $InstalledBase_{i,t}$, is computed as the percentage of the cumulative units of the format *i* compatible flash memory cards sold by month *t*. The level of digital converter adoption, $ConverterAdoption_t$, is measured by the percentage of the unit sales volume of digital converters relative to the total flash memory cards sold during month *t*. Two product attribute variables, capacity and speed, are included as control variables to account for variations due to memory card size and product specifications. Other format specific product features are captured by the six format dummy variables. Finally, three other dummy variables are also created to control for brand, seasonal and year effects.

Table 3: Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
$CardPrice_{i,j,k,t}$	61.08	85.29	.01	1611.81
$InstalledBase_{i,t}$	0.23	0.13	0.01	0.48
$ConverterAdoption_t$	0.65	0.13	0.35	0.78
Capacity	420.74	804.97	4	8192
Speed	20.68	15.04	1.3	40
D_CF	.32	.46	0	1
D_MS	.11	.28	0	1
D_MMC	.09	.30	0	1
D_SD	.29	.45	0	1
D_SM	.11	.31	0	1
D_xD	.76	.26	0	1
D_Sandisk	.12	.32	0	1
D_Sony	.036	.18	0	1
D_Lexar	.11	.31	0	1
D_Pny	.05	.21	0	1
D_Fuji	.06	.24	0	1
D_Dane	.025	.15	0	1
D_Kingston	.047	.21	0	1
D_Kodak	.029	.16	0	1
D_Viking	.047	.21	0	1
D_Promaster	.05	.22	0	1
D_Spring	.26	.44	0	1
D_Summer	.27	.45	0	1
D_Fall	.23	.42	0	1
D_Winter	.22	.41	0	1
D_2003	.22	.42	0	1
D_2004	.26	.44	0	1
D_2005	.30	.46	0	1
D_2006	.22	.41	0	1

[*] Note that the means of the dummy variables represent the percentages of the observations, rather than the market share, of the corresponding dummy categories.

The descriptive statistics are presented in Table 3 and the correlations of the key variables are presented in Table 4. As expected, two control variables, capacity and speed, are both positively correlated with flash memory card price. The other two key variables, flash memory card installed base and converter adoption, have opposite directions of correlation with flash memory card price (positive and negative, respectively).

Table 4: Correlations of Key Variables

	$CardPrice_{i,j,k,t}$	$InstalledBase_{i,t}$	$ConverterAdoption_t$	Capacity	Speed
$CardPrice_{i,j,k,t}$	1.000				
$InstalledBase_{i,t}$	0.056**	1.000			
$ConverterAdoption_t$	-0.096**	0.010	1.000		
Capacity	0.637**	0.117**	0.237**	1.000	
Speed	0.192**	0.237**	0.011	0.231**	1.000

*: p<5%; **: p<1%.

5. Econometric Models, Estimation and Results

We construct the following econometric model to test our hypotheses. Given that the effect of converters cannot be captured by the independent predictor of product price in the classic linear hedonic model framework, we test Hypotheses 1 through 3 by modifying the classic hedonic regression model to include an interaction term between installed base and the adoption of digital converters.

$$\text{CardPrice}_{i,j,k,t} = \alpha_0 + \alpha_1\text{InstalledBase}_{i,t-1} + \alpha_2\text{ConverterAdoption}_{t-1} + \alpha_3\text{InstalledBase}_{i,t-1} * \text{ConverterAdoption}_{t-1} + \alpha_4\text{Capacity} + \alpha_5\text{Format}_i + \alpha_6\text{Brand}_j + \alpha_7\text{Year} + \varepsilon_{i,t}$$

When the variable ConverterAdoption and its associated interaction term are both absent, the model reduces to a classic hedonic price regression where the coefficient α_1 is expected to be positive and significant when there are strong network effects. However, when these two variables are included in the model, the main effect of the installed base is not solely captured by coefficient α_1. Instead, the impact of the interacting variable also needs to be taken into account. More specifically, the main effect should be computed as the partial derivative of the dependent variable with respect to the variable of interest. Therefore, Hypothesis 1, which predicts that, *ceteris paribus*, a larger installed base will increase the price premium of a flash memory card even in the presence of a converter, can be evaluated as:

H1: $\frac{\partial CardPrice_{i,j,k,t}}{\partial InstalledBase_{i,t-1}} = \alpha_1 + \alpha_3 ConverterAdoption_{t-1} > 0$, when evaluating at the means of $\text{InstalledBase}_{i,t-1}$

and ConverterAdoption$_{t\text{-}1}$. Similarly, Hypothesis 2, which predicts that the adoption of digital converters will lead to a flash card price premium, can be represented as:

$$\text{H2}: \frac{\partial CardPrice_{i,j,k,t}}{\partial ConverterAdoption_{t\text{-}1}} = \alpha_2 + \alpha_3 InstalledBase_{i,t\text{-}1} > 0,$$ when evaluating at the means of InstalledBase$_{i,t\text{-}1}$ and ConverterAdoption$_{t\text{-}1}$.

Finally, Hypothesis 3, which focuses on the interaction between the installed base and converters, can be tested by examining the significance level of coefficient α_3, and by conducting an F-test on the restricted model (the one without the interaction term) and the unrestricted model (the one with the interaction term).

We first estimate a restricted model (without the interaction term) and then include the interaction term in an unrestricted model to examine if the coefficient estimates and model fit statistics are sensitive to this specification change. Other variables in the restricted model include capacity and speed, as well as format, brand, and seasonal and year dummies. The brand dummies cover the top ten flash card brands in our dataset. The omitted dummy variables for the other categories are, for format, the Smartmedia format, for season, spring quarter, and for year, 2003. Therefore, the constant term estimated in the model may be interpreted as the predicted price of a non-major brand Smartmedia card sold in the spring of 2003.

The Ordinary Least Square (OLS) regression results of both the restricted model and the unrestricted model are provided in Table 5 below. In the restricted model, the coefficient for InstalledBase$_{i,t\text{-}1}$ is positive, and the coefficient for ConverterAdoption$_{t\text{-}1}$ is negative and only the latter is significant at the 1% level. When the interaction term is included into the restricted model, the signs of coefficients for both InstalledBase$_{i,t\text{-}1}$ and ConverterAdoption$_{t\text{-}1}$ remain unchanged, but both become significant at the 1% level. The interaction term is negative and significant at the 1% level as well. Before we proceed to interpret the coefficients and test the hypotheses, we also conduct several econometric adjustments to ensure that our results are robust to various specification errors and violations of OLS estimation assumptions.

Table 5: Regression Results†♀

Dependent Variable: $CardPrice_{i,j,k,t}$	OLS Regression Restricted Model (No interaction)	OLS Regression Unrestricted (Interaction) Model[6]	GLS Estimation Interaction Model
Constant	34.691 (3.34)**	45.310 (3.42)**	43.005 (3.47)**
$InstalledBase_{i,t-1}$	17.676 (9.61)*	83.543 (10.84)**	43.573 (3.97)**
$ConverterAdoption_{t-1}$	-35.450 (11.45)**	-41.677 (11.40)**	-20.323 (1.96)**
$InstalledBase*ConverterAdoption_{t-1}$		-514.728 (39.99)**	-190.87 (14.48)**
Adjusted R^2	0.532	0.553	Log likelihood = –54658.9
Fit Stat	F(23, 15067) = 747.9	F(24, 15066) = 761.47	Wald χ^2 (24) = 12208.97

† N=15,091, N_i=6, N_j=45, N_k=12, N_t=44 (706 panels across 44 months).
♀ Standard errors in parentheses. *: p<5%; **: p<1%.

Tests for Multicollinearity

Due to the multiplicative nature of our model, the interaction term is highly correlated with the two variables from which it is computed. A multicollinearity check also reveals that the condition number of the interaction model and the variance inflation factors (VIF) values of the interaction term and the original variables are above the recommended threshold values of 20 and 10, respectively (Greene 2003 pp. 57-58). Prior studies (Jaccard *et al*., 1990, Aiken and West, 1991, pp 35-36) have suggested that with such models, the original interacting variables should be centered before computing other variables from them, which is done by subtracting the mean from every observation. After centering, the means of the centered variables are zero and the

[6] As some of the literature on network effects considers a non-linear specification, we also added a squared term of the installed base into the model to examine whether the impact of converters is sensitive to the specification of network effects. The results indicate that the network effects increase at a faster rate as the size of the installed base increases (the coefficient estimate for the squared term is positive and significant at the 1% level), but the effects of converters on flash card prices are still qualitatively consistent with those obtained from the linear specification. Therefore, for ease of presentation, we report the results obtained from the linear specification of the network effectsmodel.

correlations between the interaction term and the original variables become much smaller. All VIF values drop below the threshold and the condition number reduces to an acceptable level of 13.7. Therefore, after centering we can conclude that multicollinearity is not as salient in our interaction model[7].

Tests for Heteroskedasticity and Autocorrelation

We use both graphical and non-graphical methods to detect heteroskedasticity. We first plot the residuals versus fitted (predicted) values (with a reference line at y=0). From this plot it can be observed that the pattern of the data points becomes wider the greater the X-axis value, which is an indication of heteroskedasticity. A Breusch-Pagan / Cook-Weisberg test for heteroskedasticity yields a value of $\chi^2(1) = 7027.54$ ($p<0.001$), suggesting evidence of heteroskedasticity.

The Wooldridge test for autocorrelation in the panel data shows that first-order autocorrelation (AR1) cannot be ruled out for our data set. This is not surprising given the longitudinal nature of our data. The presence of heteroskedasticity and AR1 autocorrelation invalidate the use of OLS (Greene, 2000, section 15.2.3). As both heteroskedasticity and autocorrelation are present in our dataset, we address both problems together by applying Generalized Least Squares (GLS) estimation procedures with corrections to adjust for both correlated heteroskedasticity and panel specific first-order autocorrelation. As shown in Table 5, our results are robust to these corrections. The interaction effect remains significant, and the directions of the estimated coefficients for both the interacting variables and the interaction term remain the same in the GLS regression, although the price increase effects brought by converters to minority formats are smaller compared to those obtained from the OLS regressions.

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[7] For ease of comparison, both $InstalledBase_{i,t-1}$ and $ConverterAdoption_{t-1}$ are centered in the OLS regressions as well.

Main effects and interaction effect

Given that the GLS estimator is more robust to heteroskedasticity and autocorrelation, we examine both main effects and interaction effects using the results from the GLS estimation. First, to evaluate Hypotheses 1 and 2, in Table 6, we compute the main effects of the variables InstalledBase and ConverterAdoption at the means of the interacting variables and at 1 and 2 standard deviation(s) above and below the means. Following Greene (2003, pp.124), the standard errors of these main effects can be computed from:

$$Var\left(\frac{\partial E[Cardprice_{i,j,k,t} \mid InstalledBase_{i,t}, ConverterAdoption_{t}]}{\partial InstalledBase_{i,t}}\right) = Var[\hat{\alpha}_1] + (InstalledBase_{i,t})^2 Var[\hat{\alpha}_3] + 2\,InstalledBase_{i,t} Cov[\hat{\alpha}_1, \hat{\alpha}_3],$$

and similarly for $Var\left(\frac{\partial E[Cardprice_{i,j,k,t} \mid InstalledBase_{i,t}, ConverterAdoption_{t}]}{ConverterAdoption_{t}}\right)$. Note that the standard errors of the main effects at different values can be obtained by substituting the respective variables with these different values in the above equations. These standard errors are provided in parentheses.

Table 6: Main Effects

	-2 Std. Dev.	-1 Std. Dev.	Mean	+1 Std. Dev.	+2 Std. Dev.
$InstalledBase_{i,t-1}$	93.48 (3.35)**	68.52 (3.75)**	43.57 (3.97)**	18.62 (4.06)**	-6.33 (4.24)*
$ConverterAdoption_{t-1}$	28.30 (1.59)**	3.99 (1.72)**	-20.32 (1.96)**	-44.64 (2.31)**	-68.95 (2.49)**

The first row in Table 6 shows that the main effect of the flash card installed base is generally positive (except when evaluated at +2 standard deviations above the average adoption level), indicating that network effects do exist in the flash memory card market, and providing support for Hypothesis 1. The second row shows that, even though the main effect of digital converter adoption is negative when evaluated at the average size of a flash memory card installed base (Mean column), it is positive for secondary flash card formats (-1 and -2 standard deviations columns) and the price premium is stronger for platforms with smaller market share. This suggests that Hypothesis 2 is supported for flash card formats with a relatively smaller market share. For leading flash card formats the price increase effects are likely to be more than offset by the sharper price reduction effects due to the interaction between network effects and digital converters.

With regard to Hypothesis 3, as shown in the first row in Table 6 flash card price premium changes in the expected direction. Digital converters reduce the price premium of the leading formats (i.e., those with a larger installed base) more than they do that of minority formats (i.e., those with a smaller installed base). Moreover, coefficient α_3 is highly significant ($p<0.001$) in the interaction model. An F-test between the restricted model and the unrestricted model also confirms that the inclusion of the interaction term significantly contributes to the explanation of the variance in the hedonic regression. Therefore, we conclude that Hypothesis 3 is supported.

Test for Endogeneity

One possible concern about these results is that one of the independent variables, InstalledBase, is the cumulative unit sales volume of a flash memory card format. This variable could be closely correlated with the current period unit sales volume of a flash memory card format, which, in turn, could be correlated with our dependent variable, the current period flash memory card price. To address this potential endogeneity in our model, we use the lagged (t–1) cumulative market share as our measure for the installed base and perform a two-stage least square (2SLS) estimation to test for endogeneity. We use the cumulative market share with two months lag as our instrumental variable. Following Baum, Schaffer and Stillman (2003) we tested for endogeneity in our augmented form using a generalized methods of moments (GMM) estimation with specifications for autocorrelation and heteroskedasticity[8]. The results from the GMM estimation are consistent with those obtained from the OLS and the GLS estimation.

[8] The same approach is also adopted in Mittal and Nault (2006) in which they face a similar situation.

Neither a Wu-Hausman F test (p-value = 0.48) nor a Durbin-Wu-Hausman chi-square test (p-value=0.47) could reject the null hypothesis that the lagged cumulative market share is exogenous. This provides confidence in our results against potential endogeneity concerns.

6. Discussion

The overarching question in this study is why, despite the apparent benefits of product compatibility in the flash memory card market, there has been little convergence to a dominant standard. Our findings provide important insights that help to answer this question.

First, we find that the presence of digital converters has a strong effect on standards competition by offsetting some of the impact of network effects. As shown in Table 6, in markets characterized with network effects, the presence of converters weakens the relationship between installed base and price premia. The overall main effect of converters on prices is negative at the mean value of the flash card installed base and is positive only for flash memory card formats with an installed base below the average. For a flash card format with a smaller installed base (i.e. 2 standard deviations below the mean), a 1% increase in the adoption level of digital converters raises the flash card premium by $.23. But, this price premium disappears when a format's installed base is close to the industry average. This finding is still consistent with our predictions and can be explained intuitively. A converter serves as tool for data exchange between the otherwise incompatible flash card formats. Such a converter is relatively more valuable for consumers who own a minority format as it allows them to communicate with consumers of a much larger network. Hence the utility gain, and consequently the willingness to pay for a higher price, is larger for consumers of the minority formats than those of the dominant formats.

In addition to the differential impact of converters on consumers who belong to different networks, several other factors may also account for the overall price reduction that is attributed to digital converters. For example, flash memory card vendors can also profit from the sales of digital converters. If a vendor is engaged in the sales of both converters and flash cards (which is not uncommon in the flash memory card market) the vendor can transfer some of the price premium from the flash memory cards to the sales of digital converters and still profit overall. Consumers who buy the flash cards at a lower price enjoy more consumer surplus and are therefore more willing to pay for a converter to gain some additional benefit. In addition, some vendors do not produce their own converters, but license a third party vendor to do so. In this case, the licensing fee can more than compensate for the loss due to flash card price reduction.

However, it is also important to note that while network effects are weakened with the adoption of digital converters, the effects are not fully eliminated. This implies that a larger installed base is still a competitive advantage over other competing formats. This advantage is more significant as a format's installed base grows. All else being equal, a 1% increase in the installed base of a flash card format can give rise to $.43 price premium (a 0.705% price increase) of a compatible flash memory card[9]. It is also important to note that the strength of network effects, as represented by the price premium, is very sensitive to the adoption of digital converters. When the level of digital converters adoption is relatively low, i.e. at one standard deviation *below* the mean, the price premium increases by more than 50% to $.69. However, when the adoption of digital converters is high, i.e., at one standard deviation *above* the mean, such a price premium almost disappears.

Finally, when the market share advantage of the leading standards is weakened as converters are widely adopted, market competition will escalate. In light of such fierce competition the

[9] This is of a similar order of magnitude price premium of $.97 (a 0.753% price increase) found in the spreadsheet market (Brynjolfsson and Kemerer, 1996).

dominant firms might use a price war as a tool to deter potential entrants and to drive the secondary formats out of the market, as the short-term incentive to seize market share may dominate the long-term profit maximization goal. Hence, we observe a negative price premium for these dominant formats.

To illustrate the interaction between network effects (installed base) and the adoption of digital converters, we illustrate the results from Table 6 in Figures 3 and 4.

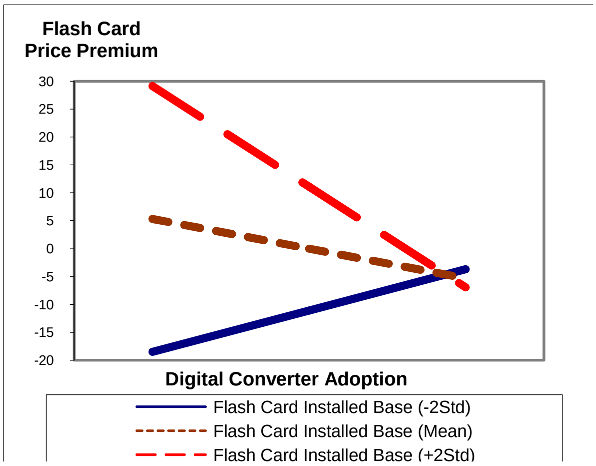

Figure 3: Price premium of a type of flash card at ±2 standard deviation of the mean converter adoption level

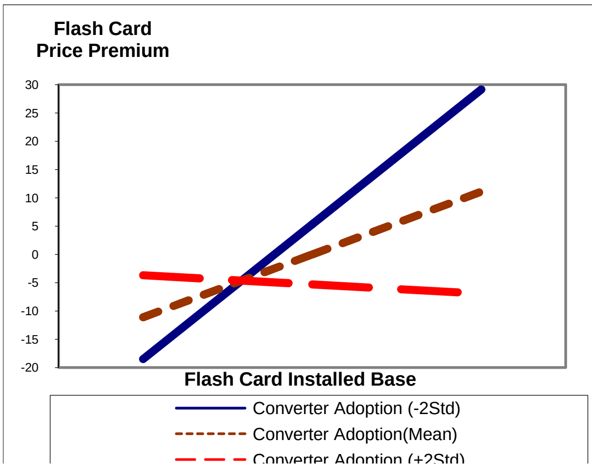

Figure 4: Price premium of a type of flash card at ±2 standard deviation of the mean flash card installed base

In Figure 3 the x-axis denotes the adoption level of digital converters and the y-axis represents the price premium of a type of flash card. The dashed, dotted, and solid lines represent the price premium of a flash card format with a large (+2 standard deviations), average, and small (–2 standard deviations) market share respectively. Figure 3 shows that the price premium of a flash card format with a larger installed base *decreases* as the adoption of digital converters increases, whereas the price premium of a flash card format with a smaller installed base *increases* as the adoption of digital converters increases, suggesting that there is a negative interaction effect between the installed base of the flash card format and the sales of digital converters. In other words, the adoption of digital converters has a completely opposite impact on majority and minority flash memory card formats. A similar interaction is depicted in Figure

4 in which the x-axis denotes the installed base of a flash memory card format and the y-axis represents the price premium of that type of flash memory card. The dashed, dotted, and solid lines represent the price premium of a flash card format when the adoption of digital converters is high (+2 standard deviations), average, and low (–2 standard deviations) respectively. One can see that network effects are present (upward slope of price premium curve) *only* when the adoption level of digital converters is below a certain level. When there is extensive adoption of digital converters (i.e., above +2 standard deviations), network effects have only a minimal impact on the market (downward slope of the price premium curve).

In addition to moderating the impact of installed base on product prices, our findings also suggest that digital converters also have the potential to change the nature of competition in the flash memory card market. As converters prevail, the market share gap among various competing formats is likely to be reduced. Consequently, buyers' expectations are more likely to hinge on other product attributes and competition will arise in other dimensions, such as quality and performance. Leading formats can no longer rely on their large installed base to deter new entrants and suppress competition as such a competitive advantage is like to be eroded over time as converters become widely available. In contrast to the self-reinforcing loop in classic network effects theory, with the presence of digital converters the larger the leading format's installed base, the more such a benefit can be appropriated among consumers of the minority formats, creating an opposite feedback loop that pushes the market towards the minimization of market consolidation. Under such a competitive environment, a standards competition characterized with extensive adoption of converters is likely to undergo a more unpredictable growth path. As is representative in the flash memory card market, the new entrant formats have been outperforming the incumbent formats since the market was launched. Nevertheless, what is predictable is the growing attention to the role of digital converters. Since their debut in the market in early 2000s, two variants of the Secure Digital (SD) format, MicroSD and MiniSD cards, have all come with free converters to the SD format, allowing them to take full advantage of the SD cards' large installed base. This action was quickly followed by Sony, the major retailer of Memory Stick cards, who announced a worldwide initiative to promote its Memory stick card reader to be installed on a variety of laptops and desktops. Today, more and more PC manufacturers are including flash memory card readers as a standard component on their PCs, suggesting increasing consensus among different market participants about the prospect and importance of digital conversion.

From a societal standpoint our findings also have important implications for technology innovation and adoption. In many IT industries when the market cannot settle on an industry-wide technology standard, both consumers and content providers (or application developers) will choose to postpone their investment until the market is clear about which standard to adopt. But, this delay in adoption results in even more uncertainty about the future of the technology. Such a dilemma repeats itself in each standards war and is illustrated in the well-publicized battle between Blu-Ray and HD-DVD, the two rival formats for the next generation high definition DVD. With about an equal number of supporters from the multimedia industry, both formats claim themselves as the next dominant standard in the high definition DVD market. However, consumers are skeptical about the time it takes for the market to unveil the winning technology. Given the high switching costs involved the sales of either format DVD players have been disappointing despite huge advertising efforts, further extending the period of intransient incompatibility. However, if a digital converter were available to convert data from the incompatible DVD discs to a form that can be mutually accepted, consumers would be more willing to embrace the new technology as the risk of being stranded on either technology is minimized. Once the excess inertia among stragglers is overcome, technology adoption will accelerate and lead itself into a traditional evolutionary path.

7. Conclusions and Future Research

The implications of network effects have been widely discussed in the academic literature and in the popular press. However, most illustrations of networks effects are drawn from existing "physical" or "analog" environments. Our contention is that the unique characteristics of digital environments may alter some of the conventional wisdom about network effects and their competitive implications.

In this study, we illustrate some of these issues in the context of the flash memory market, where in spite of apparent network effects, there are multiple competing standards and little evidence of market consolidation. Specifically, we apply a modified hedonic regression to an extensive dataset cataloging prices and sales of flash memory modules and flash memory converters. Our findings yield several *ex post* intuitive, but important insights into digital goods markets characterized with network effects. Extensive adoption of digital converters is found to reduce the magnitude of network effects, as seen by a reduced price premium of the leading flash format. As a result, new standards are more likely to attract customers than in the absence of digital converters. These findings explain the seemingly counter-intuitive trend of the lack of standards convergence currently seen in the flash memory card market, and also shed light on the evolution of standards competition in other, similar "digital" product markets.

The rich dynamic in the flash memory card market also raises several interesting questions for future research. When firms can supply both the flash memory cards and digital converters, how they exercise their pricing strategies in both markets is of particular interest to both researchers and practitioners. Moreover, although proprietary standards prevailed in the early stage of the flash memory card market, upon the advent of the digital converters, several proprietary standard owners began to reach cross-licensing agreements and promoted ease of conversion between competing formats.[10] This is considered a strategic move to take advantage of the introduction of digital converters and to cope with the perceived fierce competition in the future. Although we have demonstrated the rationale behind such moves, the actual impact on firms' profits merits future empirical examination. Finally, both social welfare and private surplus are likely to be affected by the introduction of conversion technologies. Further studies to quantify these impacts will provide important guidance for policy makers concerned about the nature and consequences of new technology adoption and innovation in markets characterized with network effects and the possibility of digital conversion.

[10] e.g., SanDisk has been selling SanDisk-branded Memory Stick products since 2001 and is a co-developer with Sony of Memory Stick Pro, and Sony has supplied a card-reader on its laptops that can read SanDisk's SD cards since 2003.

References

Aiken, L. S. and West, S. G. (1991) *Multiple Regression: Testing and Interpreting Interactions,* Sage Publications.

Asvanund, A., Clay, K., Krishnan, R. and Smith, M. D. (2004) An Empirical Analysis of Network Externalities in Peer-to-Peer Music-Sharing Networks, *Information Systems Research.* **15,** 155-174.

Baum, C. F., Schaffer, M. E. and Stillman, S. (2003) Instrumental Variables and GMM: Estimation and Testing, *Boston College, Department of Economics, Working Paper No.545.*

Berndt, E. R., Pindyck, R. S. and Azoulay, P. (2003) Consumption Externalities and Diffusion in Pharmaceutical Markets: Antiulcer Drugs, *Journal of Industrial Economics.* **51,** 243-270.

Bresnahan, T. F. (2001) Network Effects and Microsoft, Unpublished manuscript Department of Economics, Stanford University

Brynjolfsson, E. and Kemerer, C. F. (1996) Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market, *Management Science.* **42,** 1627-1647.

Chen, P.-y. and Forman, C. (2006) Can Vendors Influence Switching Costs and Compatibility in an Environment with Open Standards?, *MIS Quarterly.* **30,** 541-562.

Chen, P.-Y. and Hitt, L. M. (2002) Measuring Switching Costs and the Determinants of Customer Retention in Internet-Enabled Businesses: A Study of the Online Brokerage Industry, *Information Systems Research.* **13,** 255-274.

Choi, J. P. (1996) Do Converters Facilitate the Transition to a New Incompatible Technology? A Dynamic Analysis of Converters, *International Journal of Industrial Organization.* **14,** 825-835.

Choi, J. P. (1997) The Provision of (two-way) Converters in the Transition Process to a New Incompatible Technology, *Journal of Industrial Economics.* **45,** 139-153.

Conner, K. R. (1995) Obtaining Strategic Advantage from Being Imitated: When Can Encouraging "Clones" Pay?, *Management Science.* **41,** 209-225.

Cusumano, M. A., Mylonadis, Y. and Rosenbloom, R. S. (1992) Strategic Maneuvering and Mass-Market Dynamics - the Triumph of VHS over Beta, *Business History Review.* **66,** 51-94.

David, P. A. and Bunn, J. A. (1988) The economics of gateway technologies and network evolution: Lessons from electricity supply history, *Information Economics and Policy.* **3,** 165-202.

Dranove, D. and Gandal, N. (2003) THE DVD vs. DIVX Standard War: Empirical Evidence of Network Effects AND Preannouncement Effects, *Journal of Economics & Management Strategy.* **12,** 363-386.

Economides, N. (1989) Desirability of Compatibility in the Absence of Network Externalities, *American Economic Review.* **79,** 1165-1181.

Economides, N. (1991a) In *Electronic Services Networks: A Business and Public Policy Challenge*, Vol. Chapter 3 (Eds, Guerin-Calvert, M. and Wildman, S.) Praeger Publishing Inc, New York.

Economides, N. (1996) The Economics of Networks, *International Journal Of Industrial Organization.* **14,** 673-699.

Economides, N. and Himmelberg, C. (1995) Critical Mass and Network Size with Application to the US Fax Market, *Discussion Paper # EC-95-11, Stern School of Business, New York University.*

Farrell, J. and Saloner, G. (1985) Standardization, compatibility, and innovation, *RAND Journal of Economics.* **16,** 70-83.

Farrell, J. and Saloner, G. (1992) Converters, Compatibility, and the Control of Interfaces, *Journal of Industrial Economics.* **40,** 9-35.

Farrell, J., Shapiro, C., Nelson, R. R. and Noll, R. G. (1992) Standard Setting in High-Definition Television, *Brookings Papers on Economic Activity. Microeconomics.* **1992,** 1-93.

Gallaugher, J. M. and Wang, Y.-M. (2002) Understanding network effects in software markets: Evidence from Web server pricing, *MIS Quarterly.* **26,** 303-327.

Gandal, N. (1994) Hedonic Price Indexes for Spreadsheets and an Empirical Test for Network Externalities, *The RAND Journal of Economics.* **25,** 160-170.

Gandal, N. (1995) Competing Compatibility Standards and Network Externalities in the PC Software Market, *The Review of Economics and Statistics.* **77,** 599-608.

Greene, W. H. (2003) *Econometric Analysis,* Prentice Hall, Upper Saddle River, New Jersey.

Greenstein, S. M. (1993) Did Installed Base Give an Incumbent any (Measurable) Advantages in Federal Computer Procurement?, *The Rand Journal of Economics.* **24,** 19-39.

Hartman, R. S. (1989) An Empirical Model of Product Design and Pricing Strategy, *International Journal of Industrial Organization.* **7,** 419-436.

Jaccard, J., Wan, C. K. and Turrisi, R. (1990) The Detection and Interpretation of Interaction Effects Between Continuous Variables in Multiple Regression, *Multivariate Behavioral Research.* **25,** 467.

Katz, M. L. and Shapiro, C. (1985) Network Externalities, Competition, and Compatibility, *American Economic Review.* **75,** 424.

Kauffman, R. J., McAndrews, J. and Yu-Ming, W. (2000) Opening the `Black Box' of Network Externalities in Network Adoption, *Information Systems Research.* **11,** 61.

Lee, J., Lee, J. and Lee, H. (2003) Exploration and exploitation in the presence of network externalities, *Management Science.* **49,** 553-570.

Liebowitz, S. J. and Margolis, S. E. (1994) Network Externality: An Uncommon Tragedy, *Journal of Economic Perspectives.* **8,** 133-150.

Liu, C. Z., Gal-Or, E., Kemerer, C. F. and Smith, M. D. (2007) Winners Take Some: The Impact of Conversion Technologies on Network Effects in Digital Goods Markets, Working paper Katz Graduate School of Business, University of Pittsburgh.

Matutes, C. and Regibeau, P. (1988) "Mix and Match": Product Compatibility without Network Externalities, *The RAND Journal of Economics.* **19,** 221-234.

Mittal, N. and Nault, B. R. (2006) Investments in Information Technology: Indirect Effects and Information Technology Intensity, Working paper Haskayne School of Business, University of Calgary,37.

Park, S. (2004) Quantitative Analysis of Network Externalities in Competing Technologies: The VCR Case, *Review of Economics & Statistics.* **86,** 937-945.

Shapiro, C. and Varian, H. R. (1999) *Information Rules: A Strategic Guide to the Network Economy* Harvard Business School Press, Boston, MA

Suárez, F. F. and Utterback, J. M. (1995) Dominant designs and the survival of firms, *Strategic Management Journal.* **16,** p415-430, 16p.

Zhu, K., Kraemer, K. L., Gurbaxani, V. and Xu, X. (2006) Migration to Open-Standard Interorganizational Systems: Network Effects, Switching Costs and Path Dependency, *MIS Quarterly.* **30,** 515-539.