Backward Compatibility to Sustain Market Dominance – Evidence from the US Handheld Video Game Industry

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Abstract: The introduction of a new product generation forces incumbents in network industries to rebuild their installed base to maintain an advantage over potential entrants. We study if backward compatibility can help moderate this process of rebuilding an installed base. Using a structural model of the US market for handheld game consoles, we show that backward compatibility lets incumbents transfer network effects from the old generation to the new to some extent but that it also reduces supply of new software. We also find that backward compatibility matters most shortly after the introduction of a new generation. Finally, we examine the tradeoff between technological progress and backward compatibility and find that backward compatibility matters less if there is a large technological leap between two generations. We subsequently use our results to assess the role of backward compatibility as a strategy to sustain a dominant market position.

Keywords: backward compatibility, market dominance, network effects, two-sided markets

JEL Classification: L15, L82, O33

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1. Introduction

Network industries often tip to monopolistic structures within a single product generation (Arthur 1989). The fact that users are attracted to technologies with a large installed base of users or a large supply of complementary goods tends to amplify small initial advantages. Moreover, market dominance in network industries is remarkably stable even across generations, which suggests that providers of successful technologies can carry over some of their dominance to future generations. It has been argued that maintaining compatibility between the new and the old generation – backward compatibility – can be a way of sustaining persistent dominance (Shapiro and Varian 1999). In markets with rapid technological progress in which we would otherwise expect significant turnover of dominant firms and their technologies, backward compatibility may lead to starkly different outcomes than in markets without.

Our paper studies if backward compatibility by the market leader can be a strategy to sustain dominance across generations. To address this, we address a number of questions about the nature and implications of backward compatibility in markets with indirect network effects:

1. How does backward compatibility influence demand and supply for a new product?
2. How does the effect of backward compatibility vary along the product life cycle?
3. Is the effect of backward compatibility affected by the level of technological progress?

We analyze the US market for handheld game consoles, which is well-suited for our purposes because i) backward compatibility is possible, but not necessary in this market and ii) generational change can be identified clearly. Compared to home video consoles connected to a TV set, handheld consoles are especially interesting as they exhibit different degrees of technological change across generations, so we can analyze the tradeoff between backward compatibility and technological progress in the context of potential entry. We do not know of any prior work dealing with the market for handheld game consoles, although indirect network effects have been identified in the market for home video game consoles: existing work deals with asymmetric network effects (Shankar and Bayus 2003), changes of indirect network effects over the product life cycle (Clements and Ohashi 2005), software exclusivity (Corts and Lederman 2009) and blockbuster software (Stremersch and Binken 2009). Although these papers handle multiple console generations, they do not explore how backward compatibility affects generational change and market dominance. One exception is Clements and Ohashi (2005), who address backward compatibility simply by adding the available games of the *Playstation 1* to those of the *Playstation 2*.

The theoretical literature on cross-generational or “vertical” compatibility (Katz and Shapiro 1994) analyzes firm incentives to choose backward compatibility. Waldman (1993) and Choi (1994) find that price discrimination increases compatibility incentives, while Kende (1994) argues that backward compatibility becomes more likely as valuations for old and new technologies are similar and building an installed base of new complementary products is expensive. Kende’s (1994) results are confirmed in a simulation model by Lee et al. (2003), who find that low valuation for backward compatibility and a small installed base advantage of the old generation render backward compatibility less likely. The welfare implications of backward compatibility are ambiguous, although Nahm (2008) finds that profits for the incumbent are generally higher with backward compatibility, which may increase its incentives to upgrade beyond the social optimum (Ellison and Fudenberg 2000). Taking a demand perspective, Shy (1996) also finds that backward compatibility increases the frequency of new technology adoption.

The sparse empirical literature on cross-generational compatibility finds that backward compatibility helps carry over some installed base advantage to future generations. Liikanen et al. (2004) and Koski and Kretschmer (2005) analyze intergenerational effects between the first and second generations of mobile telephony and confirm the positive impact of backward compatibility. Greenstein (1993) studies the market for mainframe computer systems and finds that buyers are more likely to select a new mainframe if they own a compatible predecessor system. Gandal et al. (2000) study the launch of the CD and run a counterfactual analysis by assuming backward compatibility of the CD with vinyl and find that this would have accelerated diffusion by 1.5 years.

Our work also relates to the literature on entry deterrence, as backward compatibility can serve to discourage firms from entering a market or at least prevent them from attaining large market shares. However, while there are many theoretical models of strategic entry deterrence (Dixit 1980, Klemperer 1987, Milgrom and Roberts 1982, Salop 1979, Haan 2003), empirical studies of entry deterrence are rare in industrial organization (Schmalensee 1978, Smiley 1988). In the management literature, studies have focused on limit pricing (Srinivasan 1991), reputation (Clark and Montgomery 1998) and excess capacity (Harrigan 1981), while Gruca and Sudharshan (1995) integrate a wide variety of entry deterrence strategies in their conceptual framework, in part referring to product portfolio choices (brand proliferation, preannouncement, switching costs). However, technological parameters are not typically considered potential instruments for entry deterrence.[1] This is surprising as in technology-intensive industries entry is a salient phenomenon, often replacing

[1] An exception is Church and Gandal (1996), who study compatibility as a means of entry deterrence in a theoretical model.

current leaders in the process of creative destruction (Schumpeter 1942). The market for handheld consoles presents an interesting case study as entrants faced a backward compatible incumbent technology, and we are interested in studying if this strategy indeed helped the incumbent stabilize market dominance across several generations.

We estimate demand for handheld video consoles as well as supply of game titles. Our estimation strategy builds on Clements and Ohashi (2005), extending their approach to account for backward compatibility, console age and the level of technological progress from one generation to the next. Further, we identify console characteristics to allow for a meaningful comparison between the effects of backward compatibility and increased console performance. In line with prior literature, we find that backward compatibility positively affects demand for a new generation. In addition, we find that: i) backward compatibility works through the installed base of software of the compatible parent generation, ii) it matters most shortly after product launch and iii) backward compatibility matters less if there is a large technological leap between two generations. Finally, analyzing the impact of backward compatibility on the supply of new software, we find a substitutive effect.

We disentangle a (demand-enhancing) direct and a (demand-reducing) indirect effect of backward compatibility. The demand-increasing effect directly influences the adoption decision through the installed base of software for the compatible parent generations. This effect weakens over the product life cycle and for higher technological leaps between generations. The demand-reducing effect works indirectly as old software partly substitutes for new software and thus lowers new software demand, leading to reduced software supply, which in turn decreases hardware demand. The demand-enhancing effect outweighs the demand-reducing effect so that backward compatibility helps transfer network effects across generations. Indeed, we show that the market leader, Nintendo, was able to maintain its market dominance across multiple generations through a strategy of backward compatibility.

The rest of the paper is structured as follows. Section 2 gives an overview of the US market for handheld game consoles. Section 3 develops theory and hypotheses, which are tested using a structural model of hardware demand in section 4. Section 5 discusses the estimation results, and we analyze the effectiveness of backward compatibility as an entry barrier in section 6 by performing a counterfactual entry experiment and considering alternative explanations. Section 7 concludes.

2. Industry background

The market for handheld game consoles first took off with the appearance of Nintendo's *Game Boy* in 1989, the first device to sell to the mass market (Forster 2005). Handheld game consoles are – just as their (immobile) home video game counterparts – part of a system comprising both hard- and software. Hardware manufacturers supply consoles and often also software titles,[2] while software providers concentrate on the development and distribution of games. Given indirect network effects (Clements and Ohashi 2005), hardware suppliers have an interest to encourage development of complementary products, namely game titles. Ever after the "Atari shock" in the early 1980s (when the game console market collapsed due to a sharp increase in poor game titles), hardware suppliers actively manage quality of the market's software side: developers need to sign detailed licensing contracts which are then enforced by legal and technological means such as security chips (Genakos 2001). This also prevents any hardware manufacturer from developing consoles that are compatible with games for other platforms.

Our sample ranges from 1995 to 2007[3]. Industry observers typically separate consoles into generations. In industry terminology, we study generations IV to VII (Forster 2005).

Table 1 provides an overview of the consoles in the generations we study. It is striking that Nintendo – from IV up to VII – was continuously present in the market while its competitors changed continuously. Figure 1 illustrates Nintendo's market share dominance over the whole period. We now describe the competitive landscape over the four technology generations we cover.

INSERT TABLE 1 HERE

INSERT FIGURE 1 HERE

Generation IV comprised Nintendo's *Game Boy* and *Game Boy Pocket*, and Sega's *Game Gear*. At the start of our sample in 1995, these consoles had already been on the market for some time. The

[2] On average, hardware manufacturers produced 12.8% of game titles for their consoles.
[3] Extending the study period beyond 2007 would be problematic as smartphones (with Apple's iPhone as the most prominent representative) have since then developed to be close substitutes to dedicated handheld game consoles.

devices basically shared the market, with Nintendo's share ranging between 60% and 80% and Sega's moving between 20% and 40% accordingly.

The generation V console *Game Boy Pocket* reached market shares exceeding 80% from 1998 on. This is remarkable considering that: i) the device was basically a remake with a smaller body but the same hardware capabilities as its predecessor, the *Game Boy*, and ii) Tiger Electronic's *Game.com*, which had superior hardware capabilities, had also been launched in the meantime. Nintendo's *Virtual Boy* – in contrast to the company's other products – was comparably unsuccessful due to its bulkiness, problems during use[4] and little software available. It could only reach substantial market share through a harsh price cut aimed at reducing stockpiles.[5] The *Game.com Pocket Pro*, a lighter and less bulky remake of the *Game.com*, did not even reach 1% market share.

The next dominant device was Nintendo's *Game Boy Color*, which again was not the technically most advanced console of its time. Its main differentiating feature was the enormous installed base of backward compatible software titles from its predecessors. While its competitors did not have an installed base of existing games, the *Game Boy Color* could build on millions of software copies sold in the almost ten years the Game Boy platform had been on the market. *Game Boy Color* users did not have to wait for availability of new games and could buy or swap used games straight away.

The next generation (VI) started with the *Game Boy Advance*. The device, which featured improved hardware power on the one hand and backward compatibility to *Game Boy Color* games on the other reached market shares close to 100% at the top of its cycle. Admittedly, there was no device on the market at that time matching the *Game Boy Advance* in terms of hardware power, but attributing its dominance merely to weak competition would be simplistic. Backward compatibility allowed users to draw on a game library comprising more than 46 million *Game Boy Color* titles right from the outset, which clearly played a role in its success.

In early 2003 Nintendo launched the *Game Boy Advance SP*, a facelifted *Game Boy Advance* with identical technical capabilities but a new body design and minor screen improvements. It matched the success of its predecessor, completely dominating the market at the top of its cycle. It prevailed not only over dated devices like the *Neo Geo Pocket Color* but also over Nokia's *N-Gage*, which had a processor more than 6 times faster than the *Game Boy Advance SP*.

[4] Nintendo *Virtual Boy*'s image generation was based on a combination of a LED unit and oscillating mirrors. So, users had to focus on these mirrors while playing which caused many players headaches. This led to the *Virtual Boy* bearing a warning statement that its use causes headaches right from the start of retail availability in the United States (Kent 2002, pp. 513-515).

[5] The maximum market share reached by the *Virtual Boy* was 44%, reached after cutting the initial price of more than $160 to less than $30 in April 1997.

At the end of 2004 Nintendo launched generation VII of handheld game consoles. Compared to the last generation, the Nintendo *DS* was a significant improvement in terms of hardware performance. The device was again backward compatible and could play Nintendo's generation VI games. However, in this generation Nintendo shared the market with Sony. Sony's *Playstation Portable* (*PSP*) started with a market share exceeding 50% and then ranging between 20% and 40%. This is remarkable considering that Sony had to start from scratch in the business while Nintendo again had a strong installed base of games. The *PSP* was the most powerful handheld console ever and outperformed the *DS* by far – for example, it was nearly five times as fast as Nintendo's *DS*. At the end of our study period both players Nintendo and Sony launched remakes of their generation VII consoles: the *DS Lite* and the *Playstation Portable Slim*. Both are lighter and possess a smaller body than their predecessors.

Throughout the generations we study, Nintendo was successful, except with the *Virtual Boy*. At least part of its success may be due to the enormous installed bases of games that were leveraged by the company through backward compatibility. Sony's success suggests that such dominance may be overcome by significant technological progress. While many companies failed in challenging Nintendo with consoles roughly on par, Sony's *Playstation Portable*, which outperformed Nintendo's *DS* by far, gained substantial market share quickly.[6]

3. Hypotheses

We now derive hypotheses on the effect of backward compatibility on hardware demand and software supply. We first discuss how backward compatibility works directly and indirectly. Second, we focus on the changing importance of backward compatibility over time. Finally, we discuss why we expect backward compatibility to be less effective for larger technological leaps. For all hypotheses, we consider how backward compatibility influences demand for handheld game consoles and then turn to the impact of backward compatibility on games supply.

3.1. Influence of backward compatibility on demand and supply

When an incumbent launches a technologically improved product generation, it usually faces competition from two directions: from the incumbent's parent generation and from products offered by competing firms. The larger the incumbent's installed base and the more fragmented the new generation, the more difficult it is to overcome this startup problem, causing excess inertia (Farrell and Saloner 1985, Kretschmer 2008) or technological lockout (Schilling 2002). In markets

[6] Note that in this industry, success is typically measured in terms of market share.

with indirect network effects, firms face a chicken-and-egg problem: it is not enough to offer a new video console; consumers also expect to choose from a wide variety of games for it.

Gandal et al. (2000) identify three strategies for markets with indirect network effects to overcome startup problems. Firms can (1) subsidize hardware, (2) increase software availability by forward integration, and (3) make the product backward compatible with the parent generation. All three strategies are used in the videogame market. Especially shortly after product launch, consoles are often sold at or below marginal costs. Most console manufacturers also develop and publish games on their own to increase availability of software for their own consoles (Corts and Lederman 2009). The strategy we focus on in this paper is the use of backward compatibility to transfer network effects across generations, also widely used in the video games industry.

In the market for handheld game consoles, backward compatibility implies that game cartridges of the parent generation can still be used with the new console generation. If the physical format of the game cartridges changes, this may even require a second cartridge slot[7]. Backward compatibility therefore comes at a price for the console manufacturer: the enclosure has to be bigger, additional parts are needed, and the processor has to be able to process the old games.

How will backward compatibility work exactly? Indirect network effects in the videogame industry have so far been measured through the demand-increasing effect by the number of games currently offered on the market (Clements and Ohashi 2005, Corts and Lederman 2009). One way to assess the effect of backward compatibility could be to analyze in how far the number of games for the compatible parent generation still on the market influence demand for the new generation. However, it is unlikely that consumers who bought a new game console would still buy games for the parent generation. Instead, backward compatibility may work through the installed base of games for the prior generation. This captures all games previously sold that potentially could be used with the new console. A larger installed base of compatible games increases the likelihood that a potential adopter has access to some of these games and can benefit from backward compatibility. A person has access to old games if she owns the parent console, or she could get old games from friends or through second-hand trading[8].

A large installed base of old games gives more potential adopters access to these old games. If a potential adopter has access to old games, her benefit of adopting a new console increases as she

[7] This was the case for the *Game Boy Advance*, which had one slot for old *Game Boy Color* cartridges and one for new *Game Boy Advance* ones.

[8] There is a sizable second-hand market for console games. E.g., on eBay.com, as of September 30th 2009, a total of 25,793 used games for mobile devices are offered.

can play these games on the new console, which in turn increases demand for the new console. This leads to the first hypothesis.

Hypothesis D.1: Backward compatibility increases hardware demand more, the higher the prior generation's installed base of software.

We also consider the impact of backward compatibility on the supply of software titles. Prior work has focused on the hardware installed base of the current generation as the main driver affecting software variety (Clements and Ohashi 2005, Corts and Lederman 2009). We extend this by including backward compatibility as an additional factor. Following Hypothesis *D.1*, the logic of how backward compatibility should influence software supply is straightforward:[9] if consumers use old games of the compatible parent generation, demand for games decreases. Decreased demand for software lowers incentives to develop a new game, leading to the following hypothesis.

Hypothesis S.1: Backward compatibility decreases supply of software titles for the new generation more, the higher the prior generation's installed base of software.

Combining the implications of Hypotheses *D.1* and *S.1*, we expect two countervailing effects affecting hardware demand. First, the direct effect of backward compatibility suggests that availability of games for the compatible parent generation serves as a (part-)substitute for variety of new games, increasing hardware demand. Second, the indirect effect of backward compatibility implies that the substitution of new games by old games reduces new software demand, which in turn lowers software supply, which eventually reduces hardware demand.

3.2. Importance of backward compatibility over time

As discussed, backward compatibility may help solve the startup problem in network markets. The startup phase is usually characterized by a low number of available game titles for the new generation. The availability of a parent generation's installed base of compatible games can to a certain extent moderate the necessity of having a large variety of new game titles available. However, users are expected to strictly prefer game titles designed for the new generation over previous-generation titles as new games (unlike old ones) make full use of the technical features of the new console. Therefore, as more titles for the new console become available, consumers will buy the console for its supply of new games rather than for the existence of a large installed base of outdated games. This is summarized in our second hypothesis.

[9] Indeed, for the following hypotheses, the predictions for the impact of backward compatibility on software supply are always opposite to the ones on hardware demand.

Hypothesis D.2: The demand-increasing effect of backward compatibility declines over time.

Analogous to Hypotheses *D.1* and *S.1*, we expect the effect of backward compatibility on software supply to be the opposite to hardware demand. We therefore expect the substitutive effect between old and new games to decline over time, leading to increased software availability.

Hypothesis S.2: The supply-decreasing effect of backward compatibility declines over time.

3.3. Backward compatibility and technological progress

Our final pair of hypotheses addresses the potential tradeoff between backward compatibility and technological progress. Shapiro and Varian (1999) identify this as the tradeoff between "evolution" (which ensures backward compatibility but offers limited technological improvement) and "revolution" (sacrificing backward compatibility, but offering drastically increased performance) strategies. Shapiro and Varian (1999) conceptualize these as dichotomous decisions based on technological restrictions, but our empirical setting lets us identify the relative importance of both technological improvement and backward compatibility if both are present.

We expect the two to be substitutes for consumers. That is, the degree of substitutability of old and new games depends on the relative performance of the two game generations, backward compatibility and new-generation performance. As a large technological improvement on the hardware side permits the design of better (i.e. more elaborately programmed) games, an old game will be a worse substitute as the technological frontier is pushed out, leading us to our last hypothesis on hardware demand.

Hypothesis D.3: The higher technological progress between two generations, the lower the demand-increasing effect of backward compatibility.

Again, we expect the effect of backward compatibility on software supply to run counter to that on hardware demand, which gives our final hypothesis on software supply.

Hypothesis S.3: The higher technological progress between two generations, the lower the supply-decreasing effect of backward compatibility.

4. Data and Estimation Model

4.1. Data

Data Sources

The core data set for our analysis comes from the market research firm NPD Group and consists of monthly unit sales and revenues in the market for handheld game consoles in the U.S. for the period from 1/1995 to 11/2007[10]. While, to the best of our knowledge, we are the first to use the data about handheld game console, NPD data on video consoles has already been used for several other studies (Shankar and Bayus 2003, Clements and Ohashi 2005, Corts and Lederman 2009, Stremersch and Binken 2009).

Data on games for the different platforms is also supplied by NPD Group. The software data consists of monthly unit sales and revenue data for all available game titles. For each game title, the associated platform is reported. Note that game data is assigned on a platform (not console) level. We define a platform by a common game format. A platform can consist of a single console (as for the Game Boy Color) or of a family of consoles (as for the Game Boy and Game Boy Pocket) that use the same game format but are distinct regarding their hardware sales[11].

Data on technical characteristics of the different consoles are also matched to our data. We use two variables representing the key dimensions that influence user perception: CPU speed as a proxy for processing power of the console and weight as a proxy for the console's mobility. The major data source for these technical characteristics is Forster (2005, pp. 212-214). This is completed with specifications from suppliers' websites, console databases and console information websites.

All prices are deflated to enable comparison of console and game prices over the entire period. We use the US deflator provided by the International Monetary Fund.[12] We use monthly population estimates from the US census bureau to proxy for market potential. Finally, we use USD-JPY exchange rates from the Pacific Exchange Rate Service[13] for a price instrument discussed later.

[10] We include hardware-only sales, i.e. just the console, and packages comprising a console and a game. Both are treated equally in the analysis as (i) package prices do not differ significantly from that of single consoles and (ii) a clear separation is not possible with our data. Moreover, many consoles are rarely sold on their own.

[11] The other platforms consisting of two consoles are *Game Boy Advance* and *Game Boy Advance SP*, Nintendo *DS* and Nintendo *DS Lite*, *game.com* and *game.com Pocket Pro*, *N-Gage* and *N-Gage QD*, as well as *Playstation Portable* and *Playstation Portable Slim*. There are no platforms with three or more consoles in our data set.

[12] Data was retrieved from the International Monetary Fund's World Economic Outlook Database.

[13] Available at http://fx.sauder.ubc.ca/.

Variables

The variables are described in Table 2 and Table 3 reports summary statistics. In line with Corts and Lederman (2009), we eliminate the influence from outdated consoles selling remainders or products that never reached a wider audience by considering only devices that sold more than 500 units in a given month[14].

INSERT TABLE 2 HERE

INSERT TABLE 3 HERE

Market shares in the market for handheld game consoles $s_{jt|B(t)=1}$ are directly calculated by dividing the monthly unit sales of console j by the total units sold in a given month. To derive s_{jt} and s_{0t}, we have to define potential market size first. Unlike Clements and Ohashi (2005), who use the TV households to determine the number of potential buyers, we use the US population numbers as several people in a household can own handheld consoles and handheld use is independent of TV ownership. From this, we derive s_{jt}, which is a console's market share of the market potential[15] and s_{0t}, the market share of the outside good, i.e. the share of potential consumers that do not have a console and do not buy one in the given time period. By cumulating the unit sales data of hardware sales, we also derive each platform's hardware installed base IB_{gt}^{HW}[16],[17]. Finally, we divide revenue by units to calculate each console's average monthly price p_{jt}. All prices are reported in 1995 USD.

Software variety N_{gt} is taken from the NPD data. For every platform we count the number of game titles with positive sales to obtain N_{gt}. Therefore, N_{gt} can decline over time if game titles are no

[14] The mean monthly total number of units sold is 627,068.

[15] The market potential is defined as the size of the population minus the number of people who already bought a handheld console.

[16] We do not depreciate the installed base as (absolute) console performance does not deteriorate over time.

[17] At the start of our dataset (1/1995), Nintendo's *Game Boy* and Sega's *Game Gear* have had already been on the market since 8/1998 and 1/1991. We therefore use data from http://vgchartz.com to derive the initial installed base of 12.7 respectively 2.9 million units for the *Game Boy* and the *Game Gear*. Data is derived by weighing the lifetime sales for Americas with the consoles' 1995 US share from total Americas sales.

longer sold. We also generate the software installed base of the compatible preceding generation $IB^{SW}_{g-1,t}$.[18]

The last set of variables concerns the hardware characteristics of the handheld consoles. The dataset covers the period from 1995 to 2007 in which technological progress for handheld game consoles was remarkable. For example, the mean CPU speed of active consoles had grown from 3.93 MHz in 01/1995 to 187.43 MHz in 12/2007. As the data covers the entire period this causes problems in comparing devices' capabilities. Comparing a 2007 console that is technically below average to the best device from 1995 would make the first one look far too good. We therefore normalize all variables containing technical data by the characteristics of contemporaneously active consoles. This is done by calculating yearly mean values and standard deviations for CPU speed and console weight. The yearly mean values and standard deviations obtained were then used to construct a z-score for each console. Finally, $IMPR^{CPU}_{g,g-1}$ is derived as the percentage improvement of the CPU speed compared to the CPU speed of the compatible parent generation.[19]

4.2. Model specification

We estimate both hardware demand and software supply. In line with prior work on indirect network effects, we use a structural model to estimate hardware demand and a reduced-form model to estimate software supply (Nair et al. 2004, Clements and Ohashi 2005, Corts and Lederman 2009). The two estimation models are derived below.

Hardware demand

We model the demand side of the market using a structural model for hardware demand. Our model extends the discrete-choice model for differentiated products used by Clements and Ohashi (2005) and Corts and Lederman (2009) with measures of backward compatibility. We assume that each potential adopter i of handheld video consoles maximizes its utility by choosing the highest u_{ijt} where $j \neq 0$ represents the different handheld consoles and $j = 0$ represents the outside option of not buying a console. The consumer's utility function has the following (additive) functional form:

$$\begin{aligned} u_{ijt} &= x_{jt}\beta + \alpha p_{jt} + \omega N_{gt} + \xi_{jt} + v_{ijt} + \\ &+ \gamma_1 IB^{SW}_{g-1,t} + \gamma_2 a_{jt} + \gamma_3 \left[a_{jt} * IB^{SW}_{g-1,t}\right] + \\ &+ \gamma_4 IMPR_{g,g-1} + \gamma_5 \left[IMPR^{CPU}_{g,g-1} * IB^{SW}_{g-1,t}\right] \end{aligned} \tag{1}$$

[18] As for the hardware installed base, the software installed base for *Game Boy* and *Game Gear* is not directly available in our dataset. We therefore assume that the number of software titles sold per console in the years prior to the beginning of our dataset equals the number of software titles sold for each console in 1995.
[19] We set this variable to zero if there is no active parent generation.

The first part of the utility function represents the baseline model that does not consider backward compatibility: utility depends on observed product characteristics x_{jt}, the console price p_{jt}, software variety N_{gt}[20], unobserved characteristics ξ_{jt}, and the idiosyncratic error term v_{ijt}, which can be interpreted as the difference of consumer i's valuation and the mean utility.

This model is extended to capture the effects of backward compatibility. First, the installed base $IB^{SW}_{g-1,t}$ of the prior generation's compatible games is added. This variable is used to test Hypothesis *D.1* and we expect it to have a positive influence on the buyer's selection decision. Second, we add console age a_{jt} as well as an interaction term of installed base and console age, $a_{jt} * IB^{SW}_{g-1,t}$. For console age, we expect a negative influence as older consoles are less attractive to the remaining non-adopters. From Hypothesis *D.2* we also expect a negative coefficient for the interaction term between console age and installed base. Third, we add the improvement factor over the compatible parent $IMPR^{CPU}_{g,g-1}$ and its interaction with installed base $IMPR^{CPU}_{g,g-1} * IB^{SW}_{g-1,t}$. The improvement factor expresses the relative increase in CPU speed compared to the CPU speed of the earlier generation. We expect $IMPR^{CPU}_{g,g-1}$ to have a positive effect on utility as a technological leap stimulates demand for a new product generation. In line with Hypothesis *D.3* however, we expect the interaction term to have a negative effect on the buyer's utility.

As in Clements and Ohashi (2005), we assume v_{ijt} to be identically and independently distributed with an extreme value distribution function to generate a nested logit model (Berry 1994). Potential adopters decide first to buy a handheld game console or not and if they decide to buy one they then select a specific console. In contrast to a simple logit model, substitution patterns can therefore differ between the decision of buying a console and the decision which console to buy.

Setting the outside good's utility to zero (Berry 1994), we derive a linear regression equation:

$$\begin{aligned} \ln(s_{jt}) - \ln(s_{0t}) = {} & x_{jt}\beta + \alpha p_{jt} + \omega N_{gt} + \xi_{jt} + \sigma \ln(s_{jt\,|B(t)=1}) + \\ & + \gamma_1 IB^{SW}_{g-1,t} + \gamma_2 a_{jt} + \gamma_3 \left[a_{jt} * IB^{SW}_{g-1,t}\right] + \\ & + \gamma_4 IMPR_{g,g-1} + \gamma_5 \left[IMPR^{CPU}_{g,g-1} * IB^{SW}_{g-1,t}\right] \end{aligned} \tag{2}$$

[20] As noted in section 4.1, we distinguish between consoles j and platforms g which can consist of multiple consoles using the same game format.

Software supply

We follow the existing literature when estimating software supply (Clements and Ohashi 2005, Corts and Lederman 2009). Software supply is expressed by the variety of different game titles N_{gt} available for a specific platform. We estimate the following reduced-form equation:

$$N_{gt} = \alpha_b + \gamma_1 IB_{gt}^{HW} + \gamma_2 a_{gt} + \gamma_3 \left[a_{gt} * IB_{gt}^{HW}\right] + \eta_{gt} + \\ + \gamma_4 IB_{g-1,t}^{SW} + \gamma_4 \left[a_{gt} * IB_{g-1,t}^{SW}\right] + \gamma_5 IMPR_{g,g-1}^{CPU} + \gamma_6 \left[IMPR_{g,g-1}^{CPU} * IB_{g-1,t}^{SW}\right] \quad (3)$$

The first line of the equation is the base model with α_b being brand-specific dummies, IB_{gt}^{HW} the installed base of console of the current generation, a_{gt} the age of the platform, and η_{gt} an error term. We allow hardware installed base to interact with platform age (Clements and Ohashi 2005). We extend the model with the same measures of backward compatibility as for the demand estimation. Following Hypothesis *S.1*, we expect $IB_{g-1,t}^{SW}$ to negatively affect software supply as the installed base of backward compatible software might partly substitute for demand for new game titles. Further, from Hypotheses *S.2* and *S.3* we expect the interaction term of $IB_{g-1,t}^{SW}$ with platform age and relative performance increase respectively to be positive as they reduce the importance of backward compatibility on the demand side and we therefore expect less substitution.

4.3. Instruments

Hardware demand

The potential endogeneity of the three variables within-group share $s_{jt|B(t)=1}$, price p_{jt}, and software variety N_{gt} requires the identification of appropriate instruments. We use the set of instruments proposed by Clements and Ohashi (2005) and Corts and Lederman (2009). Within-group share is obviously correlated with the error term ξ_{jt} as it contains part of the dependent variable s_{jt}. As ξ_{jt} is known to firms and consumers in the market (but not to the econometrician), differences in unobserved quality might lead to different price setting and thus a correlation of the console price p_{jt} and ξ_{jt}. Finally, autocorrelation of ξ_{jt} leads to a positive correlation between ξ_{jt} and the measure of software variety N_{gt}.

First, we use exchange rates between the US and Japan as a cost side instrument for prices as many consoles come from Japan. Exchange rates seem a valid price instrument as their change would probably lead to price adjustment in the US market. However, it does not allow for identifying effects at the console level.

Further, we use the average age of software titles currently available on the market to instrument for within-group share and console price. A high average age of games is a sign for missing supply of new game titles. Hence, we expect negative correlations of average software age both with within-group share as a lack of new games reduces the console's relative attractiveness and with console price as console manufacturers may try to reduce counter this adverse effect by lowering prices.

Finally, we construct several instruments that measure the extent of competition faced by a platform (Berry et al. 1995). We use the sum of competing hardware characteristics[21], the total number of competing platforms, the number of competing platforms within a company, and the number of competing platforms within the same generation as instruments. Following Corts and Lederman (2009), these instruments are expected to be correlated with each of the three endogenous variables: with the within-group share as they affect utility of different options, with software variety as they influence incentives to provide game titles, and with price as they affect the ability to raise prices.

Software supply

The installed base of hardware IB_{gt}^{HW} is possibly endogenous as unobserved shocks in the software market might lead to increased software entry but also to increased hardware adoption. We use the instruments proposed by Clements and Ohashi (2005) to account for endogeneity. The average age of software titles on the market can be used as an instrument, although the direction in which the instrument works is not clear. A high average software age could either indicate profitable opportunities or tough competition. We also use squared platform age and an interaction term between platform age and average software age as supply-side instruments.

5. Results

The 2SLS estimation results are reported in Table 4 (hardware demand) and Table 5 (software supply). The corresponding OLS regression results can be found in Table A. 1 and Table A. 2. Columns 4-1 and 5-1 report results without the software installed base, 4-2 and 5-2 include just the linear term of the software installed base, and 4-3 and 5-3 include both the interaction terms and the hardware improvement factor. In all specifications, we use brand dummies to control for unobserved brand-specific effects as well as calendar month dummies to control for the strong seasonality in console sales. All 2SLS estimations are robust to arbitrary heteroskedasticity and arbitrary autocorrelation.

[21] We use the sums of the competing consoles' cumulative CPU speed and weight.

INSERT TABLE 4 HERE

INSERT TABLE 5 HERE

We discuss our results in the order of our hypotheses, i.e. we consider both the demand and the supply side and discuss the respective influence of backward compatibility in general in section 5.1, over time in section 5.2, and depending on technological progress in section 5.3.

All important control variables in the instrumented estimation results have the expected signs over the different specifications. Higher CPU speed increases demand, whereas higher console weight decreases demand. The industry exhibits indirect network effects as the availability of more software variety N_{jt} positively influences demand and the availability of a larger hardware installed base in turn increases software variety. Further, we find negative price elasticity of demand and a strong positive seasonal effect (not reported) in November and December for both demand and supply.[22] These results give us confidence in our model specification.

5.1. Effect of backward compatibility on demand and supply

We now discuss the first-order effect of backward compatibility on demand and supply. As outlined in section 3.1, we expect backward compatibility to work through the installed base $IB^{SW}_{g-1,t}$ of games for the parent generation.

Hardware Demand

We first observe that $IB^{SW}_{g-1,t}$ has a significantly positive coefficient for both specifications (4-2) and (4-3), which supports Hypothesis *D.1*. For specification (4-3), we compare the effect of backward compatibility with indirect network effects from software variety N_{gt}: one extra game title for the current generation has the same impact on demand as 75,694 game titles sold for the parent generation[23]. Applying this to the case of the *Game Boy Advance*, at the launch in June 2001 an

[22] As the right-hand side of the demand model is the mean utility of console j in month t, the magnitudes of the coefficients for the demand model cannot be interpreted in a meaningful way (Corts and Lederman, 2009). We therefore either compare the strengths of different effects or discuss marginal effects from exogenous changes of a console's backward compatibility.

[23] The average unit sales of games in our sample are 118,619.

installed base of 45.6 million compatible *Game Boy Color* games corresponded to the availability of 602 game titles for the new generation. In fact, at launch only 21 game titles were available for the *Game Boy Advance* and it took until October 2004 for 602 game titles to be released.

Software Supply

Adding $IB_{g-1,t}^{SW}$ to the baseline specification as in estimation (5-2), we do not see any significant effect from backward compatibility. However, in the full specification (5-3), we obtain a significant negative effect of $IB_{g-1,t}^{SW}$ on software variety[24]. For each million units of installed base, 1.22 game titles less would be offered on the market. Again looking at the example of the *Game Boy Advance*, the installed base of 45.6 million compatible *Game Boy Color* games would reduce software supply by 56 titles at its launch date. This implies that absent an installed base, there would have 76 games available immediately from the launch of the *Game Boy Advance*.

5.2. Importance of backward compatibility over time

In our second pair of hypotheses, we argued that the influence of backward compatibility declines over time as more games for the current generation become available. Therefore, we add an interaction term between platform age and the size of the installed base.

Hardware Demand

The significant and negative sign of the interaction term $IB_{g-1,t}^{SW} * a_{jt}$ supports Hypothesis *D.2*. Combining the effects of the installed base with the interaction term for specification (4-3), we see that backward compatibility has a positive effect for 47 months. Although this exceeds the lifecycle of most consoles, it is clear that the benefits of backward compatibility decrease over time.

In the related industry of video game consoles, the changing importance of backward compatibility over time can be observed for the case of Sony's *Playstation 3*. The first models of the *Playstation 3* launched in November 2006 were made fully compatible with the *Playstation 2* by additionally including CPU and graphics processor from the *Playstation 2*. The next models, launched in March and August 2007, only offered limited backward compatibility as the *Playstation 2* CPU was removed and replaced by a software emulator. Finally, all new models that appeared afterwards offer no backward compatibility at all as now even the graphic processor of the *Playstation 2* was removed[25].

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[24] This is intuitive as we find a time-varying effect in (5-3), suggesting that a simple linear term is misspecified. Indeed, we find strong serial correlation in the error term in specification (5-1).

[25] For more details see: http://kotaku.com/gaming/customer-service/sony-could-run-bc-on-40gb-ps3s-they-just-dont-want-to-308467.php.

Software Supply

Even though the interaction term $IB_{g-1,t}^{SW} * a_{gt}$ is positive at the 5% significance level for the OLS specification (A2-3), the coefficient in our 2SLS specification (5-3) is not significant. We therefore do not find support for Hypothesis *S.2*, suggesting that the supply-decreasing effect of backward compatibility on games does not change over time although of course it becomes much less important compared to the large (and growing) number of new-generation games.

5.3. Backward compatibility and technological progress

In the last part of our analysis we include an interaction term between installed base and technological progress.

Hardware Demand

Our results support Hypothesis *D.3*, as the interaction term has a significantly negative coefficient. Trading off the counteracting effects of the installed base against the interaction term for specification (4-3), we see that backward compatibility has a positive effect if the percentage increase in CPU speed compared to the compatible parent generation is smaller than 359%. The largest technological leap between two succeeding generations in our data set is the switch from the *Game Boy Advance SP* to the Nintendo *DS*. For this generation change, CPU speed increased from 16.7 MHz to 67 MHz, which is an increase by 301%. Here, backward compatibility only played a strongly reduced (although still positive) role. This coincides with the observation that the *Playstation Portable*, which entered the market only four months later, was the only console to successfully challenge Nintendo's dominance in the market for handheld game consoles – with a much improved technology and up against a less influential installed base.

Software Supply

The results from specification (5-3) strongly support Hypothesis *S.3* that higher technological progress between generations reduces the supply-decreasing effect of backward compatibility. We see a substitutive effect from backward compatibility as long as the technological leap is smaller than 239%. Therefore, the Nintendo *DS* with an increase in CPU speed of 301% more than outweighs the substitutive effect.

6. Backward Compatibility to Sustain Dominance

Our results suggest a strong effect of backward compatibility on the demand of new hardware generations. Since Nintendo is the only firm to launch successive console generations and therefore the only firm to report a positive installed base of backward compatible games, we ask if backward compatibility was a useful means of sustaining a dominant market position over multiple product generations. To isolate this effect however, we need to rule out that backward compatibility simply proxies for other unobserved factors – the Nintendo effect. We address this in two ways: First, we discuss the brand dummies in our regressions that aim to capture unobserved, brand-specific factors. Second, we run a counterfactual experiment by assigning one of the unsuccessful consoles, the Game.com console, the installed base of the then dominant console, the Game Boy.

6.1. The Nintendo Effect

Table 6 reports the brand dummies for all players in the handheld game console market, with Nintendo the base category.

INSERT TABLE 6 HERE

While Sony's brand dummy has a positive and significant sign – suggesting that both brand equity and technological advance played a role in successfully challenging Nintendo, the other dummies show no clear pattern. This implies that Nintendo's reputation does not significantly explain its success in repeatedly holding off competition. One explanation for Sony's success (and the others' failure) would be that Nintendo's reputation suffered significantly just prior to the introduction of the *PSP*, which would lead to a significant and positive brand dummy for Sony as it measures the reputation relative to Nintendo. However, there is no anecdotal evidence for this in the relevant time period.

Another consideration is that Nintendo's reputation may have grown over time and that the backward compatible installed base (which grew more or less constantly throughout our sample) simply proxies for this reputation increase rather than a "real" effect of backward compatibility. However, as the Sony *PSP* entered at the very end of the sample, this would make its success all the more improbable as it would have to be based on an implausibly high brand reputation vis-à-vis Nintendo. However, to alleviate this possible bias, we run our preferred regressions (4-3 and 5-3) using the rolling software installed base $IB_{g-1,t}^{SW}$ of the three years before the observation month instead of the overall installed base. The results are shown in Table 7 and show a qualitatively similar picture as our baseline results, ruling out this alternative explanation.

INSERT TABLE 7 HERE

6.2. A Counterfactual Experiment

To assess if backward compatibility could indeed have played a role in sustaining Nintendo's advantage by intensifying the startup problem for challenging platforms, we run a counterfactual experiment in which we hypothetically assume that games for the *Game Boy* generation can be played on the *Game.com* console (and Nintendo consoles).[26] In reality, the *Game.com* console was not backward compatible to any other parent console and was a commercial failure. Following Corts and Lederman (2009), we derive the counterfactual as follows. First, mean utility δ_{jt} for console *j* at time t is derived from the regression results of our preferred specification (4-3). With the nested logit formula discussed in Berry (1994), the implied market shares can be obtained as follows:

$$s_{jt} = \frac{\exp\left(\delta_{jt}/(1-\sigma)\right)}{D^{\sigma}(1+D^{1-\sigma})} \tag{4}$$

with $D \equiv \sum_j \exp\left(\delta_{jt}/(1-\sigma)\right)$. In a next step, we assume that the *Game.com* console, which was launched in 9/1997 could have played titles for the *Game Boy.* The installed base of compatible software titles for the parent generation $IB^{SW}_{g-1,t}$, the performance increase of the *Game.com* CPU compared to the *Game Boy* CPU $IMPR^{CPU}_{g,g-1}$, and the interaction terms from equation (2) are adjusted accordingly. We then use the updated values to recalculate mean utilities and implied market shares. We repeat these steps for every month in the first year since the launch of the *Game.com* console and report average changes and the actual outcome in the top half of Table 8.

INSERT TABLE 8 HERE

First off, we observe that backward compatibility leads to an increase in total demand: the average additional demand of 217,541 *Game.com* units is nearly twice as large as the average decrease in demand for the competing platforms of 109,646 units. Without backward compatibility, the technologically superior *Game.com* never takes off and the outdated *Game Boy Pocket* maintains a dominant position, as can be seen from *Game.com*'s actual market share of 2.68%. Assigning the

[26] Such a move of mandating compatibility with a promising entrant could also be imposed by an antitrust authority as a pro-competitive measure ((Shapiro 1996)).

Game Boy's installed base to *Game.com* changes the dynamics of the market drastically, and *Game.com*'s counterfactual market share is almost as high as Nintendo's actual one.[27]

In the bottom part of Table 8, we add the indirect effect of backward compatibility, which we found to decrease supply of new games. We proceed as follows. We first simulate backward compatibility of the *Game.com* console by changing the installed bases analogous to hardware demand. We then use the coefficients from our supply estimation (5-3) to predict the number of available games N_{gt}. We finally substitute this (lower) number of available games in the utility function δ_{jt} of the demand-side equation and can again derive implied changes in units sold and in market shares.

The indirect effect moderates the direct effect somewhat (as game providers for *Game.com* would have been deterred by the installed base of backward compatible games serving as imperfect substitutes). However, the direct effect dominates the indirect effect, so that backward compatibility would still have helped the *Game.com* console capture a large chunk of the market at the time.

7. Conclusion

In this paper we study the effects of backward compatibility in a market with indirect network effects, the US handheld game console industry. Backward compatibility helped the market leader Nintendo maintain their dominant position over a number of product generations despite having an inferior technology in many instances. Backward compatibility in this market works through the installed base of games for a compatible parent generation and its strength is affected by the age of the console and the degree of technological improvement between successive generations.

On the demand side, our results lend support to the role of backward compatibility. If a new generation is backward compatible with the old one, the installed base of games for the prior generation increases sales for the new generation console. However, this demand-increasing effect is strongest directly after product introduction and declines over time as more games specifically for the new generation appear. Finally, large technological improvements across generations come at the cost of consumers valuing backward compatibility less as their utility from using the old complementary products is comparatively low. Therefore, benefits from large technological improvement are partially offset by the reduced benefits from backward compatibility. On the supply side, we find that backward compatibility lowers the supply of new software, and that this effect is less pronounced for consoles with higher technological progress.

[27] Note that we maintain *Game Boy*'s backward compatibility so that *Game Boy* and *Game.com* have equal installed bases.

By jointly analyzing hardware demand and software supply, we identify a tradeoff between the demand-enhancing effect of backward compatibility directly affecting hardware demand and the demand-reducing effect that works indirectly through reduced software variety for a platform. We find that the demand-increasing effect clearly outweighs the demand-decreasing effect.

We discuss if backward compatibility may have stabilized market structure in the US handheld console market by giving Nintendo a head start for every new generation, making it difficult for challengers to enter successfully. Sony's *PSP*, the most successful challenger, entered with a much superior technology at a time when Nintendo had just made a significant technological leap from their previous generation, which is in line with our results that backward compatibility matters less if the generations are very different technologically, so that Nintendo was comparably more vulnerable at that junction. To further substantiate the claim that backward compatibility helped Nintendo maintain a dominant position over technologically superior challengers, we run a counterfactual experiment and assign Nintendo's *Game Boy* installed base to a technologically superior, but ultimately unsuccessful challenger, the *Game.com* console. We find that if *Game.com* had been backward compatible, market dominance would have been reversed.

Our findings illustrate the dynamic effects of backward compatibility and emphasize the importance of backward compatibility in maintaining a dominant position across several product generations. While backward compatibility indeed helps overcoming the startup problem, its importance decreases over time. Also, for generation changes with large technological improvements, backward compatibility will be a less successful strategy to sustain market dominance across generations.

Our results have both managerial and policy implications. Managers in network industries must consider backward compatibility an important parameter that helps stabilize market shares across generations and establish persistent dominance. Judiciously managing the tradeoff between backward compatibility and technological progress is thus a key challenge for technology strategists. Conversely, antitrust authorities may consider scenarios of asymmetric backward compatibility anticompetitive since they may prevent large-scale entry by technologically superior challengers and thus hinder the process of creative destruction (Schumpeter 1942).

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Figures and tables

Table 1: Mobile handheld consoles sold between 1995 and 2007

Console	Platform	Backward Compatibility	U.S. launch	Manufacturer	Hardware CPU [MHz]	Hardware Weight [g]
Generation IV						
Game Boy Game Boy Pocket	Game Boy	No	8/1989 9/1996	Nintendo	4.2	300 148
Game Gear	Game Gear	No	1/1991	Sega	3.6	500
Generation V						
Game Boy Color	GB Color	Yes	11/1998	Nintendo	8.4	188
Virtual Boy	Virtual Boy	No	8/1995	Nintendo	20	760
game.com game.com Pocket Pro	game.com	No	9/1997 12/1999	Tiger	10	380 n/a
Generation VI						
Game Boy Advance Game Boy Advance SP	Game Boy Advance	Yes	6/2001 3/2003	Nintendo	16.7	180 142
Neo Geo Pocket Color	NGP Color	No	8/1999	SNK	6.14	145
N-Gage N-Gage QD	N-Gage	No	10/2003 8/2004	Nokia	104 104	137 143
Generation VII						
DS DS Lite	DS	Yes	11/2004 6/2006	Nintendo	67	275 218
Playstation Portable Playstation Portable Slim	Playstation Portable	No	3/2005 9/2007	Sony	333	280 189

Table 2: Variable definitions

Variable	Definition
s_{jt}	Market share of console j at time t (relative to market potential)
s_{0t}	Market share of the outside good (no console purchase)
$s_{jt\,\vert B(t)=1}$	Within-group market share (share within the handheld market)
N_{jt}	Available software titles for current format
p_{jt}	Deflated console price (1995 prices)
$x_{jt}^{weig\,ht}$	Normalized weight of the console
x_{jt}^{CPU}	Normalized CPU speed of the console
IB_{gt}^{HW}	Installed base of consoles for the current platform format (millions)
$IB_{g-1,t}^{SW}$	Installed base of games for the compatible parent platform (millions)
a_{jt}	Age of the console (months)
$IMPR_{g,g-1}^{CPU}$	Percentage improvement of CPU to compatible parent platform

Table 3: Summary statistics

Variable	N	Mean	SD	Min	Max
$\log(s_{jt}/s_{0t})$	503	-8.69	2.09	-13.07	-4.68
$\log(s_{jt\,\vert B(t)=1})$	503	-2.33	1.96	-7.74	0
N_{jt}	503	257.91	233.72	2	844
p_{jt}	503	76.39	41.77	8.50	238.16
x_{jt}^{weight}	501	0	1	-1.57	3.52
x_{jt}^{CPU}	503	0	1	-1.44	3.25
IB_{gt}^{HW}	503	11.66	10.42	0	34.42
$IB_{g-1,t}^{SW}$	503	39.36	47.14	0	174.72
a_{jt}	503	35.07	30.70	0	131
$IMPR_{g,g-1}^{CPU}$	503	0.65	0.88	0	3.02

Table 4: Hardware demand estimates (2SLS)

	DEPENDENT VARIABLE: $\ln(s_{jt}) - \ln(s_{0t})$		
INDEPENDENT VARIABLES	(4-1)	(4-2)	(4-3)
SW installed base $IB_{g-1,t}^{SW}$ [millions]		0.0142***	0.0144**
		(0.00110)	(0.00680)
Interaction term $IB_{g-1,t}^{SW} * a_{jt}$			-0.000306***
			(0.0000953)
Interaction term $IB_{g-1,t}^{SW} * IMPR_{g,g-1}^{CPU}$			-0.00401***
			(0.00128)
HW improvement $IMPR_{g,g-1}^{CPU}$			0.862***
			(0.189)
Number of available games N_{gt}	0.00429***	0.000771**	0.00109**
	(0.000512)	(0.000301)	(0.000499)
Deflated price p_{jt}	-0.00947*	-0.0102***	-0.00815**
	(0.00547)	(0.00318)	(0.00410)
ln(within-group share $s_{jt\,\vert B(t)=1}$)	0.781***	0.738***	0.654***
	(0.116)	(0.0638)	(0.0950)
Console age a_{jt}	-0.0228***	-0.0105***	-0.00485**
	(0.00397)	(0.00230)	(0.00232)
Normalized console weight x_{jt}^{weight}	0.217	-0.252***	-0.324***
	(0.145)	(0.0914)	(0.104)
Normalized CPU speed x_{jt}^{CPU}	0.170	0.159**	0.165*
	(0.114)	(0.0682)	(0.0854)
Observations	501	501	501
R-squared	0.869	0.954	0.958
Hansen's J	8.950	34.47	33.68

*** p<0.01, ** p<0.05, * p<0.1

Standard errors in parentheses are robust to arbitrary heteroskedasticity and arbitrary autocorrelation. Brand dummies, calendar month dummies, and constant are not reported.

Table 5: Software supply estimates (2SLS)

	DEPENDENT VARIABLE: N_{gt}		
INDEPENDENT VARIABLES	(5-1)	(5-2)	(5-3)
SW installed base $IB^{SW}_{g-1,t}$ [millions]		-0.107	-1.220***
		(0.0830)	(0.283)
Interaction term $IB^{SW}_{g-1,t} * a_{gt}$			-0.00106
			(0.00382)
Interaction term $IB^{SW}_{g-1,t} * IMPR^{CPU}_{g,g-1}$			0.510***
			(0.0608)
HW improvement $IMPR^{CPU}_{g,g-1}$			-22.02*
			(12.09)
HW installed base IB^{HW}_{gt}	34.56***	35.08***	38.14***
	(0.565)	(0.591)	(1.200)
Interaction term $IB^{HW}_{gt} * a_{gt}$	-0.133***	-0.139***	-0.149***
	(0.0104)	(0.0104)	(0.0128)
Format age a_{gt}	-1.539***	-1.564***	-2.115***
	(0.155)	(0.157)	(0.117)
Observations	417	417	417
R-squared	0.979	0.979	0.983
Hansen's J	13.26	11.29	18.35

*** p<0.01, ** p<0.05, * p<0.1

Standard errors in parentheses are robust to arbitrary heteroskedasticity and arbitrary autocorrelation. Brand dummies, calendar month dummies, and constant are not reported.

Table 6: Omitted brand dummies from estimation (4-3)

BRAND	
Sega	0.565**
	(0.239)
Tiger	-0.747***
	(0.231)
SNK	0.165
	(0.390)
Nokia	0.194
	(0.718)
Sony	2.781***
	(0.303)

*** p<0.01, ** p<0.05, * p<0.1

Table 7a: Hardware demand estimates (2SLS) for a 3-year rolling window of $IB^{SW}_{g-1,t}$

DEPENDENT VARIABLE: $\ln(s_{jt}) - \ln(s_{0t})$ INDEPENDENT VARIABLES	(7-a)
SW installed base $IB^{SW}_{g-1,t}$ [millions]	0.0156***
	(0.00478)
Interaction term $IB^{SW}_{g-1,t} * a_{jt}$	-0.000336***
	(9.82e-05)
Interaction term $IB^{SW}_{g-1,t} * IMPR^{CPU}_{g,g-1}$	-0.00878***
	(0.00317)
HW improvement $IMPR^{CPU}_{g,g-1}$	1.255***
	(0.290)
Number of available games N_{gt}	0.000268
	(0.000662)
Deflated price p_{jt}	-0.00625
	(0.00421)
ln(within-group share $s_{jt\,\vert B(t)=1}$)	0.641***
	(0.0869)
Console age a_{jt}	-0.00559**
	(0.00226)
Normalized console weight x^{weight}_{jt}	-0.357***
	(0.108)
Normalized CPU speed x^{CPU}_{jt}	0.0831
	(0.0905)
Observations	501
R-squared	0.954
Hansen's J	30.86

*** p<0.01, ** p<0.05, * p<0.1
Standard errors in parentheses are robust to arbitrary heteroskedasticity and arbitrary autocorrelation. Brand dummies, calendar month dummies, and constant are not reported.

Table 7b: Software supply estimates (2SLS) for a 3-year rolling window of $IB^{SW}_{g-1,t}$

DEPENDENT VARIABLE: N_{gt} INDEPENDENT VARIABLES	(7-b)
SW installed base $IB^{SW}_{g-1,t}$ [millions]	-0.710**
	(0.312)
Interaction term $IB^{SW}_{g-1,t} * a_{gt}$	-0.000118
	(0.00537)
Interaction term $IB^{SW}_{g-1,t} * IMPR^{CPU}_{g,g-1}$	0.838***
	(0.125)
HW improvement $IMPR^{CPU}_{g,g-1}$	-67.11***
	(16.02)
HW installed base IB^{HW}_{gt}	37.51***
	(1.024)
Interaction term $IB^{HW}_{gt} * a_{gt}$	-0.147***
	(0.0111)
Format age a_{gt}	-2.024***
	(0.139)
Observations	417
R-squared	0.982
Hansen's J	3.568

*** p<0.01, ** p<0.05, * p<0.1
Standard errors in parentheses are robust to arbitrary heteroskedasticity and arbitrary autocorrelation. Brand dummies, calendar month dummies, and constant are not reported.

Table 8: Average monthly changes (9/1997-8/1998) assuming that the Game.com console is backward compatible with software for the Game Boy

	Game.com	Game Boy Pocket	Virtual Boy[28]	Game Gear
Actual market shares	2.68%	89.03%	5.64%	4.84%
Predicted market shares base model	2.91%	74.50%	12.29%	10.66%
Direct effect of backward compatibility				
Unit change prediction vs. counterfactual	+217,541	-79,371	-18,255	-12,020
Market share change prediction vs. counterfactual	+69.38%	-53.46%	-8.50%	-7.63%
Indirect effect of backward compatibility				
Additional unit change	-13,744	+3,723	+612	+544
Additional market share change	-3.08%	+2.46%	+0.29%	+0.35%

[28] Nintendo's Virtual Boy has only been on the market for the first six months since the launch of the Game.com console.

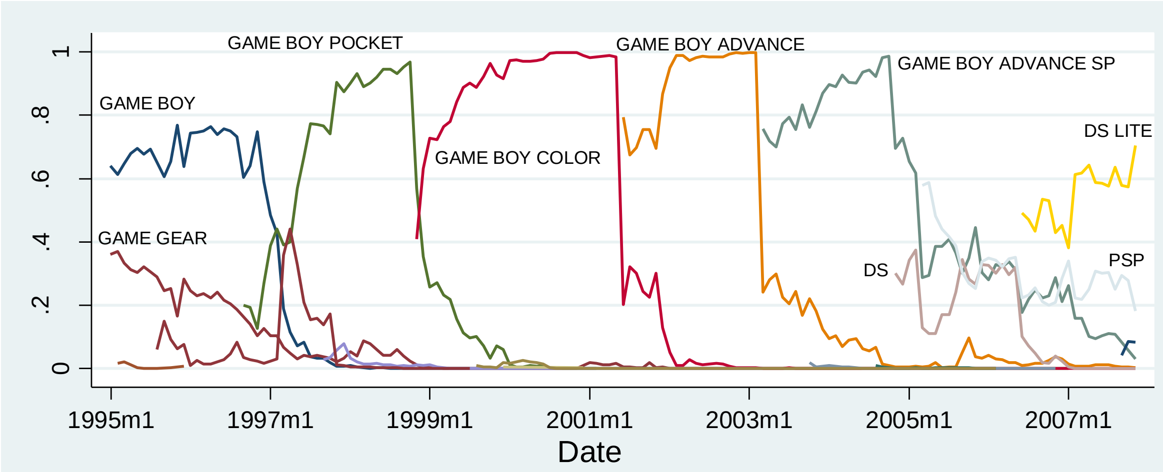

Figure 1: Monthly market shares from 1995 to 2007

Appendix A

Table A. 1: Hardware demand estimates (OLS)

DEPENDENT VARIABLE: $\ln(s_{jt}) - \ln(s_{0t})$

INDEPENDENT VARIABLES	(A1-1)	(A1-2)	(A1-3)
SW installed base $IB^{SW}_{g-1,t}$ [millions]		0.0126***	0.00967***
		(0.000664)	(0.00180)
Interaction term $IB^{SW}_{g-1,t} * a_{jt}$			-0.000124***
			(2.78e-05)
Interaction term $IB^{SW}_{g-1,t} * IMPR^{CPU}_{g,g-1}$			-0.00336***
			(0.000418)
HW improvement $IMPR^{CPU}_{g,g-1}$			0.00967***
			(0.00180)
Number of available games N_{gt}	0.00186***	0.000789***	-0.000124***
	(0.000136)	(0.000117)	(2.78e-05)
Deflated price p_{jt}	0.000310	-0.00483***	-0.00475***
	(0.00115)	(0.000844)	(0.000924)
ln(within-group share $s_{jt\,\|B(t)=1}$)	0.972***	0.924***	0.888***
	(0.0198)	(0.0158)	(0.0172)
Console age a_{jt}	-0.00820***	-0.00226*	-0.000521
	(0.00147)	(0.00116)	(0.00124)
Normalized console weight x^{weight}_{jt}	0.246***	-0.0495	-0.0664**
	(0.0393)	(0.0376)	(0.0337)
Normalized CPU speed x^{CPU}_{jt}	-0.207***	0.0247	0.0421
	(0.0484)	(0.0412)	(0.0428)
Observations	501	501	501
R-squared	0.939	0.970	0.974

*** p<0.01, ** p<0.05, * p<0.1
Robust standard errors in parentheses.
Brand dummies, calendar month dummies, and constant are not reported.

Table A. 2: Software supply estimates (OLS)

	DEPENDENT VARIABLE: N_{gt}		
INDEPENDENT VARIABLES	(A2-1)	(A2-2)	(A2-3)
SW installed base $IB^{SW}_{g-1,t}$ [millions]		-0.00178	-1.028***
		(0.0592)	(0.196)
Interaction term $IB^{SW}_{g-1,t} * a_{gt}$			0.00581**
			(0.00283)
Interaction term $IB^{SW}_{g-1,t} * IMPR^{CPU}_{g,g-1}$			0.390***
			(0.0466)
HW improvement $IMPR^{CPU}_{g,g-1}$			-17.49*
			(9.520)
HW installed base IB^{HW}_{gt}	32.98***	32.99***	35.19***
	(0.339)	(0.351)	(0.667)
Interaction term $IB^{HW}_{gt} * a_{gt}$	-0.110***	-0.110***	-0.127***
	(0.00692)	(0.00688)	(0.00756)
Platform age a_{gt}	-1.757***	-1.757***	-2.053***
	(0.112)	(0.116)	(0.101)
Observations	417	417	417
R-squared	0.980	0.980	0.984

*** p<0.01, ** p<0.05, * p<0.1

Robust standard errors in parentheses.

Brand dummies, calendar month dummies, and constant are not reported.