3-1-2010

Standards Competition in the Presence of Digital Conversion Technology: An Empirical Analysis of the Flash Memory Card Market

Charles Z. Liu
University of Pittsburgh

Chris F. Kemerer
University of Pittsburgh

Sandra A. Slaughter
Georgia Institute of Technology - Main Campus

Michael D. Smith
Carnegie Mellon University, mds@andrew.cmu.edu

Follow this and additional works at: http://repository.cmu.edu/heinzworks

**STANDARDS COMPETITION IN THE PRESENCE OF DIGITAL CONVERSION TECHNOLOGY:
AN EMPIRICAL ANALYSIS OF THE FLASH MEMORY CARD MARKET**

Charles Z. Liu
Chris F. Kemerer
University of Pittsburgh, Pittsburgh, PA, 15260

Sandra A. Slaughter
Georgia Institute of Technology, Atlanta, GA 30308

Michael D. Smith
Carnegie Mellon University, Pittsburgh, PA 15213

{zhliu, ckemerer}@katz.pitt.edu,
sandra.slaughter@mgt.gatech.edu,
mds@cmu.edu

This version: May 2008

STANDARDS COMPETITION IN THE PRESENCE OF DIGITAL CONVERSION TECHNOLOGY: AN EMPIRICAL ANALYSIS OF THE FLASH MEMORY CARD MARKET

Abstract

Theoretical and empirical evidence suggest that in many markets with standards competition, network effects make the strong grow stronger and can "tip" the market toward a single, winner-take-all standard. We hypothesize, however, that this sort of standards-induced market dominance may be less common in the context of digital systems, where the presence of low cost conversion technologies may facilitate easy compatibility across competing standards. We empirically test our hypotheses in the context of the digital flash memory card market.

We first test for the presence of network effects in this market, and find that network effects strongly influence competition between flash memory standards. We then analyze whether these network effects are moderated by the adoption of digital converters, and find that the availability of digital converters provides a measurable reduction in the price *premium* of the leading flash card formats relative to that of formats with lower market shares. These market dynamics imply that producers of non-dominant digital goods standards are better off with the provision of conversion technology, as this technology tends to neutralize the impact of network effects. In addition, further analysis shows that market concentration in the flash memory market decreases as converters become more widely available.

Key words: *Network effects, network externalities, standards competition, conversion technologies, flash memory, digital goods, market competition.*

1. Introduction

Network effects arise in many information technology (IT) markets where the value of a product or service to one consumer is at least partially dependent upon the choices made by other consumers. These interoperability benefits make the choice of a technology standard or platform an important strategic decision for both consumers and firms (Katz and Shapiro, 1985, Economides, 1996). Examples of technologies for which network effects have been demonstrated include computer hardware, operating systems, application software, and, more recently, popular instant messaging and social networks.

In addition to ease of communications, a widely adopted product may also give rise to a 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 there is increasing awareness of these compatibility benefits, consumers are more likely to opt for a product that adopts a more popular standard. This behavior in turn creates a virtuous cycle for the leading (majority) 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 becomes subject to 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 in the markets for U.S. desktop operating systems and office productivity software (Bresnahan, 2001), among others.

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

1

competitive dynamics in these digital goods markets appear to be different, i.e., why are these markets not converging to a single standard as in other IT markets with network effects.

In this study we investigate this issue in the context of the flash memory market. Flash memory is a class of non-volatile, electrically rewritable memory that was introduced into the consumer electronic market in the 1990s.[1] With the capability to store large amounts of data in digital format, fast read/write speeds, and compact size, flash memory 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 the 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 expansion of the digital consumer electronics market and the heavy reliance of these digital devices on flash memory for data storage and transfer.

However, what *is* surprising is the variety of distinct card formats that exist in the market in spite of apparent demand side economies of scale. If network effects were present, consumers who purchased a particular flash memory format would be more likely, all else equal, to take this format into consideration when purchasing their next digital device in order to be able to reuse the flash memory cards and to easily transfer digital outputs from one device to another. For example, family members can swap memory cards from one camera to another while on vacation. Or, consumers can transfer digital data from an older device to a newer one when they replace it, e.g., the flash memory card in a cell phone which contains the user's stored phone numbers. And, to the degree that one format became widely adopted, more manufacturers would find it desirable to make their devices compatible with the emerging standard, which would generate the classic increasing returns to adoption found in network effects.

Indeed, anecdotal evidence suggests that vendors of flash memory perceive that there *are* demand side economies of scale in this market and highlight this in their promotional materials. For example,

---

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

Sony describes the use of its Memory Stick product as follows (emphasis in bold and underline is ours):

> *...in addition to navigation data, **<u>Memory Stick can be used to store a variety of data for</u> <u>reproduction on an extensive range of compliant products</u>**. For example, photos taken during a trip can be viewed immediately on your navigation system's large-screen monitor. To print the pictures you like, stop at a store with a kiosk terminal. You can get high-quality prints quickly and easily. ... With a Memory Stick compatible car audio system, you can enjoy music while you drive.[3]*

Sony has also highlighted compatibility with a large variety of consumer products in its strategic partnership with Samsung (emphasis added):

> *This agreement strengthens the cooperative relationship existing between the two companies beyond the basic agreement reached in August of 2001. Under the 2001 agreement, **<u>Sony worked</u> <u>with Samsung to add Memory Stick compatibility to a range of Samsung products including</u> <u>DVD players, mobile phones, PCs and televisions</u>**.[4]*

SanDisk, another major manufacturer of flash memory cards, similarly promotes the universality of its format to a wide range of consumer products, including its use to ease upgrading to a new device (emphasis added):

> ***<u>Another benefit of SanDisk's 256 MB mini SD card is that it will allow you to move the</u> <u>information from your phone to another phone or to your computer.</u>*** *Instead of keeping all of those cute pictures of the kids on your cell phone you can move them to your computer and ensure that you can keep them forever. **<u>This mini card will also come in handy if you decide to get a new</u> <u>cell phone but you don't want to lose all of the information you have on your current phone.</u>** Simply save all of the information on this mini SD card and move the information to your new phone![5]*

It also seems clear that vendors see a strategic advantage in promoting their format as the leading standard. For example, consider this comment by Sony President Kunitake Ando in reference to the Sony-Samsung deal:

> *"Memory Stick is a network media allowing seamless connection of content and services between PCs and various digital consumer electronics. Samsung Electronics is a major semiconductor manufacturer and its manufacture and sale of Memory Stick media will accelerate the growth of Memory Stick throughout the world. **<u>Together with media, the expansion of Samsung's lines of</u> <u>digital cameras, mobile phones and other Memory Stick compatible products will enable</u> <u>Memory Stick's 'Connected World' to expand allowing customers to enjoy a broad range of</u> <u>content and services through a diverse array of devices. ... I am convinced that it will strengthen</u> <u>the Memory Stick format's position as the global standard within the memory card market."</u>***

---

[3] http://www.memorystick.com/en/lifestyle/incar/index.html
[4] http://www.sony.net/SonyInfo/News/Press_Archive/200308/03-0806E/
[5] *Business Wire*, September 2, 2006. http://findarticles.com/p/articles/mi_m0EIN/is_2006_Sept_2/ai_n16702773

Beyond these vendor announcements, the business press has also suggested the likelihood of demand side economies of scale for flash memory cards. For example, the *Wall Street Journal* has reported:

> *Memory-card selection has increasingly important ramifications for gadget owners. Having a card that you can pop in and out of different devices lets you do things you couldn't otherwise. You can, for instance, take a picture on a digital camera, transfer the memory card to your personal organizer, and then bring up the picture on its screen.* [6]

However, despite vendors' stated strategic efforts and the acknowledgement by the business press of demand side economies of scale for flash memory devices, the typical self-reinforcing feedback loop of a popular format becoming more popular and leading to a winner-take-all market has not occurred in the flash memory market to date. There are currently six major distinct formats in the market, and a number of variants deriving from each format. Further, early success has not necessarily translated into future success, as incumbent formats have experienced a decline in market share and as new formats continue to emerge. As depicted in Figure 1, the SmartMedia and Compact Flash formats, despite their first mover advantage (approximately 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.
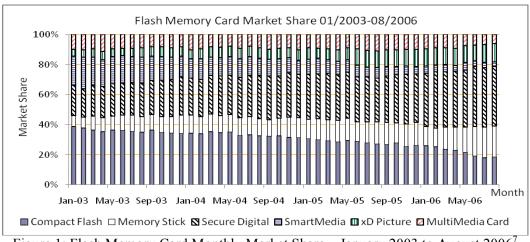

Figure 1: Flash Memory Card Monthly Market Share – January 2003 to August 2006[7]

This "winners-take-some" market outcome raises two main research questions. The first question is: *are network effects actually present in this market*? The industry and popular press documents the belief that network effects are present in the flash memory market. However, if consumers do not perceive value from format compatibility, the lack of a dominant firm outcome is not surprising. The second question is: *if network effects are present in the flash memory market why is there little evidence of standards convergence in a market that desires compatibility and would benefit from network effects*? In short, what distinguishes the flash memory card market from other markets with similar characteristics that have seen market consolidation?

Our aim in this study is to empirically address these two research questions. We theorize that, in contrast to other IT Markets studied in the network effects literature, a candidate explanation for the apparent anomalies in the competitive dynamics of the flash memory card market 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. This means that, unlike many other technologies commonly studied in the literature, their contents can be transferred easily and losslessly between devices using a variety of inexpensive PC- and USB-based converters.[8] The existence of these conversion technologies enables compatibility across different formats without compromising product performance or features (Farrell *et al*., 1992). This aspect of the flash memory market has not typically been observed in other markets for analog products with network effects. For example, converting between the VHS and Betamax videotape standards was costly and resulted in signal loss (Cusumano *et al*., 1992).

We evaluate our hypotheses by analyzing a unique and extensive dataset obtained from the market research firm NPD. The data include monthly retail prices and unit sales for flash memory converters and for all six flash memory card formats sold from 2003 to 2006. We use this data to empirically examine the role of digital converters in shaping the competition in the flash memory market. We first test for and

---

[8] These converters (also known as multi-format readers) have multiple slots for different types of otherwise 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 of converters are available in the market (www.amazon.com/exec/obidos/tg/browse/-/1197398).

find the presence of network effects in the flash memory market as demonstrated by an associated product price premium for formats with greater installed bases. Given the presence of network effects in this market, we then consider the lack of market dominance and find a potential explanation in digital converters for flash memory cards. Specifically, we find that the increasing adoption of digital converters reduces the impact of the installed base on the product price premium, despite the demonstrated evidence of network effects. In particular, digital converters reduce the price premium of the leading formats *more* than they do that of the minority formats. Not only is the impact of network effects less significant when there is greater adoption of digital converters, but market concentration also decreases as digital converters are widely adopted, suggesting increasing competitiveness with converter introduction. Thus, our results suggest that, in the presence of low cost conversion technologies and digital content, the probability of market dominance driven by network effects can be lessened to the point where multiple incompatible standards are viable.

In addition to addressing a relevant practical question regarding potential winner-take-all markets, our findings have both theoretical and managerial implications for the growing literature on network effects in IT markets. Specifically our empirical study complements the analytic literature on conversion technologies in markets with standards 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 digital goods technologies and the associated interaction between network effects, converters, and market evolution. Our empirical analysis of this question using market data thus contributes to the existing body of knowledge on network effects by providing new 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 the value of network effects decrease, since compatibility can be achieved at a lower cost. Consequently, the choice of

a product may rely more on factors other than market share, such as brand and quality attributes. If this shift in consumer preferences occurs, vendors' marketing and pricing strategies should adjust accordingly. Thus, the consumer decision-making process and the interaction between vendors and consumers may both 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 reasonable 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 circumstances in which the net value 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 product markets with network effects, early success in accumulating a large installed base of customers 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 and lock-in among 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 of network effects 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, as network effects are often perceived to follow 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 a consumer's willingness to pay for the dominant standard. Several empirical studies have found a significant advantage for dominant standards in markets for IBM compatible microcomputers (Hartman, 1989), mainframe computers (Greenstein, 1993), 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 antecedents of network effects, they all adopt the same notion of *price premium* in interpreting the estimated coefficients on the compatibility variables. Price premium refers to the price advantage a product enjoys over the other competing products due to one or more distinct product features such as brand, quality, or in the above studies, compatibility. A number of techniques have been used to identify the price premium resulted from network effects, of particular interest is the use of hedonic regressions in capturing this value.

Hedonic regressions were 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 disaggregate consumers' consumption utility into independent valuations of different aspects of a product, the hedonic regression has been widely employed in estimating the marginal benefit of products that include multiple attributes, and has been usefully employed in the empirical literature on network effects. By treating various antecedents of network effects, such as the size of the installed base or learning costs, as implicit features of a product, hedonic regressions allow researchers to obtain estimates of the parameters capturing a consumer's willingness to adopt a standard (or the opportunity costs to switch to a different network). Hence price premium can be computed as the portion of the listed price that is attributed to the size of the product installed base, 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 (e.g. brand, capacity, speed), we follow the literature and adopt the hedonic framework in our study as an appropriate approach to distinguish the impact of network effects from 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 with network effects. Although the extant empirical literature has identified a variety of sources and consequences of network effects, little attention has been devoted to the interaction between conversion technologies and technology adoption in markets characterized with standards competition. The studies that do address this topic have relied 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. There are no empirical studies of this phenomenon that we are aware of.

The lack of empirical studies on this topic may derive from the difficulty 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. Via the provision of converters, consumer benefits include both greater product variety and the increased 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 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 incompatibility 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 it is typically modeled in the network effects literature. A consumer's valuation of product compatibility, as measured by product price, needs to be further disaggregated into variation due to the product's installed base, the adoption of conversion technologies, and the interaction of the two effects. Drawing on the findings from the above literature, below 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 magnitude of network effects is an important first step in evaluating the nature of standards competition in the flash memory card market. As discussed in section 2, we adopt the same notion of price premium to capture network effects. In the flash memory market, price premium of a flash memory card measures the importance (or value) a consumer places on the size of this flash memory format's installed base, controlling for other flash memory card attributes such as brand, capacity, speed, etc. Note that since price premium only measures the relative impact of a particular product attribute (i.e. network size) on listed price, it does not always move in the same direction as listed price. This distinction is especially important in IT industry (and the flash memory market in particular) where a declining product price is commonly observed due to rapid technological development. Although the listed price is declining, a product format could still enjoy a positive price premium from its installed base if consumers believe that compatibility is important.

Our first hypothesis considers the effects of market power and reasons whether dominant producers can charge more for their flash memory cards. In particular, the size of the installed base may play a dual role with respect to the price premium of a flash memory card. On the one hand, when network effects are present, a larger installed base for a product format confers greater utility to consumers. Hence the price premium of a flash memory format could be expected to vary positively with the size of the flash memory format's installed base. For example, in the context of software, consumers of the dominant operating system will find that they can use a larger number of software applications than users of a competing, but minority system. On the other hand, due to economies of scale in production, a flash memory format with a larger sales volume can enjoy a greater cost advantage over those with a smaller sales volume. Hence the price premium of a flash memory format could also be expected to vary negatively with the size of its installed base.

According to the classic network effects theory, if 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 this standard should be able to charge a higher price, reflecting the higher value that consumers perceive. However, in contrast to this typical scenario, in the flash memory card market there is little evidence of standards convergence despite consumers' desire for product compatibility. Thus, an alternative possibility is that the magnitude of positive network effects is not strong enough to warrant a dominant firm market outcome. The dual role of the installed base allows us to empirically examine this alternate explanation. Given the magnitude of network effects, we expect that if there exists a strong demand for compatibility, the price premium due to market power will dominate the price reduction effect due to production economies of sale, such that:

Hypothesis 1a: *in the presence of strong network effects, the price premium of a flash memory card is positively associated with the size of the installed base of the same format.*

Conversely, if there is no demand for compatibility in the flash memory market, or such demand is insufficiently strong, the price of a product will depend largely on its product attributes and production cost. That is, the increment in the price attributable to network effects will be smaller. Hence in this alternative case we would expect that:

Hypothesis 1b: *in the absence of strong network effects, the price premium of a flash memory card is negatively associated with the size of the installed base of the same format.*

Hypotheses 1a and 1b serve as two competing hypotheses about the magnitude of network effects in the flash memory market, which is an important prerequisite for the analysis of the impact of conversion technologies in the flash memory market.

Our second hypothesis considers how the introduction of digital converters affects the price premium of flash memory cards and argues that digital converters increase the usefulness and thereby the value of flash memory cards, in general (i.e., at an average level of the installed base). When digital converters are available, consumers of flash memory cards with incompatible formats can still exchange

content with each other and thereby obtain the benefits of compatibility. Thus, digital converters can increase the 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 premium, of flash memory cards, even if the cards are not compatible. Therefore:

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

Our third hypothesis considers the interaction between producers' market power and the introduction of digital converters and posits that the presence of converters increases product substitutability and thereby reduces the value of flash memory cards, especially for the dominant producers (i.e., those with an installed base that is larger than average). 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 widely present, consumers are not as motivated to purchase a dominant standard as there is less benefit from it; this lowers the producer's market power and consequently, its price premium due to network effects. 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 they have more value to lose from being 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 price premia such that the price reduction effect is stronger for products with a larger installed base than for products with a smaller installed base*.

Finally, in Hypothesis 4, we consider the effects of digital converters on market concentration for flash memory card producers. Classic network effects theory predicts that product markets will tip toward

a single dominant standard when there are strong network effects. Consequently, market concentration will typically increase once the installed base of the leading standard has reached a critical mass. However, as argued here, it is possible that the presence of conversion technology will affect the nature of competition as conversion technology can offset some of the impact of network effects. If this is true, it is less likely that a dominant producer will emerge in a market with an increasing presence of converters. The flash memory card market could then be expected to be less likely to tip toward one dominant producer as many different formats can be converted to become compatible. Therefore:

Hypothesis 4: *Market concentration of flash memory card producers decreases as the adoption of digital converters increases.*

Figure 2 summarizes these four hypotheses and illustrates the conceptual framework for our empirical analysis along with the predicted directions of the hypothesized interaction between the adoption of digital converters and product's installed base. Figure 2 also illustrates two important market outcomes of network effects: price premium and market concentration. Control variables are shown in dashed boxes.
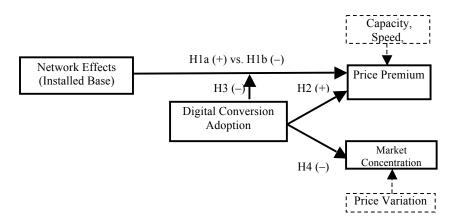

Figure 2: Research Model and Hypotheses

4. Data and Measures

4.1. *Sample*

To test our hypotheses we assembled a large panel dataset including data on the products and the producers in the flash memory card market. 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 all the six current formats are present. Our primary data were generously provided by the NPD research group. These data include detailed information on monthly retail prices and unit sales data of the major flash memory cards and digital converters sold each month by major U.S. retailers. These data are obtained by NPD directly from point-of-sale (POS) terminals in major retailers across a range of outlets and cover the period 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 review data from *Amazon.com* on a daily basis. We use the sales rank and product review data to control for the popularity of different flash memory card models. Price data from Amazon.com are used to validate the retail prices from the NPD dataset. Finally, we gathered the flash memory cards' product specification data from each flash card format's official trade association.

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 product panels[9] across 44 months. Each product panel represents 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 time series data allow us to control for variation due to potential "seasonal fluctuations" (e.g., holiday sales surge) and time trends (e.g., declining costs). The distribution of observations, broken down by format and year, is shown in Table 1 below.

---

[9] 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 cards are discontinued after a certain period of time.

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 include up to August, 2006

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 cumulative sales volume (in units) of format i flash cards as of month t
$ConverterAdoption_t$	number of digital converters[†] sold as a percentage of the total number of flash memory cards sold 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 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.
[†] We only include converters that can read from and write to multiple flash memory formats as they represent the majority of the flash memory cards sold in the market (more than 90% based on our data) and they better capture the demand for compatibility than single-format converters which only transfer data between flash memory cards and PC.

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. We compute flash memory card price, $CardPrice_{i,j,k,t}$, as the deflated (in 2003 Q1 dollars) average retail price of flash memory cards of format i, brand j, and capacity k sold during month t (Brynjolfsson and Kemerer, 1996). The current installed base, $InstalledBase_{i,t}$, is the percentage of the cumulative units of format i compatible flash memory cards sold in month t. The level

of digital converter adoption, *ConverterAdoption$_t$*, is the number of the digital converters sold as a percentage of the total flash memory cards sold during month *t*. We include two product attribute variables, capacity and speed, as control variables to account for possible variations due to memory card capacity and product specifications. We capture other format specific product features with six format dummy variables. Finally, we create three other dummy variables to control for brand, seasonal and year effects.

Table 3: Descriptive Statistics

Variable	Mean	Std. Dev.
CardPrice$_{i,j,k,t}$	61.08	85.29
InstalledBase$_{i,t}$	0.23	0.13
ConverterAdoption$_t$	0.65	0.23
Capacity	420.74	804.97
Speed	20.68	15.04

We present descriptive statistics in Table 3 and the correlations of the key variables in Table 4. The inter-correlations between the variables in our model are generally low. As expected, two control variables, capacity and speed, are both positively correlated with flash memory card price, with cards having larger capacities and faster speeds commanding higher prices, *ceteris paribus*. The other two key variables, flash card installed base and converter adoption are modestly correlated with price, with installed base having a positive correlation and converter adoption a negative correlation.

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

5.1 Network effects, digital converters and price premia

We construct several econometric models to test our hypotheses. Given that the effect of converters is nonlinear, it cannot be captured by the independent predictor of product price in the classic linear

hedonic model framework. Therefore, we test Hypotheses 1 through 3 by modifying the classic hedonic model to include an interaction term between installed base and the adoption of digital converters[10].

[Model 1]

$$CardPrice_{i,j,k,t} = \alpha_0 + \alpha_1 InstalledBase_{i,t-1} + \alpha_2 ConverterAdoption_{t-1} +$$
$$\alpha_3 InstalledBase_{i,t-1} * ConverterAdoption_{t-1} + \alpha_4 Capacity + \alpha_5 Format_i + \alpha_6 Brand_j + \alpha_7 Year + \alpha_8 Quarter + \varepsilon_{i,t}$$

When the variable *ConverterAdoption* and its associated interaction term are both absent, Model 1 reduces to a classic hedonic price regression where the coefficient α_1 represents the impact of network size on price premium and is expected to be positive and significant when there are strong network effects. However, when these two variables are included in the model, the marginal effect of the installed base on price premium 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 marginal effect on price premium should be computed as the partial derivative of the dependent variable with respect to the variable of interest. Thus, Hypothesis 1a (or Hypothesis 1b), which predicts that, *ceteris paribus*, a larger installed base will increase (or decrease) the price premium of a flash memory card, can be represented as:

$$H1a: \frac{\partial CardPrice_{i,j,k,t}}{\partial InstalledBase_{i,t-1}} = \alpha_1 + \alpha_3 ConverterAdoption_{t-1} > 0 \text{ (or} < 0 \text{ for H1b)},$$ when evaluated at the mean of

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

$$H2: \frac{\partial CardPrice_{i,j,k,t}}{\partial ConverterAdoption_{t-1}} = \alpha_2 + \alpha_3 InstalledBase_{i,t-1} > 0,$$ when evaluated at the mean of *InstalledBase$_{i,t-1}$*.

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).

---

[10] We use quarterly dummy variables instead of monthly dummy variables because quarterly dummies explain the variation in price better than monthly dummies do (higher adjusted R^2). However, the results are consistent across both specifications.

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, the Smartmedia format, spring quarter, and the 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.

Table 5: Regression Results[†‡] – Model 1

Dependent Variable: $CardPrice_{i,j,k,t}$	OLS Regression Restricted Model (No interaction)	OLS Regression Unrestricted (Interaction) Model[11]	GLS Estimation Interaction Model	2SLS Estimation Interaction Model
Constant	34.691 (3.34)**	45.310 (3.42)**	43.005 (3.47)**	21.53 (2.518)**
$InstalledBase_{i,t\text{-}1}$	17.676 (9.61)*	83.543 (10.84)**	43.573 (3.97)**	49.814 (10.34)**
$ConverterAdoption_{t\text{-}1}$	-35.450 (11.45)**	-41.677 (11.40)**	-20.323 (1.96)**	-75.24 (11.49)**
$InstalledBase$ * $ConverterAdoption_{t\text{-}1}$		-514.728 (39.99)**	-190.87 (14.48)**	-802.28 (56.53)**
Adjusted R^2	0.532	0.553	Log likelihood $=-54658.9$	0.538
Fit Statistic	$F(23, 15067) = 747.9^{**}$	$F(24, 15066) = 761.47^{**}$	Wald $\chi^2 (24) = 12208.97^{**}$	$F(23, 14827) = 749.21^{**}$

[†] 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%.

The Ordinary Least Square (OLS) regression results of both the restricted and unrestricted models are provided in Table 5. 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 in 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

---

[11] As some of the literature on network effects considers a non-linear specification, we also tested a model with an additional variable, a squared term of the installed base, to examine whether the impact of converters is sensitive to the specification of network effects. The results indicate that 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 interpretation we report the results obtained from the linear specification of the network effects model.

and test the hypotheses, we also conduct several econometric analyses to ensure that our results are robust to various specification errors and violations of the OLS estimation assumptions.

The multiplicative nature of our model implies that the marginal effects of the linear variables can be confounded with the influence of the interaction term. To make our interpretation of the linear terms more straightforward we follow the current practice in the literature (Jaccard *et al*., 1990, Aiken and West, 1991, pp 35-36) and center the original interacting variables before computing the interaction term. This is done by subtracting the mean from every observation for both interacting variables. After centering, the means of the centered variables are zero, and the correlations between the interaction term and the original variables are much smaller.[12] A multicollinearity check also reveals that after centering, the condition number of the interaction model and the variance inflation factor (VIF) values of the interaction term and the original variables are both below the recommended threshold values of 20 and 10, respectively (Greene 2003, pp. 57-58). Therefore, we conclude that our interaction model does not exhibit multicollinearity.

A Breusch-Pagan / Cook-Weisberg test for heteroskedasticity yields a value of $\chi^2(1) = 7027.54$ (p<0.001), suggesting the presence of heteroskedasticity. This is consistent with a plot of the residuals versus fitted (predicted) values, which exhibits a wider scatter with greater X-axis values.

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 would argue against the use of OLS (Greene, 2003). As both heteroskedasticity and autocorrelation are present in our dataset we address both problems together by applying Generalized Least Squares (GLS) estimation procedures[13] with corrections to adjust for both heteroskedasticity and panel specific first-order autocorrelation. As shown in Table 5, column 3 our results are robust to these corrections. The interaction effect remains significant and the directions of

---

[12] For ease of comparison, both *InstalledBase*$_{i,t-1}$ and *ConverterAdoption*$_{t-1}$ are centered in the OLS regressions.
[13] We also run a Hausman test to examine if there are fixed or random effects in our data. The Hausman test rejects the null hypothesis that individual effects are uncorrelated with the other regressors and suggests that fixed effects exist in our data. However, a fixed effect specification results in excessive collinearity (many variables are dropped in a fixed effect model). Therefore, we adopt the GLS estimator.

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.

As the GLS estimator is more robust to heteroskedasticity and autocorrelation, we examine both marginal effects and interaction effects using the results from the GLS estimation. To evaluate Hypotheses 1 and 2 in Table 6, we compute the marginal effects of the variables *InstalledBase* and *ConverterAdoption* at the means of the interacting variables.[14] Following Greene (2003, pp.124), the standard errors of these marginal effects can be computed from:

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

similarly for $Var(\frac{\partial E[Cardprice_{i,j,k,t} \mid InstalledBase_{i,t}, ConverterAdoption_t]}{\partial ConverterAdoption_t})$. Note that the standard errors of the

marginal 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: Marginal Effects

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

The "Mean" column of the first row in Table 6 shows that the marginal effect of the flash memory card installed base is positive at the mean value of the converter adoption level. This indicates that network effects *do* exist in the flash memory card market such that the price premium of a flash memory card is positively associated with the size of the installed base for the same format. This provides support for Hypothesis 1a and rejects Hypothesis 1b. The "Mean" column of the second row shows that the marginal effect of digital converter adoption is negative when evaluated at the mean value of the installed

---

[14] We also compute the marginal effects at different values of the interacting variables to show how the marginal effects change as the value of the interacting variables varies.

base. Thus, the price premium of a flash memory card is negatively associated with the level of converter adoption, and Hypothesis 2 is not supported.

With regard to Hypothesis 3, as shown in Table 6, the flash card price premium changes in the expected direction. The first row suggests that, at average levels of digital converter adoption, digital converters reduce the price premium of leading formats (i.e., those with a larger installed base — the +1 and +2 standard deviation columns) more than minority formats (i.e., those with a smaller installed base — the -1 and -2 standard deviation columns). The second row shows that, at average levels of the installed base for a flash memory card format, the marginal effect of digital converter adoption is larger when the level of converter adoption is higher (the +1 and +2 standard deviation columns) than when the level of converter adoption is lower (the -1 and -2 standard deviation columns). 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 confirms that the inclusion of the interaction term significantly contributes to the explanation of the variance in the hedonic regression. Therefore, Hypothesis 3 is supported.

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. We use this approach as the lagged differences in cumulative installed base are less likely to be correlated with the present differences in product prices. 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.[15] The results from the GMM estimation (summarized in Table 5) are consistent with those obtained from the OLS and GLS estimations. 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

---

[15] The same approach is also used in Mittal and Nault (2006) in a similar situation.

that the lagged cumulative market share is exogenous. This provides confidence in our results against potential endogeneity concerns.

5.2 *The effect of converters on market concentration*

When converters are not available in markets with strong network effects, a large installed base can give firms a significant advantage in standards competition and may lead to a "winner-take-all" outcome. However, Hypothesis 4 predicts that when converters are available this competitive advantage will be weakened and market concentration will decrease as the adoption of digital converters increases. To test Hypothesis 4 we use the following model to examine the relationship between the adoption of digital converters and the shift in market shares of the competing flash memory card formats:

[Model 2]

$$MarketConcentration_t = \beta_0 + \beta_1 ConverterAdoption_{t-1} + \beta_2 Var(CardPrice/MB)_{k,t} + \varepsilon_{k,t}$$

In Model 2, the dependent variable, market concentration, is measured by the Herfindahl-Hirschman Index (HHI). HHI is widely used as a measure of the size of firms in relationship to the industry and as an indicator of the amount of competition in a market (Calkins, 1983). A larger value of the HHI indicates higher market concentration and hence less intense standards competition. Note that in our model HHI is computed as the sum of squares of the market shares of the competing *formats* rather than *brands* as we are primarily interested in competition among technology formats rather than firms. To perform this analysis we break the data down by month and by capacity, which results in 428 data panels. Next, the value of HHI in each panel is regressed against the lagged adoption level of digital converters of the corresponding panel, controlling for the variance of flash memory card retail prices in each panel.[16] In order to correct for price differences across different memory capacities, retail price is calculated as the average price per megabyte in each panel.

The new dataset consists of panels spanning 12 capacity categories and 44 consecutive months. As above, a Breusch-Pagan / Cook-Weisberg test and a Wooldridge test on the residuals of the OLS

---

[16] This controls for variation in market concentration due to price variation that is associated with other exogenous factors.

regression confirm that both heteroskedasticity and panel specific first-order autocorrelation (AR1) are present in our data. Therefore, we adopt the GLS adjustments to correct for heteroskedasticity and autocorrelation.

Table 7 presents the GLS regression results for Model 2. The coefficient estimate of the variable *ConverterAdoption$_{t-1}$* is negative and significant at a 5% level in both specifications, suggesting that across different flash memory card capacity categories, market concentration decreases as the adoption of digital converters increases. Hence Hypothesis 4, that market concentration of flash memory card producers decreases as the adoption of digital converters increases, is supported.

Table 7: Regression Results[†‡] – Model 2

Dependent Variable: HHI	Coefficients
Constant	.531
	(.0532)[**]
ConverterAdoption$_{t-1}$	-.180
	(.081)[*]
Var(Card_Price/MB$_t$)	8.72e-07
	(7.54e-07)
Condition Number	10.29
Log likelihood	431.2

[†]N=428 (12 different capacities across 44 month).
[‡] Standard errors in parentheses. *: p<5%; **: p<1%.

6. Discussion

The main empirical 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, consistent with views in the industry and in the trade press, the flash memory market *does* exhibit positive network effects as demonstrated by a product price premium for formats with larger installed bases; this provides support for Hypothesis 1a, but not for Hypothesis 1b. Thus, one might expect a dominant standard in this market. However, we also find that the presence of digital converters moderates standards competition by offsetting some of the impact of network effects. As shown in Table 6, in markets characterized by network effects, the presence of converters weakens the

relationship between installed base and price premia. At average levels of the flash card installed base, the marginal impact of converters on price premia is negative, contradicting our Hypothesis 2. The impact 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 an estimated $0.28. But, this price premium disappears when a format's installed base is close to the industry average. This finding is consistent with our predictions and may 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 a higher price, is larger for consumers of the minority formats than for those of the dominant format.

In addition to the differential impact of converters on consumers who belong to different networks, several other factors may account for the lack of support for Hypothesis 2. For example, flash memory card vendors can also profit from the sales of digital converters. If a vendor is engaged in the sale of both converters and flash cards, the vendor can theoretically transfer some of the price premium from the flash memory cards to the sales of digital converters and still profit overall. A similar argument applies for vendors who do not produce their own converters, but license a third party vendor to do so. In this case, the licensing fee could 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 gives rise to $0.43 price premium (0.705% price increase) of a compatible flash memory card.[17] It is also important to note that the strength of network effects, as represented by the price premium, is very

---

[17] Interestingly, this is a price premium of a similar order of magnitude (0.753% price increase) as that found in the microcomputer spreadsheet software market (Brynjolfsson and Kemerer, 1996).

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 $0.69. However, when the adoption of digital converters is high, *i.e.*, at one standard deviation *above* the mean, such a price premium almost disappears.

Figures 3 and 4 illustrate the interaction between network effects (installed base) and the adoption of digital converters. 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. This supports our Hypothesis 3 and suggests 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 an opposite impact on the price premia of majority and minority flash memory card formats.
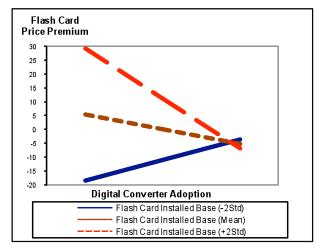
Figure 3: Price premium of a type of flash card at + or - 2 standard deviations of the mean converter adoption level
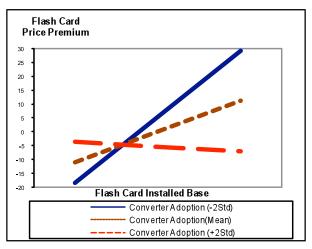
Figure 4: Price premium of a type of flash card at + or - 2 standard deviations of the mean flash card installed base

A similar interaction is depicted in Figure 4 where 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 reveal that digital converters have the potential to change the nature of competition in the flash memory card market. The results from Model 2 suggest that market competition intensifies as converters are widely adopted, and that first-mover advantage from installed base is relatively low. This may heighten the attractiveness of these markets to new entrants (Clemons et al., 1996; Grimm et al. 2005, pp. 129-155).

The results from Model 2 indicate that, consistent with our Hypothesis 4, as converter penetration increases, the market share gap among various competing formats is 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 a 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 effect that pushes the market away from high concentration. Under such a competitive environment a standards competition characterized with extensive adoption of converters is likely to undergo a more unpredictable growth path.

Our results are also consistent with observed market behavior: converters have become increasingly important in the market and have been disproportionately adopted by new entrants and minority formats.

26

Since their introduction in the market in early the 2000s, MicroSD and MiniSD formats 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) postpone their investment until the market is clear about which standard to adopt. However, this delay in adoption results in even more uncertainty about the future of the technology. However, if a digital converter were available to convert data from one incompatible form to another 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. And, once any excess inertia among stragglers is overcome, technology adoption can be expected to accelerate and lead to a traditional evolutionary path.

7. Conclusions and Future Research

The implications of network effects have been widely discussed in both the academic literature and the popular press. However, most illustrations of networks effects are drawn from existing physical and 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 cards and flash memory converters. Our findings yield several important

27

insights into digital goods markets characterized with network effects. Extensive adoption of digital converters reduces 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. Competition intensifies as the market power of the leading format is weakened, as reflected by a decreasing market concentration ratio with increasing converter adoption. These findings explain the seemingly counter-intuitive trend of the lack of standards convergence currently seen in the flash memory card market. Our findings also shed light on the likely evolution of standards competition in other, similar digital product markets.

The dynamic nature of the flash memory card market also raises several interesting questions for future research. When firms can supply both flash memory cards and digital converters, how they exercise 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.[18] 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.

---

[18] For example, 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., West, S. G. 1991 *Multiple Regression: Testing and Interpreting Interactions,* Sage Publications.

Asvanund, A., Clay, K., Krishnan, R., Smith, M. D. 2004. An Empirical Analysis of Network Externalities in Peer-to-Peer Music-Sharing Networks. *Information Systems Research,* **15**(2) 155-174.

Baum, C. F., Schaffer, M. E., 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., Azoulay, P. 2003. Consumption Externalities and Diffusion in Pharmaceutical Markets: Antiulcer Drugs. *Journal of Industrial Economics,* **51**(2) 243-270.

Bresnahan, T. F. 2001. Network Effects and Microsoft. *Department of Economics, Stanford University Working Paper*.

Brynjolfsson, E., Kemerer, C. F. 1996. Network Externalities in Microcomputer Software: An Econometric Analysis of the Spreadsheet Market. *Management Science,* **42**(12) 1627-1647.

Calkins, S. 1983. The New Merger Guidelines and the Herfindahl-Hirschman Index *California Law Review,* **71**(2) 28.

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

Chen, P. Y., 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**(3) 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**(6) 825-835.

--- 1997. The Provision of (two-way) Converters in the Transition Process to a New Incompatible Technology. *Journal of Industrial Economics,* **45**(2) 139-153.

Clemons, E. K., Croson, D. C., Weber, B. W. 1996. Market Dominance as a Precursor of a Firm's Failure: Emerging Technologies and the Competitive Advantage of New Entrants. *Journal of Management Information Systems,* **13**(2) 17.

Conner, K. R. 1995. Obtaining Strategic Advantage from Being Imitated: When Can Encouraging "Clones" Pay? *Management Science,* **41**(2) 209-225.

Cusumano, M. A., Mylonadis, Y., Rosenbloom, R. S. 1992. Strategic Maneuvering and Mass-Market Dynamics - the Triumph of VHS over Beta. *Business History Review,* **66**(1) 51-94.

David, P. A., Bunn, J. A. 1988. The economics of gateway technologies and network evolution: Lessons from electricity supply history. *Information Economics and Policy,* **3**(2) 165-202.

Dranove, D., Gandal, N. 2003. THE DVD vs. DIVX Standard War: Empirical Evidence of Network Effects AND Preannouncement Effects. *Journal of Economics & Management Strategy,* **12**(3) 363-386.

Economides, N. 1989. Desirability of Compatibility in the Absence of Network Externalities. *American Economic Review,* **79**(5) 1165-1181.

--- 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.

--- 1996. The Economics of Networks. *International Journal Of Industrial Organization,* **14**(6) 673-699.

Economides, N., 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., Saloner, G. 1985. Standardization, compatibility, and innovation. *RAND Journal of Economics,* **16**(1) 70-83.

--- 1992. Converters, Compatibility, and the Control of Interfaces. *Journal of Industrial Economics,* **40**(1) 9-35.

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

Gallaugher, J. M., Wang, Y.-M. 2002. Understanding network effects in software markets: Evidence from Web server pricing. *MIS Quarterly,* **26**(4) 303-327.

Gandal, N. 1994. Hedonic Price Indexes for Spreadsheets and an Empirical Test for Network Externalities. *RAND Journal of Economics,* **25**(1) 160-170.

--- 1995. Competing Compatibility Standards and Network Externalities in the PC Software Market. *Review of Economics and Statistics,* **77**(4) 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? *RAND Journal of Economics,* **24**(1) 19-39.

Grimm, C. M., Lee, H., Smith, K. G. 2005. Strategy As Action: Competitive Dynamics and Competitive Advantage. Oxford University Press, Oxford, UK.

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., Turrisi, R. 1990. The Detection and Interpretation of Interaction Effects Between Continuous Variables in Multiple Regression. *Multivariate Behavioral Research,* **25**(4) 467.

Katz, M. L., Shapiro, C. 1985. Network Externalities, Competition, and Compatibility. *American Economic Review,* **75**(3) 424.

Kauffman, R. J., McAndrews, J., Yu-Ming, W. 2000. Opening the `Black Box' of Network Externalities in Network Adoption. *Information Systems Research,* **11**(1) 61.

Lee, J., Lee, J., Lee, H. 2003. Exploration and exploitation in the presence of network externalities. *Management Science,* **49**(4) 553-570.

Liebowitz, S. J., Margolis, S. E. 1994. Network Externality: An Uncommon Tragedy. *Journal of Economic Perspectives,* **8**(2) 133-150.

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

Matutes, C., Regibeau, P. 1988. "Mix and Match": Product Compatibility without Network Externalities. *RAND Journal of Economics,* **19**(2) 221-234.

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

Park, S. 2004. Quantitative Analysis of Network Externalities in Competing Technologies: The VCR Case. *Review of Economics & Statistics,* **86**(4) 937-945.

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

Suárez, F. F., Utterback, J. M. 1995. Dominant designs and the survival of firms. *Strategic Management Journal,* **16**(6) p415-430, 16p.

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