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RESEARCH ARTICLE

STANDARDS COMPETITION IN THE PRESENCE OF DIGITAL CONVERSION TECHNOLOGY: AN EMPIRICAL ANALYSIS OF THE FLASH MEMORY CARD MARKET[1]

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Both 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 low cost digital conversion technologies, which facilitate easy compatibility across competing standards, may reduce the strength of these network effects. 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, as measured here, are associated with a significant positive price premium for leading flash memory card formats. We then find that the availability of digital converters reduces the price premium of the leading flash card formats and reduces the overall concentration in the flash memory market. Thus, our results suggest that, in the presence of low cost conversion technologies and digital content, the probability of market dominance can be lessened to the point where multiple, otherwise incompatible, standards are viable.

Our conclusion that the presence of converters weakens network effects implies that producers of non-dominant digital goods standards benefit from the provision of conversion technology. Our analysis thus aids managers seeking to understand the impact of converters on market outcomes, and contributes to the existing literature on network effects by providing new insights into how conversion technologies can affect pricing strategies in these increasingly important digital settings.

Keywords: Network effects, network externalities, standards competition, conversion technologies, flash memory, digital goods, market competition

[1]Vijay Gurbaxani was the accepting senior editor for this paper. Bruce Weber served as the associate editor.

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 on the choices made by other consumers. These direct interoperability benefits make the choice of a technology standard or platform an important strategic decision for both consumers and firms (Economides 1996; Katz and Shapiro 1985). Examples of information technologies with demonstrated network effects include computer hardware (Chen and Forman 2006), operating systems (Bresnahan 2001), application software (Brynjolfsson and Kemerer 1996; Gallaugher and Wang 2002; Gandal 1994), and popular instant messaging and social networks (Sundararajan 2007).

In addition to direct network benefits, a widely adopted product may indirectly give rise to a longer product life cycle, better product support and services, and a greater variety of complementary goods. Given these direct and indirect benefits, consumers are more likely to choose products that adopt more popular standards. This behavior can, in turn, create a virtuous cycle for the leading (majority) formats and helps the strong grow stronger (Shapiro and Varian 1999). This type of market evolution has been documented in the VHS and Betamax "standards competition" (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; Brynjolfsson and Kemerer 1996).

However, in the past decade, a new and different pattern of competition seems to be emerging in several IT markets with digital data storage and exchange. Despite strong demand for compatibility, these markets have, to date, not clearly tipped toward a single standard, nor do we see a significant advantage for the incumbent over the new entrants. Witness, for example, markets for *digital media files* (e.g., Real Media, Windows Media, QuickTime, AVI, and MPEG), *digital image files* (e.g., JPEG, GIF, TIFF, and PNG), and—importantly for our study—*digital flash memory cards* (e.g., Compact Flash, SmartMedia, Secure Digital, Memory Stick, XD Picture, and Multimedia). Why are the competitive dynamics in these digital goods markets seemingly different from the "tipping" markets mentioned earlier?

In this study, we investigate this question in the context of the flash memory card market. Flash memory is a class of non-volatile, electrically rewritable memory that was introduced into the consumer electronic market in the 1990s.[2] With the capability to store large amounts of data in a 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, and audio players. The popularity of these platforms has made the flash memory card market one of the fastest growing sectors in the IT industry.[3] This growth may not be surprising given the rapid expansion of consumer electronics devices using 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 direct and indirect network effects.

Direct network effects may arise from an individual user desiring to transfer, edit, or share media content across various digital devices that she owns, or from the desire to share digital content between different users.[4] These sorts of direct network benefits are commonly discussed in the industry literature and in the popular press. For example, Sony has touted the ability to use the Memory Stick format on "an extensive range of compliant products," including the possibility that "photos taken during a trip can be viewed immediately on your [Memory Stick compatible] navigation system's large screen monitor" or printed at an in-store kiosk terminal that accepts the Memory Stick format.[5] Similarly, SanDisk, another major manufacturer of flash memory cards, promotes the availability of its format on a wide range of consumer products, and that if you upgrade between SD compatible phones you can "Simply save all of the information on this SD card and move the information to your new phone!"[6] Likewise, 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" (McWilliams 2003).

[2]http://en.wikipedia.org/wiki/Flash_memory_card.

[3]http://www.usatoday.com/tech/products/2006-06-04-storage-drive_x.htm.

[4]See, for example, McWilliams (2003): "Mike Rogers snapped his way through France last year, taking heaps of digital pictures at every stop. Whenever he ran out of storage space on his camera, he simply bought another memory card to pop in the back. Mr. Rogers is among a growing number of Americans who, having loaded up on personal organizers, MP3 players and digital cameras, are quickly running out of room to save all their addresses, videos, songs and pictures. That is forcing them back into the stores to stock up on extra memory—and fueling a huge new business for the consumer-electronics industry."

[5]http://www.sony.net/Products/memorycard/en_us/memorystick/index.html.

[6]"SanDisk Launches V-Mate," *Business Wire*, September 2, 2006 (http://findarticles.com/p/articles/mi_m0EIN/is_2006_Sept_2/ai_n16702773).

There is increasing awareness among (especially younger) consumers that, by adopting the same flash memory card format for their collection of digital devices, they can easily exchange data (e.g., play the video they recorded with a digital camcorder on an HDTV[7]) and eliminate the need to purchase a variety of different memory card formats (e.g., family members on vacation can benefit from being able to swap memory cards from one camera to another when one card becomes full of photographs[8]).

Given the above, market share may be a critical factor for new consumers who face their first adoption decision of digital devices, as once they have decided to adopt a particular flash memory format it could be costly to reverse such a decision. To the degree that direct network effects are present in this market, consumers who purchased a particular flash memory format will be more likely, *ceteris paribus*, 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. These network effects could reasonably extend beyond consumers' own digital devices to the format choices of other family members or friends with whom they might exchange digital data.

In addition to direct network effects, *indirect* network effects may arise in the flash memory card market to the degree that, as one format becomes widely adopted, more manufacturers would find it desirable to make their devices compatible with an emerging standard for flash memory cards, which would generate increasing returns to adoption. In this way, the market for flash memory cards may reflect the accumulation of individual consumer decisions since, as consumers recognize the advantages of easy digital exchange and flash memory card reuse, they may tend to purchase cards and devices that are compatible with cards that they have already purchased. As manufacturers observe this, they would be more likely to bring products to market that have compatible slots for the most popular formats, which would create positive feedback for greater use of those formats.

However, despite vendors' stated efforts and the acknowledgement by the business press of network effects 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 yet occurred in the flash memory market as might have been predicted.[9] As depicted in Figure 1, the flash memory market has been split among several different formats, with little evidence of market consolidation during this time period. This lack of consolidation has been observed in the popular press in reporting back to consumers, for example, in the *New York Times*.[10]

It is also interesting to note that the same phenomenon exists in Europe as well as in the United States. Some Dutch researchers have conducted a study to investigate why multiple flash memory card formats coexist despite the expectation that network effects would drive the market toward a winner-take-all outcome (de Vries et al. 2009). The researchers conducted face-to-face interviews with marketing managers from several large flash memory card manufacturers (SanDisk, Sony, and Olympus) and MediaMarket, the largest consumer electronics retailer in Europe. Based on the interviews, the researchers argue that both manufacturers and consumers are aware of the existence of network effects in the flash memory card market and they hypothesize that a combination of factors may result in multiple memory formats coexisting, including the presence of converters, or what they term "gateway technologies."

The apparent "winners-take-some" market outcome reflected in Figure 1 raises two main research questions. The first question is: *Are network effects present in this market*? The industry, press reports and academic research mentioned above document the belief that network effects are present in the flash memory card market. However, the flash memory card market may be different from the classic "network effects driven" markets such as those for VCRs and fax machines. Unlike many other technologies commonly studied in the literature, flash memory cards carry digital content that can be transferred easily and losslessly between devices using a variety of inexpensive PC- and USB-based converters. These converters, or multiformat readers, are not physical adapters that provide direct interoperability; rather, they are USB-based hardware devices that have multiple memory card slots for different types of otherwise incompatible flash

[7]*Business Wire*, September 2, 2006 (http://findarticles.com/p/articles/mi_m0EIN/is_2006_Sept_2/ai_n16702773). Also see McWilliams (2003); http://www.ehow.com/how_5220958_transfer-one-wireless-phone-another.html; and http://www.memorystick.com/en/lifestyle/incar/index.html.

[8]This actually happened to one of the authors.

[9]Figure 1 shows the market shares of the six major flash memory card formats (slot interfaces) from 01/2003 to 08/2006. As flash memory card technology has advanced after 2006, newer memory card formats are not directly comparable with the prior versions examined in our study and are therefore not shown here.

[10]See the *New York Times* video segment, "Yo, Jude, Memory Cards 101," http://video.nytimes.com/video/2009/09/28/technology/personaltech/1247463931097/yo-jude-deciphering-memory-cards.html?nl=technology&emc=techupdateema5.

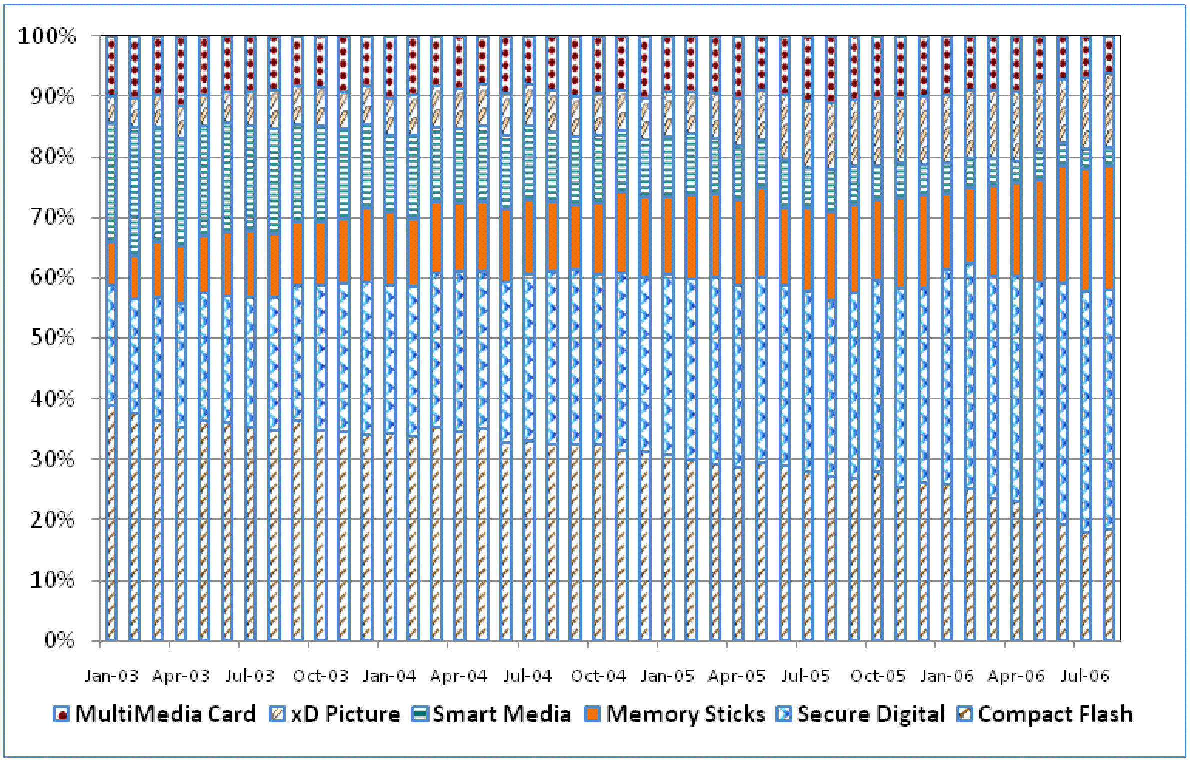
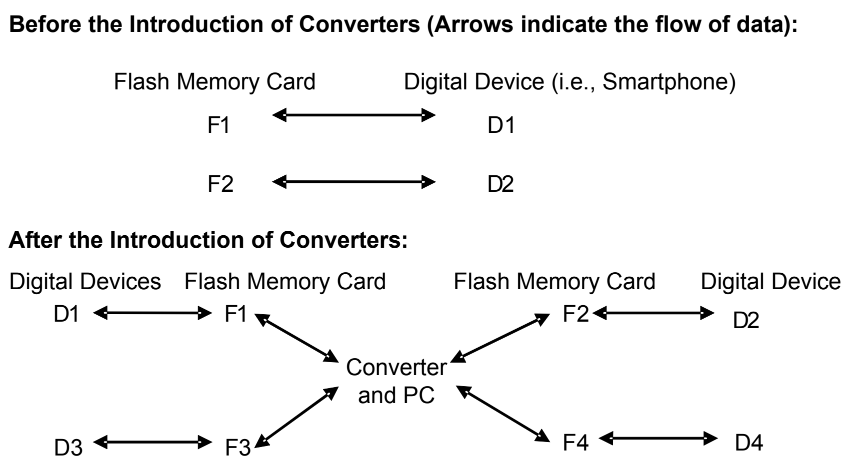


Figure 1. Flash Memory Card Monthly Market Share, January 2003 to August 2006 (NPD Group)



The two-way arrows are meant to indicate general data flows across a variety of settings. In specific applications, it is possible that data may only flow in one direction.

Figure 2. Consumer’s Choice Set Before and After the Introduction of Converters

cards.[11] Through a USB cable, consumers can read from or write to multiple flash memory cards simultaneously from a PC. Figure 2 illustrates the consumer's choice set before and after the introduction of converters. As can be seen in Figure 2, converters expand the consumer's ability to use digital devices of different formats by allowing conversion from one flash memory format to another. We provide a more detailed list of "use cases" where consumers might use a converter to share data across otherwise incompatible flash memory formats in the Appendix.

Currently, more than 100 models of converters are available in the market. The existence of these conversion technologies may enable 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 lower quality output (Cusumano et al. 1992).

These observations suggest a second research question: *How do digital converters influence standards competition in the flash memory card market*? We theorize that, in contrast to other IT markets studied in the network effects literature (e.g., Song and Walden 2003, 2009), a candidate explanation for the apparent anomalies in the competitive dynamics of flash memory cards involves both the digital nature of flash memory products and the associated presence of conversion technologies. Ultimately, however, the direction and size of the impact of flash memory converters on competitive dynamics in this market is an empirical question.

In this paper, we attempt to test the impact of flash memory converters directly by analyzing a unique and extensive data set primarily 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 first use this data to test whether there is a product price premium for formats with larger installed bases—a standard test in the literature for the presence of network effects (Brynjolfsson and Kemerer 1996; Gallaugher and Wang 2002; Gandal 1994).

Finding the presence of network effects as measured in this manner, we then analyze why these network effects may not have led to rapid market dominance, as seen in other settings. Specifically, we hypothesize and find that the increasing adoption of digital converters reduces the impact of the installed base on the product price premium. 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 the installed base less significant when there is greater adoption of digital converters, but market concentration also decreases as digital converters are widely adopted, suggesting increasing competitiveness among flash memory card manufacturers with converter introduction. Thus, our results suggest that, in the presence of low cost conversion technologies and digital content, the probability of market dominance can be lessened to the point where multiple otherwise incompatible standards are viable.

In addition to addressing a relevant and practical question regarding potential winner-take-all markets, our findings have both theoretical and managerial implications for the growing literature on standards competition in digital goods markets. Specifically, our empirical study complements the analytic literature on conversion technologies in markets with standards competition (Choi 1996, 1997; Economides 1989, 1991; Farrell and Saloner 1992; Liu et al. 2011; Matutes and Regibeau 1988). Although the presence and magnitude of network effects have been empirically demonstrated in the literature (Asvanund et al. 2004; Brynjolfsson and Kemerer 1996; Gallaugher and Wang 2002; Gandal 1994), our current empirical work suggests differences in the nature of network effects in digital goods technologies, and documents an associated interaction between network effects, converters, and market evolution. Our empirical analysis thus contributes by providing new insights into how conversion technologies affect pricing strategies in digital markets, which are of significant and increasing practical commercial importance.

Our findings on the effects of conversion technologies also have potentially 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. As consumers broaden their choice sets, vendors' marketing and pricing strategies should adjust accordingly. 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 by high consumer heterogeneity. Given that it is difficult to achieve industry-wide compatibility without lengthy and costly coordination, our analysis provides an alternative way to overcome the compatibility barrier without incurring significant costs of standardization.

[11]In our study a converter is a device that can accept at least two flash memory card formats.

The paper proceeds as follows: the next section briefly reviews the literature on network effects and conversion technologies, providing the theoretical basis for our work. The subsequent section presents the conceptual model and hypotheses. We then describe the data and measures of our key variables. In the following sections, the econometric models and results are presented and further discussed. Finally, we present our conclusions and suggest directions for future research.

Related Literature

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 (Katz and Shapiro 1985). Prior research has 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, 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.[12] 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 (Brynjolfsson and Kemerer 1996; Gandal 1994), databases (Gandal 1995). and communications equipment (Chen and Forman 2006).

[12]There is also a stream of research that uses elasticities to measure indirect network effects (i.e., Clements and Ohashi 2005; Nair et al. 2004). However, the flash memory card market differs from the markets studied in these papers as it exhibits both direct and indirect network effects. Since, as a practical matter, it would be extremely difficult to collect sales data on all possible digital devices that use a flash memory card (to measure indirect network effects), we follow the lead of other researchers and adopt a direct effects (hedonic price) model in our paper.

Although these empirical studies differ in their highlighted antecedents of network effects, they all adopt the same notion of a price premium in interpreting the estimated coefficients on the compatibility variables. A *price premium* refers to the price advantage a product enjoys over the other competing products due to particular 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 resulting 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 to 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. The hedonic approach regresses a product's listed price on a number of product attributes, and the coefficients on these attributes represent the price premia associated with these attributes. 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, the 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.

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 by standards competition. The studies that do address this topic have relied on either analytic frameworks (Choi 1996, 1997; Farrell and Saloner 1992), or an historical case study (David and Bunn 1988) to illustrate the effect of converters on technology adoption.

There are no large-scale empirical studies of this phenomenon of which we are aware.

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. Prior research has suggested that consumer benefits via the provision of converters include both greater product variety and the increased size of the network to which the consumer belongs (Economides 1989; Matutes and Regibeau 1988). 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 competition (Liu et al. 2011).

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, we develop a conceptual model with specific hypotheses to examine the dynamics between conversion technologies and the various antecedents and outcomes of network effects.

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. Following the literature, we adopt a hedonic model to measure network effects in the flash memory market, where the price premium of the installed base measures the value a consumer places on the size of a flash memory format's installed base (and thus network effects), controlling for other flash memory card attributes such as brand, capacity, and speed. Note that since the price premium only measures the relative impact of a particular product attribute (i.e., installed base) on listed price, it does not always move in the same direction as listed price. This distinction is important in the IT industry—and in the flash memory card 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 (a positive coefficient of the installed base variable in the hedonic regression) if consumers believe that compatibility is important.

Our first hypothesis considers the effects of market power on price premiums for leading vendors. 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 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 vary positively with the size of the flash memory format's installed base. For example, in the context of software, due to indirect network effects, consumers of the dominant operating system will find that they can use more software applications than users of a competing, but minority, system. This is similar to the case where owners of a dominant flash memory card format will find that their flash memory cards are supported by more digital devices than owners of a less popular flash memory card.

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 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. 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 scale, 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.*

Our second hypothesis considers how the introduction of digital converters affects the price of flash memory cards, arguing 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, a consumer who owns a flash memory card of a particular format can exchange data not only with the other digital devices she owns and other devices within the same flash memory network, but also with out-of-network consumers who own digital devices that use incompatible flash memory cards, and can thereby obtain the benefits of compatibility. Figure 2 illustrates the expanded consumer choice set that is afforded by converters. 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 overall utility for flash memory cards, even if the cards are not compatible. Therefore,

> **Hypothesis 2**: *The prices of flash memory cards are 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 consumers who own incompatible products to exchange data with each other. 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 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 prices 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 3 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 a product's installed base. This figure also illustrates two important market outcomes: card price and market concentration. Control variables are shown in dashed boxes.

Data and Measures

Sample

To test our hypotheses, we assembled a large panel data set including data on flash memory card products and their producers. We selected a sample period from 2003 to 2006 for our analysis as this is a critical period in the development of the flash memory card market during which all six major 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 data set, we also implemented a software agent to retrieve daily observations of flash memory card prices, sales rank, and product review data from Amazon.com. We use the customer review ratings to control for the reputation of different flash memory card models, and we use the price data to validate the retail prices from the NPD data set. Finally, we gathered the flash memory cards'

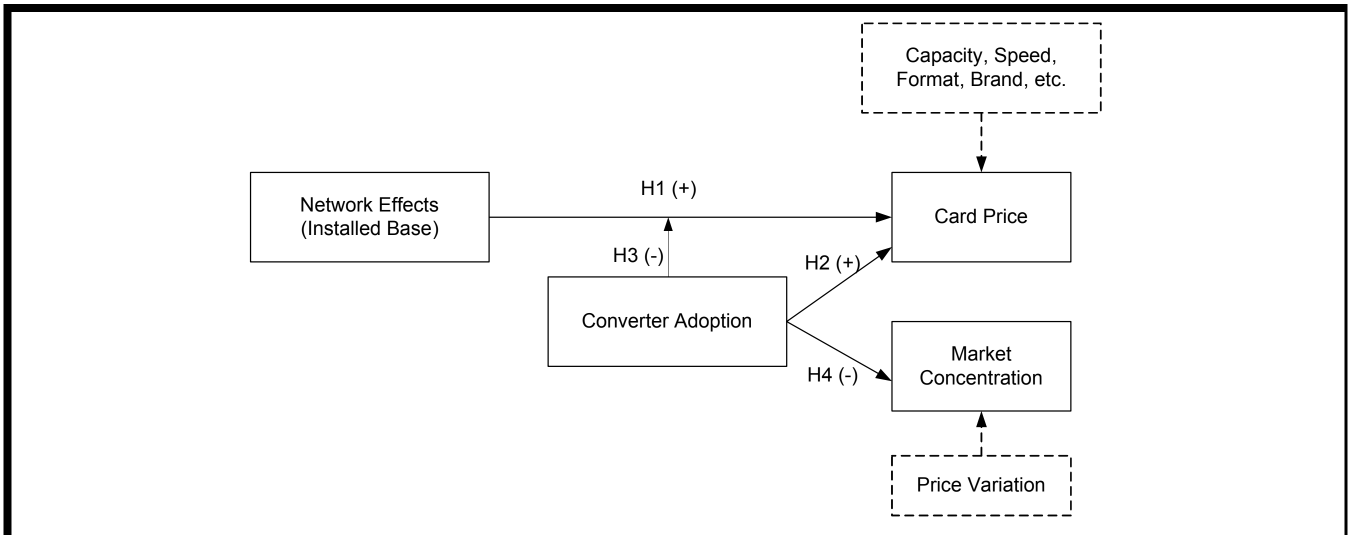


Figure 3. Research Model and Hypotheses

product specification data from each flash card format's official trade association.

The final data set consists of 15,091 observations of 706 product panels[13] across 44 months, and covers all six major flash card formats and 45 major brands, with capacities ranging from 4 megabytes to 8 gigabytes. 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.

Variables

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

The key variables for our analysis are card 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 computed as the cumulative units of format *i* compatible flash memory cards sold up to month *t*. The level of digital converter adoption, $ConverterAdoption_t$, is the cumulative number of the digital converters sold up to month *t*. Our control variables include the product's capacity and speed, to account for possible variations due to memory card capacity and product specifications, as well as six format dummy variables to capture other format specific product features. Moreover, since different flash memory cards may be at different stages of their own product life cycles and different products may experience different levels of competition within their own product category, we also construct two variables—*product life cycle* and *intra-format competition* at the product level to control for these effects.[14] The variable *product life cycle* is a binary variable and is coded as zero for flash memory cards that were discontinued before the end of our sample period and one for flash memory cards that were still being sold on the market at the end of our sample period. The variable *intra-format competition* is measured by counting the number of brands in a given product capacity category. To control for price premium due to product reviews, we create a *reputation* variable using the average of the Amazon customer review ratings for the product.[15] Finally, we create three other dummy variables to control for brand, seasonal and year effects.

[13]Note that this is not a balanced panel due to the fact that some brands may only produce a type of flash memory card at certain capacities, and some flash memory cards are discontinued after a certain period of time.

[14]We thank two anonymous referees for their suggestions to include these two control variables.

[15]We also used Amazon's sales rank as an alternative measure of this variable. However, both measures turn out to be insignificant in our estimation.

Table 1. Distribution of Flash Memory Card Observations and Annual Sales by Card Type/Year*

Card Type	2003	2004	2005	2006**	Total	(%)
Compact Flash	1,205	1,309	1,412	921	4,847	(32.12%)
	3,504,914	3,955,887	3,050,276	1,404,866	11,915,943	(17.65%)
Memory Stick	334	453	492	343	1622	(10.75%)
	2,745,576	3,460,319	4,452,578	3,270,090	13,928,563	(20.63%)
Multimedia	317	360	453	267	1,397	(9.26%)
	858,478	1,905,180	775,550	337,450	3,876,658	(5.74%)
Secure Digital	742	1,063	1,386	1,251	4,442	(29.43%)
	3,531,643	7,309,169	10,027,432	7,110,514	27,978,758	(41.43%)
Smart Media	583	461	387	200	1,631	(10.81%)
	1,044,834	461,388	261,202	76,019	1,843,443	(2.27%)
xD Picture	190	264	385	313	1152	(7.63%)
	1,306,797	2,195,741	2,864,649	1,608,493	7,975,680	(11.81%)
Grand Total	3,371	3,910	4,515	3,295	15,091	
	12,992,242	19,287,684	21,431,687	13,807,432	67,519,045	

*The first row in each flash memory category shows the number of observations and the second row shows annual unit sales.
**Note that 2006 observations include up to August, 2006

Table 2. Definitions of Key Variables

Variable Name	Definition
CardPrice	Deflated (in 2003 Q1 dollars) average retail price of a format ***i***, brand ***j*** and capacity ***k*** flash memory card sold during month ***t***.
InstalledBase	Cumulative number of format ***i*** flash memory cards sold up to (and including) month ***t***.
ConverterAdoption	Cumulative number of digital converters[†] sold up to month ***t***.
Capacity	Capacity (in MegaBytes) of a flash memory card.
Speed	Average read/write speed of a flash memory card.
Product Life Cycle	A dummy variable that measures a flash card's life cycle stage, coded as zero for products that were discontinued before the end of our sample period and one for products that were still being sold on the market by the end of our sample period.
Intra-format Competition	The number of brands within a given flash memory card category.
Reputation	The average customer review rating on amazon.com for the flash memory card of format ***i***, brand ***j*** and capacity ***k***, ranging from 1 (low) to 5 (high).
Compact Flash	Dummy variable, 1 if the flash memory card is compatible with the Compact Flash format.
Memory Stick	Dummy variable, 1 if the flash memory card is compatible with the Memory Stick format.
Multimedia	Dummy variable, 1 if the flash memory card is compatible with the Multimedia Card format.
Secure Digital	Dummy variable, 1 if the flash memory card is compatible with the Secure Digital format.
Smart Media	Dummy variable, 1 if the flash memory card is compatible with the SmartMedia format.
xD Picture	Dummy variable, 1 if the flash memory card is compatible with the xD Picture format.
D_Brand	A "make effect" dummy variable, 1 if the flash memory card is manufactured by Firm ***j****.
D_Quarter	A seasonal effect dummy, 1 if the observation belongs to quarter ***q*** (***q*** = 1, 2, 3 or 4).
D_Year	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 PCs.

Table 3. Descriptive Statistics of Key Variables

Variable	Mean	Std. Dev.
CardPrice	61.08	85.29
InstalledBase	18951540	7983519
ConverterAdoption	234874	162905
Capacity	420.74	804.97
Speed	20.68	15.04
Product Life Cycle (Dummy)	0.793	0.405
Intra-format Competition	3.71	1.53
Reputation (review rating)	3.12	1.69

Table 4. Correlations of Key Variables†

	Card Price	Installed Base	Converter Adoption	Capacity	Speed	Reputation	Product Life Cycle	Intra-format Competition
CardPrice	1.000							
InstalledBase	0.049**	1.000						
ConverterAdoption	-0.099**	0.069	1.000					
Capacity	0.637**	0.183**	0.276**	1.000				
Speed	0.192**	0.137*	0.016	0.231**	1.000			
Reputation	0.076*	0.183	-0.044	-0.149*	0.357**	1.000		
Product Life Cycle	0.165**	0.246**	0.253**	0.187*	0.059	0.182	1.000	
Intra-format Competition	-0.131**	0.267**	0.226**	0.215	0.043	0.325*	0.150	1.000

*$p < 5\%$
**$p < 1\%$
†As converters convert between multiple formats, at any given point of time they could have an impact on prices of flash memory cards of all formats at all capacities. Therefore, within a given month, we can replicate the value of *ConverterAdoption* for each observation of flash memory card and perform the correlation test. In other words, when computing the correlation between the *CardPrice* variable and the *ConverterAdoption* variable, the *CardPrice* column consists of a number of data points with different values and the *ConverterAdoption* column consists of the same number of data points with an identical value.

We present descriptive statistics in Table 3 and the correlations of the key variables in Table 4. The intercorrelations 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.

Econometric Models, Estimation, and Results

Network Effects, Digital Converters, and Price Premia

We construct several econometric models to test our hypotheses. Given that the proposed effect of converters is nonlinear, it should not be modeled as a linear predictor of product price as has been done in the classic linear hedonic models. Therefore, to test Hypotheses 1 through 3 we construct an interaction model as shown in Model 1.[16]

$$CardPrice_{i,j,k,t} = \alpha_0 + \alpha_1 InstalledBase_{i,t-1} + \alpha_2 ConverterAdoption_{t-1} + \alpha_3 InstalledBase_{i,t-1} * ConverterAdoption_{t-1} + \alpha_4 Capacity_k + \alpha_5 Speed_{i,j,k} + \alpha_6 Reputation_{i,j,k,t} + \alpha_7 ProductLifecycle\_Dummy_{i,j,k,t} + \alpha_8 IntraFormat\ Competition_{i,k,t} + \alpha_9 Format\_Dummy_i + \alpha_{10} Brand\_Dummy_j + \alpha_{11} Year\_Dummy_t + \alpha_{12} Quarter\_Dummy_t + \varepsilon_{i,j,k,t} \quad \text{[Model 1]}$$

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 the installed base on product price 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 product price 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 product price should be computed as the partial derivative of the dependent variable with respect to the variable of interest. Thus, Hypothesis 1, which predicts that, *ceteris paribus*, a larger installed base will increase the price of a flash memory card, can be represented as

$$\text{H1:} \quad \frac{\partial Card\ Price_{i,j,k,t}}{\partial InstalledBase_{i,t-1}} = \alpha_1 + \alpha_3 ConverterAdoption_{t-1} > 0,$$

when evaluated at the mean of $ConverterAdoption_{t-1}$.

Similarly, Hypothesis 2, which predicts that the adoption of digital converters will lead to a higher flash card price, can be represented as[17]

$$\text{H1:} \quad \frac{\partial Card\ Price_{i,j,k,t}}{\partial ConverterAdoption_{t-1}} = \alpha_2 + \alpha_3 InstalledBase_{i,t-1} > 0,$$

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) versus the unrestricted model (the one with the interaction term).

We first estimate a restricted model 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, speed, product reputation, product life cycle, and intra-format competition, as well as format, brand, and seasonal and yearly dummies. The brand dummies cover the top 10 flash card brands in our data set. The omitted (base) dummy variables for the other categories are the SmartMedia format, winter quarter, and the year 2006. 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 last quarter of 2006.

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 $InstalledBase_{i,t-1}$ is positive, and the coefficient for $ConverterAdoption_{t-1}$ 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 the coefficients for both $InstalledBase_{i,t-1}$ and $ConverterAdoption_{t-1}$ remain unchanged, but both become significant at the 1% level. The interaction term is negative and significant at the 1% level as well. The signs of the coefficient estimates of the control variables are largely consistent with our expectation: the coefficients for *capacity*, *speed*, and *product life cycle* are all positive and significant, suggesting that a larger capacity, higher speed, and current generation flash memory cards are associated with a price premium. The coefficient for *intra-format competition* is negative and significant, indicating that more competitors in the same product category will lead to a more intense competition and hence a lower average flash memory card price.[18] The coefficient for *reputation* is positive, but only marginally significant in the unrestricted model. Finally, the decreasing coefficient estimates of the yearly dummies show that flash card price declines over time. The results are summarized in Table 5.

[16]Note that although quarterly dummy variables are used in this equation, the results are equivalent to a specification with monthly dummy variables.

[17]Note that in the expressions to evaluate H1 and H2, α_3 is the same coefficient obtained from the estimation of Model 1.

[18]We also evaluated an alternative measure of this variable using the standard deviation of prices from different vendors selling the same product (a smaller value indicates that there is more intense competition within this product category). This alternative measure yields a consistent result.

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

Dependent Variable: *CardPrice*$_{i,j,k,t}$	OLS Regression Restricted (No interaction)	OLS Regression Unrestricted (Interaction)	GLS Estimation (Interaction)	2SLS Estimation (Interaction)
Constant	15.13 (4.29)**	30.89 (4.65)**	6.38 (3.89)**	16.78 (2.91)**
InstalledBase$_{i,t-1}$	3.57e-07 (1.45e-07)*	1.74e-06 (2.60e-07)**	1.93e-06 (1.30e-07)**	5.21e-06 (2.48e-07)**
ConverterAdoption$_{t-1}$	-.00015 (1.51e-07)**	-.0001845 (.0000156)**	-.0000689 (4.17e-06)**	-.0000922 (.0000191)**
*InstalledBase * ConverterAdoption*$_{t-1}$		-8.65e-12 (8.93e-13)**	-1.44e-11 (3.69e-13)**	-1.04e-11 (7.67e-13)**
Capacity	.0772 (.00070)**	.0773 (.00069)**	.068 (.0011)**	.054 (.0017)**
Speed	1.56 (.19)**	1.52 (.186)**	0.62 (.178)**	1.57 (.648)**
Reputation	4.32 (2.17)*	3.55 (2.41)	2.15 (1.77)	1.66 (1.12)
Dummy Product Life cycle	18.14 (2.97)**	17.85 (1.35)**	12.17 (1.16)**	33.01 (4.35)**
Intra-format Competition	-1.14 (0.27)**	-1.76 (0.13)**	-0.63 (0.047)**	-2.74 (0.146)**
Dummy_2003	27.26 (11.93)*	58.29 (12.32)**	3.87 (1.68)*	24.75 (5.56)*
Dummy_2004	23.11 (9.38)**	43.36 (9.49)**	2.34 (1.18)*	12.68 (4.32)*
Dummy_2005	14.48 (5.13)**	16.78 (5.12)**	1.06 (.49)*	3.53 (2.46)*
Adjusted R^2	0.5609	0.564	Log likelihood = –43671	0.5014
Fit Statistic	F(25, 15065) = 731.51**	F(26, 15064) = 768.39**	Wald χ^2 (26) = 6045.61**	Wald χ^2 (26) = 8139.60**

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

Before we proceed to interpret the coefficients and test the hypotheses, we also conduct several robustness analyses[19] 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 (Aiken and West 1991, pp. 35-36; Jaccard et al. 1990) 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.[20] 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

[19]As some of the literature on network effects considers a nonlinear 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.

[20]For ease of comparison, both *InstalledBase*$_{i,t-1}$ and *ConverterAdoption*$_{t-1}$ are centered in the OLS regressions.

2003, pp. 57-58). Therefore, we conclude that our interaction model does not exhibit excessive multicollinearity.

A Breusch–Pagan/Cook–Weisberg test for heteroskedasticity yields a value of $\chi^2(1) = 5120.7$ ($p < 0.001$), 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 data set, we address both problems simultaneously by applying a generalized least squares (GLS) estimation procedure[21] 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 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 *Converter Adoption* at the means of the interacting variables.[22] Following Greene (2003, p. 124), the standard errors of these marginal effects can be computed from

$$Var\left(\frac{\partial E\left[CardPrice_{i,j,k,t} \mid InstalledBase_{i,t}, ConverterAdoption_t\right]}{\partial InstalledBase_{i,t}}\right) =$$

$$Var\left[\hat{\alpha}_1\right] + (InstalledBase_{i,t})^2 Var[\hat{\alpha}_3) + 2\,InstalledBase_{i,t} Cov\left[\hat{\alpha}_1, \hat{\alpha}_3\right]$$

and similarly from

$$Var\left(\frac{\partial E\left[Cardprice_{i,j,k,t} \mid InstalledBase_{i,t}, ConverterAdoption_t\right]}{\partial ConverterAdoption_t}\right)$$

Note that the standard errors of the marginal effects at different values can be obtained by substituting the respective variables with these different values into the above equations. These standard errors are provided in parentheses.

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 provides support for Hypothesis 1, suggesting that network effects as measured here *do* exist in the flash memory card market such that the price of a flash memory card is positively associated with the size of the installed base for the same format. The "Mean" column of the second row shows that the marginal effect of converter adoption is negative when evaluated at the mean of the installed base. Thus, the price 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 second row shows that the marginal effect of digital converter adoption is larger (in absolute value) for flash memory formats with a larger installed base (the +1 and +2 standard deviation columns) than those with a smaller installed base (the –1 and –2 standard deviation columns). Moreover, coefficient α_3 is highly significant ($p < 0.001$) in the interaction model. An F-test of the difference between the restricted model and the unrestricted model confirms that the interaction term explains 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 the same 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, we perform a two-stage least square (2SLS) estimation in the following two steps: (1) we first-difference the *CardPrice* variable and the *InstalledBase* variable to compute their residual values, and (2) we use the lagged term of the differenced *InstalledBase* variable as our instrumental variable and the differenced *CardPrice* variable as our dependent variable and perform a 2SLS estimation. Since the lagged difference of the *InstalledBase* (the variable) is uncorrelated with the present difference of *CardPrice*

[21] We also estimated a fixed effects model. Our main results still hold. However, a fixed effect specification results in excessive collinearity (many of the control variables are dropped in a fixed effect model). Therefore, we adopt the GLS estimator.

[22] 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.

Table 6. Marginal Effects

	-2 Std. Dev.	-1 Std. Dev.	Mean	+1 Std. Dev.	+2 Std. Dev.
Marginal effect of *InstalledBase*$_{i,t-1}$	6.62E-06 (3.42E-06)*	4.28E-06 (0.62E-06)**	1.93E-06 (0.26E-06)**	-4.16E-07 (0.66E-07)**	-6.62E-06 (1.14 E-06)**
Marginal effect of *ConverterAdoption*$_{t-1}$	1.61E-04 (0.86 E-04)*	4.61E-05 (0.83 E-05)**	-6.9E-05 (0.94E-05)**	-1.8E-04 (0.43E-04)**	-2.99E-04 (0.52E-04)**

*p < 5%
**p < 1%

(the dependent variable), and is highly correlated with the present difference of the *InstalledBase* variable, it satisfies the requirements for an instrument. 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.[23] 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 = 0.31) nor a Durbin–Wu– Hausman chi-square test (*p*-value = 0.35) could reject the null hypothesis that the lagged cumulative market share is exogenous. This provides confidence in our results against potential endogeneity concerns.

In addition to these corrections, we performed several sensitivity analyses to ensure the robustness of our results. One potential issue is the computation of the *InstalledBase* variable in the initial sample period. Since some formats had been in the market for several years before our sample period, the installed base of these formats should also include their prior sales figures. Although NPD did not have flash memory card sales data prior to 2003, we were able to obtain additional annual sales data of these six flash memory formats prior to 2003 from another independent market research firm. We found that including pre-2003 cumulative sales data does not materially change our results.[24]

Since our data set is an unbalanced panel, we also examine whether selection bias exists in our sample. Our results will be biased if there is a relationship between our dependent variable and some inherent characteristics of the missing data. Following Verbeek (2004) and Verbeek and Nijman (1996), we took the following steps to check for potential selection bias. First, we removed the observations that do not exist for the entire period of our sample and created a balanced subpanel. Second, we estimated both fixed and random effects models on the balanced subpanel and contrasted the results with those obtained from the original unbalanced set. We found that the vector of coefficients and the variance–covariance matrix for the balanced panel and for the unbalanced panel are not significantly different from each other, suggesting that there is no significant selection bias in our estimation.

Finally, the data on converters used in the paper pertains only to external multiformat converters. We note that many computers and printers are sold with integrated multiformat readers, which are not included in the study. To address this issue, we performed a sensitivity analysis on the measure of the *ConverterAdoption* variable used in our analysis. We found that in order for our results to become insignificant, the measure of the *ConverterAdoption* variable needs to be 12.87 times larger than the current measure of the *Converter Adoption* variable.[25] Since it is not reasonable to expect that there are nearly 13 times as many converters bundled with PCs and printers as those sold directly in the market, we believe that our results are robust to this data limitation.

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 signi-

[23]The same approach is also used in Mittal and Nault (2009) in a similar situation.

[24]We believe that this is due to two reasons. First, the inclusion of new data makes the impact of the converters' price reduction for leading formats more significant (as the installed base measures for those initially leading formats are even larger than before). Second, the impact of converters is relatively smaller in 2003 than later in our sample period, and the sales volume prior to 2003 is relatively smaller than that after 2003, hence it does not lead to a significant change in our results.

[25]To perform this sensitivity test we multiplied our *ConverterAdoption* measure step by step (i.e., X2, X3, X4,...X13) until the results become insignificant, and then calculated backward to determine the exact threshold value (i.e., X12.9, X12.8,...).

Table 7. Regression Results† – Model 2

Dependent Variable: HHI	Coefficients‡
Constant	.531 (.0532)**
$ConverterAdoptionRatio_{t-1}$	–.180 (.081)*
$Var(Card\_Price/MB_t)$	8.72e-07 (7.54e-07)
Condition Number	10.29
Log likelihood	431.2

†N = 428. ‡Standard errors in parentheses. *$p < 5\%$;. **$p < 1\%$.

ficant 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 that market concentration will decrease as the adoption of digital converters increases. We use the following model to test Hypothesis 4 and to examine the relationship between the adoption of digital converters and the shift in market shares of the competing flash memory card formats:

$$MarketConcentration_t = \beta_0 + \beta_1 ConverterAdoptionRatio_{t-1} + \beta_2 Var(CardPrice / MB)_{k,t} + \varepsilon_{k,t} \quad \text{[Model 2]}$$

In Model 2, the dependent variable, market concentration, is measured by the Herfindahl–Hirschman Index (HHI), a widely used measure of competition in a market (Calkins 1983). A larger HHI value indicates higher market concentration and hence less intense 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 account for the fluctuation of the flash memory card sales volume, we normalize our key independent variable, *ConverterAdoption*, by computing a new variable, *ConverterAdoptionRatio*, as the cumulative number of converters sold up to time t divided by the cumulative number of flash memory cards sold up to time t. To perform this analysis, we compute the HHI for each month–capacity pair, which results in 428 data panels. Next, we regress the HHI value in each panel against the lagged adoption ratio of digital converters of the corresponding panel, controlling for the variance of flash memory card retail prices in each panel.[26] In order to correct for price differences across different memory capacities, we calculate retail price as the average price per megabyte in each panel.

The new data set 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 regression confirm that both heteroskedasticity and panel specific first-order autocorrelation (AR1) are present in our data. Therefore, as before, we adopt the GLS adjustments to correct for heteroskedasticity and autocorrelation.[27]

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

Interpretation of Results

The main empirical question in this study is how conversion technologies affect standards competition in digital markets. Our findings provide insights that help to answer this question.

First, we find that, consistent with both industry views and the academic literature, the leading flash memory card formats enjoy a product price premium that is mainly attributed to the

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

[27]We have also taken some steps to address the potential endogeneity in Model 2. First, we use the lagged term of converter adoption as our dependent variable as the present adoption of flash memory cards is less likely to drive the previous period adoption of multiformat converters. Next, we construct an instrumental variable using a similar approach as in Model 1. We differenced the variable and used the residuals as the instrument and performed 2SLS. Following Baum et al. (2003), we tested for endogeneity in our augmented form using a generalized methods of moments (GMM) estimation. The results from the GMM estimation are consistent with those obtained from the OLS and GLS estimations. This provides confidence in our results against potential endogeneity concerns.

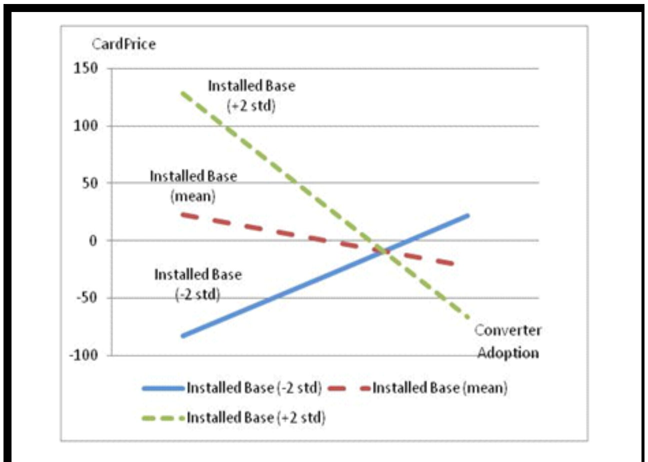


Figure 4. Price Premium of a Type of Flash Card at + or – 2 Standard Deviations of the Mean Flash Card Installed Base

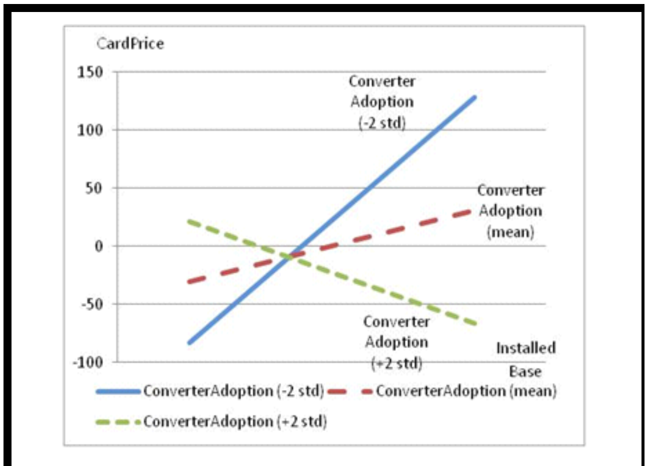


Figure 5. Price Premium of a Type of Flash Card at + or – 2 Standard Deviations of the Mean Converter Adoption Level

format's installed base. This provides support for Hypothesis 1.

Given this and the earlier arguments, one might expect a dominant standard to emerge in this market. However, we also find that the presence of digital converters offsets some of the impact of the installed base on product prices. As shown in Table 6, the presence of converters in the flash memory card market weakens the relationship between the installed base and price premia. At average levels of the flash memory card installed base, the marginal impact of converters on price premia is negative, contradicting Hypothesis 2. The impact is positive only for flash memory card formats with an installed base *below* the average. For a flash memory card format with a smaller installed base (i.e., one standard deviation below the mean), a 1% increase in the adoption level of digital converters raises the flash card premium by an estimated $0.10. But, this price premium disappears when a format's installed base is close to the industry average. Intuitively, a converter serves as a tool for data exchange between devices using otherwise incompatible flash memory formats. Such a converter is *relatively* more valuable for consumers who own a minority format as it allows them to communicate with consumers in 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.

Of course, in addition to the differential impact of converters on consumers who belong to different networks, 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 memory card price reduction.

However, it is also important to note that, while the price premium of the leading formats is weakened with extensive 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, and that 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 a $0.37 price premium (0.61% price increase) for a compatible flash memory card,[28] whereas a 1% increase in other key product features such as capacity, speed, and product reputation (review ratings) is associated with a price increase of $0.28, $0.16, and $0.07, respectively. The comparison shows that network effects, as measured in this study, have a significant impact on the prices of the flash memory cards. Moreover, it is also important to note that the strength of network effects, as measured by the price premium associated with the size of the installed base,

[28]Interestingly, this is a price premium of a similar order of magnitude (0.75% price increase) as that found in the microcomputer spreadsheet software market by Brynjolfsson and Kemerer (1996).

is sensitive to the adoption of digital converters. When the level of digital converters adoption is relatively low (i.e., one standard deviation below the mean), the price premium increases by more than 100%, to $ 0.81. However, when the adoption of digital converters is high (i.e., one standard deviation above the mean), the price premium almost disappears.

Figures 4 and 5 illustrate the interaction between network effects (installed base) and the adoption of digital converters. In Figure 4, 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) installed base, respectively. Figure 4 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 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 in our data.

A similar interaction is depicted in Figure 5, 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 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 as measured here are present (indicated by the upward slope of the price premium curve) *only* when the adoption of digital converters is below a certain level. When there is extensive adoption of digital converters (i.e., above +2 standard deviations), our measure of network effects has no impact on the market (the slope of the price premium curve is negative).

In addition to moderating the impact of installed base on product prices, our findings reveal that digital converters may play an important role in 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. Moreover, increasing converter penetration reduces the competitive gap between various flash memory card formats. This may cause buyers to focus on other product attributes, in turn allowing competition to arise in other dimensions, such as quality and performance. Producers of leading formats may no longer be able to rely on a large installed base to deter new entrants and to suppress competition, as such a competitive advantage is likely to erode over time as converters become widely available. In contrast to the self-reinforcing loop in classic network effects theory, in 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 less predictable 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. Sony, the major retailer of Memory Stick cards, has 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 prospects for, and the importance of, digital conversion.

From a societal standpoint, our findings 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) may postpone their investments until the market is clear about which standard to adopt, resulting in uncertainty about the future of the technology (so-called "excess inertia"). However, if digital converters were available to convert data between otherwise incompatible formats, consumers may be more willing to embrace the new technology because the risk of being stranded would decline. Moreover, once any excess inertia among stragglers is overcome, technology adoption can be expected to accelerate and lead to a traditional evolutionary path.

Limitations and Future Research

Of course, as is generally true with empirical research, our results are subject to interpretation, and are limited to the data available. The most obvious threat to the validity of the conclusions reached here is the longitudinal nature of the data. Although this data set demonstrates the lack of an expected winner-take-all result during the time period of our study, it is possible that the role of converters has been to only greatly delay such an outcome, and not prevent it. Future research could be devoted to extending these results through additional years of data, to the degree that technological progress will permit such comparisons.[29]

The current data also do not allow for a clear separation of the degree to which the network effects as measured here are direct network effects or indirect network effects. Although examples of both have been suggested, it is unclear whether one or the other dominates. Future research could focus on deepening the analysis to collect data to disambiguate these two effects.

It is also worth noting that, although we have performed various robustness tests to ensure that our model captures the dynamics in the flash memory card market, there are several additional factors that may be relevant. For example, despite the superiority of the newer generation formats, the older formats may still persist (with small and generally declining market shares) due to incremental technical advances and the presence of older model devices needing cards in these formats. Moreover, no single format dominates the other formats in terms of attributes such as form factor, transfer speed, upgradability, or cost, which may lead to a horizontally differentiated market. Parsing out the potential magnitude of these alternative effects could be interesting extensions of our research that could be pursued in future studies.

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, their pricing strategies in both markets will be important 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.[30] This could be considered a strategic move to take advantage of the introduction of digital converters and to cope with the perceived future competition. Although we have demonstrated a possible 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 could provide important guidance for policy makers concerned about the nature and consequences of new technology adoption in markets with network effects and digital conversion.

Conclusions

While the implications of network effects have been widely discussed in both the academic literature and in the popular press, most illustrations of network 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. While managers have been taught to expect strong network effects to dominate platform competition (e.g., VHS versus Blu-Ray versus HD-DVD), this wisdom may not serve them well in a digital environment where content can be converted easily between standards.

In this study, we illustrate some of these issues in the context of the flash memory card market, where, in spite of apparent network effects, there are multiple competing standards and little evidence of market consolidation during the time period of the study. Specifically, we apply a modified hedonic regression to an extensive data set cataloging prices and sales of flash memory cards and flash memory converters. Our findings yield several important insights into the dynamics of standards competition in digital goods markets. First, extensive adoption of digital converters reduces the importance of a format's installed base, as seen by a reduced price premium of the leading flash format. As a result, new formats are more likely to attract customers than in the absence of such digital converters. Second, 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 counterintuitive 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, such as the digital media and image files markets. In these markets, various kinds of conversion software have emerged to facilitate the conversion between the incompatible formats. At the same time, we have seen increasing efforts from vendors of different media formats to promote such conversion. These efforts have significantly motivated consumers to adopt the new media formats, leading to technological development in these markets.

[29] As technologies evolve it may make it difficult to create "apples to apples" longitudinal data sets, as newer products of a flash memory card format may be incompatible with older products of the same format.

[30] For example, SanDisk has been selling SanDisk-branded Memory Stick products and is a codeveloper with Sony of Memory Stick Pro, and Sony has supplied a card reader on its laptops that can read SanDisk's SD cards.

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Appendix

Converter Use for Data Exchange Examples

A number of people like to view the video they took with their digital camcorders on large-size high definition TVs. To cater to these consumers, some manufacturers have developed TVs (or TV accessories such as DVD players) that are capable of playing digital video/photos stored on flash memory cards. For example, Panasonic's VIERA plasma TVs have several models that come with a built-in SD card slot. These TVs enable consumers to play video stored on a SD card and record TV directly onto an SD card in the MPEG4 format. A consumer can then replay the recordings on the TV itself, or on any portable video player that supports the SD format. Other manufacturers such as Philips, Sharp, and Sony have also developed TVs that support a similar feature. If users have digital devices that support incompatible formats, then data exchange between cards (through a converter) can occur in both ways.

(1) TV < SD card < PC < Converter < Digital Camcorder with a Memory stick, – or –
(2) Portable video player (that supports memory stick) < memory stick < PC < Converter < SD card < TV (with recording capability)

Digital picture frames (a.k.a. digital photo viewers) are a popular device to display digital photos in a regular size photo frame. Some of these digital picture frames only support a certain number of flash memory formats (i.e., SD). If a consumer has pictures taken by a camera that is not compatible with the formats supported by the digital picture frame (i.e., Memory Stick), then in order to display her pictures in the digital picture frame she will need to undergo the following conversion process:

Digital Picture Frame < SD card < PC < Converter < Memory Stick

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Printing digital photos using a self-assisted kiosk in retail stores such as Wal-Mart, Target, and CVS, is a common consumer behavior. The digital printers in these kiosks do not always support the full array of flash memory formats (for example, many kiosks do not support MMC, xD, or SmartMedia cards). Suppose a consumer has her pictures stored on one of these less popular flash memory cards. She should then take the following steps before she can print her photos:

Digital Printer < SD card (or a USB thumb drive) < PC < Converter < MMC card

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Many GPS devices allow consumers to save the map file (or route information) to a flash memory card and this map file can be transferred to another GPS or a Smartphone that has the navigation function. If these devices support different flash memory formats, then a conversion is needed:

GPS1 (or Smartphone 1) < SD card < PC < Converter < MMC card < GPS2 (or Smartphone 1)

Another clearly unofficial but apparently popular use of the converters involves transferring games stored on different incompatible flash memory cards and playing them on different game consoles. As we know, different video game consoles are not compatible with each other and support different flash memory card formats as their storage media (i.e., SD card for Nintendo, Memory Stick for PSP). However, there are game enthusiasts who have come up with ways to play the video games on the rival company's previously incompatible game console (i.e., with a "modded" Nintendo Wii it may be possible to run homebrew emulators from SD cards and to play Xbox games on a PSP). In this case, the following conversion process is required:

PSP < Memory Stick < PC < Converter < SD card < Xbox
