The Role of Network Effects in the US VCR Market, 1978–1986

Hiroshi Ohashi
University of British Columbia
and
University of Tokyo
7-3-1 Hongo, Bunkyo
Tokyo, Japan, 113-0033
hiroshi.ohashi@commerce.ubc.ca

This paper estimates the importance of indirect network effects in the US video cassette recorder (VCR) market between 1978 and 1986. Estimation reveals the significant role of networks in the format competition between VHS and Beta. The paper also finds that if Sony, the system sponsor of Beta, had aggressively introduced its VCRs at the early stage of competition, Beta would likely have dominated the market in 1985; instead, the format disappeared in 1989. Finally, the paper measures consumer welfare for the value of network effects in VCRs, and assesses the consumer welfare effect of standardization.

1. Introduction

The benefit derived from the consumption of a particular good often depends on the number of other consumers who purchase compatible goods. This characteristic of a positive consumption effect, called a network effect, can be either direct or indirect (see, for example, Katz and Shapiro, 1985; Church and Gandal, 1992a, b). If it is direct, as in a telephone network, the value of access to a network depends directly on the total number of subscribers to the same network. An indirect network effect arises when the benefit to consumers of adopting a product is increasing in the number of consumers who adopt compat-

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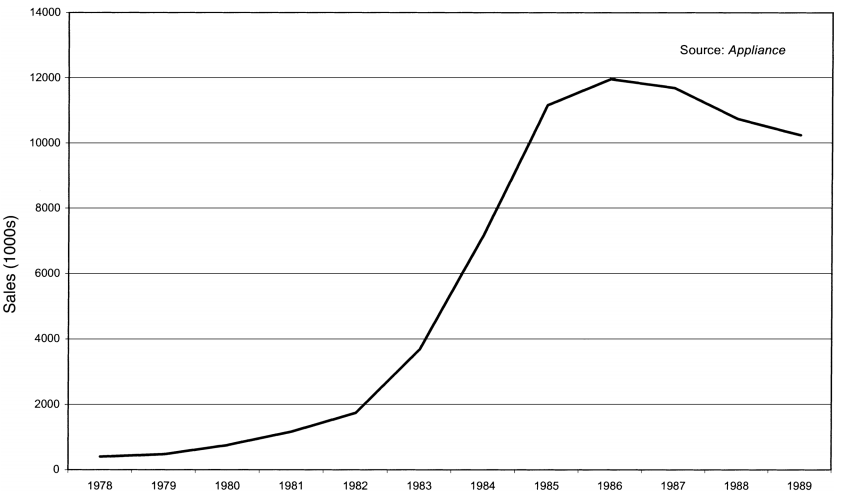

FIGURE 1. VCR ANNUAL SALES, 1978–1989

ible products, because it leads to an increase in the variety of compatible complementary products. This is often the situation in the computer industry, where the greater the variety of software, the greater the benefit derived from the capital good (hardware). Software variety in turn depends on the number of consumers who adopt the compatible hardware.

Indirect network effects are pervasive in the world of consumer electronics products, such as personal computers, DVDs, and video games. The size of the networks associated with a particular product often influences the outcome of standards competition among incompatible systems. Often not all the networks initially present in the market survive in the long term. Consumers often settle on one network that they expect will prevail in the future. While theoretical research on network effects has long recognized these features of information technology, few empirical studies have identified them.

This paper studies one classical episode illustrating the importance of networks: the home video cassette recorder (hereafter VCR) market in the United States (see Fig. 1). Indirect network effects are a critical feature in the VCR market, since the success of a format system depends mainly on the availability of complementary products. In particular, a specific VCR format becomes more valuable as more consumers use it, because as more consumers use it, more movie titles for that format will be available. Although the Beta format of the VCR

had a first-mover advantage of more than a year,[1] it lost the standards war to the incompatible VHS format and exited the consumer market in 1989. This paper investigates the role of network effects in the standards competition between VHS and Beta, and also measures the size of consumers' benefit associated with the network effects.

To address these issues, consumer demand is first estimated for VCRs. Consumer preference presumably evolves over time in a market for new products such as that for VCRs in the US over 1978–1986. During this period, consumers' attention was continually stimulated by the constant introduction of small new features in VCRs. VCR manufacturers announced new functions about once every three months (see Itami, 1989). Structural changes are thus allowed for in the demand estimation by dividing the nine-year sample into several periods, rather than pooling the estimates over the whole sample.

Based on a unique data set, the paper studies the role of network effects in format competition. It identifies two types of factors explaining consumers' VCR purchasing behavior: network factors and nonnetwork factors. The nonnetwork factor consists of VCR attributes, including price. I examine how the relative intensity of these two factors influenced the format battle over the period 1978–1986. Although the study finds evidence that the Beta format offered higher quality in some attributes, consumers valued VHS's better programming functions: More consumers thus favored the VHS format in the early stages of competition. Consequently, Beta's network effect advantage disappeared toward 1981. Around 1983 (presumably in response to the switchover of Zenith from Beta to VHS), Sony attempted to redress VHS's superiority in the characteristics domain with a move to high-end and mid-range VCR models. Although consumers perceived the consequences of this move favorably, the improvement in Beta characteristics could not overturn VHS's growing advantage in network effects. It appears that the format war between VHS and Beta was already over in 1981–1982; by the time Sony realized they were falling behind, it was too late to overcome their disadvantage.

In an industry with strong network effects, it is crucial to establish a larger network in the early stage of systems competition. Heavy promotional spending and deep discount offers are common in a network market. However, it is well known that Beta VCRs were initially more expensive than VHS models ($60 more in price). In this paper, I perform simulation exercises to see what would have hap-

1. Sony launched the first standalone Beta machine in February 1976, whereas the first VHS was introduced to the US in September 1977 (*Journal of the Electronics Industry*, May 1978, pp. 22–23).

pened to Beta's market share if Sony, the sponsor of Beta, had aggressively introduced its VCRs much earlier in the competition. The paper finds that, in contrast to its actual market share of 8.6% in 1986, if Sony had cut its price strategically in the first three years of the VHS introduction, it would have driven VHS out of the market in 1985. These simulation exercises confirm the effectiveness of pricing strategies in the early stages of product introductions in a network market.

Another way to estimate the importance of networks is to measure consumer surplus for the network effects in VCRs. This is similar to estimating consumers' willingness to pay for being able to watch prerecorded tapes rented from video shops.[2] The paper estimates that the value of the network effect grew from $5.6 million in 1978 to $343 million in 1986 for all US households (in constant 1978 US dollars). The paper also measures the welfare effects of standardization. It asks how much consumer surplus would have accrued had the two formats been compatible. The analysis discovers that, if VHS and Beta had been compatible, the consumer welfare would have ranged from $7 million in 1978 to $460 million in 1986 for all US households. The total value of standardization in 1986 was the value of the indirect network effect ($343 million), which was mostly attributable to the VHS network, plus an additional value ($116 million) if the Beta network had been compatible. The fact that Sony, the sponsor of Beta, did not act unilaterally to establish compatibility with VHS implies that the construction cost of an adapter exceeded Sony's increased profit through compatibility: Sony's compatibility benefit should have been at most $116 million in 1986.

This paper contributes to a small but growing body of work on the estimation of network effects. Most research in this area is concerned with the identification of indirect network effects. Some examples include studies of computer software (Dranove and Gandal, 1999; Gandal et al., 1999), ATMs (Saloner and Shepard, 1995), CD players (Gandal et al., 2000), and Yellow Pages (Rysman, 2002). Evidence of the existence of direct network effects is found in PC adoption (Goolsbee and Klenow, 2002), the spreadsheet-programs market (Gandal, 1994; Brynjolfsson and Kemerer, 1996), and the diffusion of facsimile machines (Economides and Himmelberg, 1995).

Park (2001) also explores the U.S. VCR market over the period 1981–1988.[3] In his study, Park builds a dynamic rational-expectations model with a nested logit structure to describe consumer and

2. This paper gives explicit consideration to the outside option and to the presence of replacement buyers in the welfare analysis.

3. Park (2003) details the econometric technique used in Park (2001).

firm decisionmaking. The present paper uses a static framework, but also contains three additional differences from Park (2001). The first difference is the study period. Our paper considers the early stage of the format battle in the years of 1978–1981, the period that was crucial to explaining the competition outcome. The paper finds that the format war was essentially over by 1982, the year Park's sample begins. Our simulation exercises are thus solely based on this three-year period. The second difference is related to the estimation strategy. Despite his explicit dynamic model, Park (2001) eventually estimates a static model with format-year dummies to represent the network effects. This proxy may be vulnerable to other noises, including time-specific demand shocks. The current paper uses both the installed-base variable and time-specific dummies to address this concern. Furthermore, Park's identification of network effects critically depends on the assumption that the rates of characteristics upgrading are the same across the formats. This assumption does not hold in our dataset.[4] Lastly, Park's dataset fails to identify the existence of multiformat and multibrand companies. This can generate a misspecification bias in his demand estimates through supply-side equations.[5] Our paper substantially expands Park's dataset and makes it possible to consider the ownership structure in the supply estimation.

The rest of this paper is organized as follows: Section 2 presents an overview of the market between 1978 and 1986, and presents summary statistics of the dataset. Section 3 introduces a VCR demand model and investigates a two-stage nested logit structure of consumer demand. Section 4 describes the data and instruments used in the estimation. Section 5 discusses estimation results and analyzes the robustness, with a particular focus on the treatment of an installed-base variable. Using the estimation results, Section 6 describes how the format competition between VHS and Beta unfolded in the period 1978–1986. It also describes simulation exercises to illustrate the importance of pricing strategies in a network market. Section 7 measures consumer's benefits from network effects and format compatibility. Section 8 contains the paper's conclusion.

4. Table II shows, for example, that the number of days for which a VCR could memorize preset program times was upgraded much faster in VHS than in Beta. Comparison of other VCR characteristics is made in Section 2.

5. While the estimate of the within-format share coefficient [in our model, σ in equation (2)] is particularly susceptible to a misspecified ownership structure, the direction of the bias is not definitive.

TABLE I.
SALES MARKET SHARES FOR THE US VCR MARKET, 1978–1986

	Market Share (%)						
	By VCR Brand					By Format	
Year	RCA (VHS)	Sony (Beta)	Panasonic (VHS)	Fisher (VHS)	Magnavox (VHS)	VHS	Beta
1978	25.5	28.8	14.3	—	6.8	56.8	43.2
1979	34.1	38.1	4.3	—	3.8	55.0	45.0
1980	29.3	28.8	9.3	—	3.9	60.0	40.0
1981	28.0	14.2	15.3	—	4.5	72.4	27.6
1982	22.0	13.0	17.8	2.0	4.0	74.4	25.6
1983	16.0	7.0	15.0	5.0	4.7	81.9	18.1
1984	16.0	6.5	14.0	6.0	4.0	82.2	17.8
1985	13.8	4.8	12.1	7.7	4.0	87.8	12.3
1986	12.0	3.1	11.3	6.8	4.0	91.4	8.6

The five brands with highest average sales market shares in 1978–1986 are chosen in order. Thus the brands in the table are not necessarily in the top five in market share by year. Sources: *Annual Consumer Electronics Video Data Book,* 1st ed.–7th ed., and *Economic World* (February 1980).

2. OVERVIEW OF THE US VCR MARKET, 1978–1986

Today's VCRs were invented by Japanese firms, whose basic technology came from the United States.[6] The Japanese succeeded in downsizing broadcasting videotape recorders and applying these to home use in the 1960s. There were initially two different and incompatible formats: Betamax and VHS.[7] The most prominent differences between the two formats were cassette construction and tape-drive mechanisms. The Beta cassette played only on a Beta machine, and the VHS cassette only on a VHS machine.

Table I shows two aspects of market shares by year. We define market shares as based on quantities sold in the paper. The left part of the table presents sales market shares of the top five VCR brands in descending order of average market share over 1978–1986. We can observe that the incumbents lost market share over time, whereas

6. This article focuses on tabletop VCRs, which sit close to a television and are not designed to be moved around. In addition there were three other types of VCRs more or less connected with video photography. Portable-type VCRs were lightweight and supposed to be carried with a video camera. Dockable or convertible VCRs were similar, except that they could be docked with a tuner-timer assembly to make a regular VCR for home use. Finally, camcorders (short for "cameras-cum-recorders") used a smaller video cassette (quarter-inch tape size).

7. Betamax and VHS were not the only formats in worldwide VCR markets. Ohashi (2002) discusses the V-2000 format, popular in Europe. However, I could not find any evidence of formats other than Betamax and VHS entering the US market in 1978–1986.

entrants, represented by Fisher in the table, gained share. A substantial drop in share was observed for Sony over this period, from 28.8% to 3.1%, because Beta VCRs were generally less favored by consumers over time.

The right-hand part shows sales market share by format. Despite being launched first in the US, Beta could not capture half of the market in 1978, and its market share gradually diminished to 8.6% in 1986. Over this period several Beta brands dropped the format and switched to VHS. In 1986, however, Sony was still not the only Beta supplier. Section 6 analyzes the evolution of this market.

The number of VCR brands and models available for the dataset is shown in the first and second columns of Table II. The total number of models increased tenfold between 1978 (17) and 1986 (171). The Beta models substantially decreased in number in 1985, a year after one major Beta supplier, Zenith, switched to VHS. The number of brands shows a similar trend. VCR brands on average expanded their array of models over time (from 1.9 models in 1978 to 8.6 in 1986) to accommodate various types of customers.

The VCR industry was characterized by a rapid turnover of models. The average lifetime of a model was less than a year,[8] and major VCR brands such as Matsushita, RCA, and Sony had a practice of showing new models at the Consumer Electronics Shows held every year in January and June. Frequent model turnover was accompanied by rapidly upgrading characteristics and significant market growth.

Table II lists the six characteristics explored in this paper. The first two columns to the right of price display recording capabilities. The rest are secondary features. No doubt these six characteristics do not cover all the important functions of VCRs. A number of functions on which data are unavailable to us in a complete form, such as the number of heads, speed scanning, and the maximum recording hours per cassette, were also important attributes in enhancing the convenience and accessibility of VCRs. The six attributes at hand, however, give us good information on how characteristics evolved over the nine years.

The number of programs indicates how many program times could be preset in a VCR. The number of days shows how many days ahead a model could memorize preset program times. As is seen in Table II, just one TV program could be set up to 24 hours ahead in 1978. Nine years later, the number of preset programs had increased

8. The life of a VCR model was on average 10.4 months for major brands whose average market share in 1978–1987 was more than 3.0%.

TABLE II.

MEAN VALUES OF PRICES AND ATTRIBUTES OF VCR MODELS BY YEAR AND FORMAT, 1978–1986

Year	No. of Brands	No. of Models	CPI-Deflated Price	No. of Programs	No. of Days	Proportion				Average Real Price Change (%)
						Wired	Wireless	Hi-Fi	HQ/Superbeta	
					Total					
1978	9	17	761.01	0.94	1.02	0.78	0.00	0.00	0.00	
1979	11	27	698.23	1.69	2.49	0.99	0.00	0.00	0.00	−8.25
1980	10	31	620.70	3.04	6.57	0.97	0.00	0.00	0.00	−11.10
1981	10	44	530.22	3.89	7.73	0.83	0.09	0.00	0.00	−14.58
1982	13	63	415.16	4.12	8.90	0.52	0.38	0.03	0.00	−21.70
1983	14	92	348.69	3.41	10.64	0.47	0.48	0.10	0.00	−16.01
1984	16	113	317.61	4.33	13.12	0.20	0.77	0.26	0.01	−8.91
1985	17	138	266.02	4.89	20.01	0.12	0.86	0.36	0.05	−16.24
1986	20	171	245.00	4.87	47.77	0.03	0.97	0.38	0.55	−7.90
Max/Total/Mean	20	696	466.96	3.46	13.14	0.55	0.40	0.13	0.07	−13.09
					VHS					
1978	6	12	727.89	1.25	1.50	0.94	0.00	0.00	0.00	
1979	6	21	686.24	2.30	3.56	0.98	0.00	0.00	0.00	−5.72
1980	6	22	609.32	3.70	6.01	1.00	0.00	0.00	0.00	−11.21
1981	6	30	524.40	4.51	7.52	0.86	0.14	0.00	0.00	−13.94
1982	9	40	415.86	4.73	9.10	0.53	0.46	0.05	0.00	−20.70
1983	10	59	361.61	3.75	11.57	0.49	0.49	0.11	0.00	−13.04
1984	12	78	323.65	4.46	13.97	0.20	0.78	0.23	0.00	−10.50
1985	14	121	264.27	4.86	21.12	0.12	0.85	0.32	0.01	−18.35
1986	19	154	244.33	4.77	49.58	0.03	0.97	0.36	0.53	−7.54
Max/Total/Mean	19	537	461.95	3.81	13.77	0.57	0.41	0.12	0.06	−12.62

					Beta					
1978	3	5	787.70	0.60	0.40	0.60	0.00	0.00	0.00	
1979	5	6	711.89	1.00	1.26	1.00	0.00	0.00	0.00	−9.62
1980	4	9	634.41	2.27	7.25	0.94	0.00	0.00	0.00	−10.88
1981	4	14	542.77	2.62	8.13	0.77	0.00	0.00	0.00	−14.45
1982	4	23	413.15	2.73	8.46	0.50	0.21	0.00	0.00	−23.88
1983	5	33	310.49	2.40	7.87	0.39	0.45	0.05	0.00	−24.85
1984	6	35	292.02	3.79	9.14	0.19	0.76	0.39	0.08	−5.95
1985	4	17	284.49	5.19	10.51	0.06	0.94	0.73	0.39	−2.58
1986	4	17	261.08	6.54	11.50	0.00	1.00	0.79	0.93	−8.23
Max/Total/Mean	6	159	470.89	3.02	7.18	0.50	0.37	0.22	0.16	−12.56

Total sample size: 1237. Prices are constant January 1978 US dollars. Prices and VCR attribute indices are constructed as follows: First take an arithmetic mean over VCR models by month to construct a brand-level index. Then aggregate the brand-level indices into an industry-level index by using quantity-units brand market share as weight. Finally aggregate the monthly industry indices into an annual industry-level index by weighting in proportion to monthly VCR sales units. The number of VHS and Beta brands does not sum to the total number of brands in 1983–1986, due to the existence of multiformat brands.

about five times to 4.9 events, and the number of days had extended more than 40 times to 47.8 days.

Initially 78% of VCR models had a wired remote control. As VCRs added more special effects such as freeze motion, speed search, and frame-by-frame advance, the available remote control functions increased dramatically. In the meantime wireless infrared remotes appeared in 1981, and 97% of the models had wireless remotes by 1986.

Audio quality had traditionally been poor in TV equipment, and accordingly VCRs started with conventional monophonic recording. High-quality sound became prevalent in VCR specifications with the advent of stereo broadcasts and stereo TV sets. Table II includes statistics on high-fidelity (hi-fi) sound. Hi-fi VCRs record stereo sound similar to an FM broadcast, so that a tape captures a wider frequency response with lower background noise. Hi-fi was introduced first on VHS machines in 1982. Seventy-nine percent of the Beta models included this audio function by 1986, while the proportion for VHS models was about 40%.

"HQ" on the VHS models and "Superbeta" on the Beta ones were able to deliver higher-quality pictures than conventional VCR machines. These high-quality picture systems were first introduced in 1984 for Beta, spreading to 93% of all Beta machines by 1986, whereas only half of the VHS models had such systems by that date.

The VCR prices presented in Table II and used in the analyses are prices deflated by the overall CPI index to constant January 1978 US dollars. The mean deflated price of VCR models drastically dropped from 1978 ($761) to 1986 ($245). The average percentage price change was −13.1% per year, shown in the last column in Table II. Though both formats show the same average percentage price drop at 12.6% per annum, prices by format moved somewhat differently over the period. The VHS price was lower than the Beta price by $60 in 1978, but the ranks were reversed after 1981. In 1985 VHS became cheaper again.[9]

The features of the US VCR market described above have a direct bearing on the formulation of empirical strategies and the interpretation of quantitative results.

9. Korean firms had been barred from exporting VCRs to the US by provisions in their contracts with Sony and JVC. These arrangements expired in March 1985. In anticipation of the Korean entry (most of the formats were VHS), several Japanese VHS marketers were reported to have begun slashing VCR prices (*Advertising Age*, January 10, 1985, p. 3). Quality-adjusted price indices are discussed in Ohashi (2003).

3. Choice Model for VCRs

This section explains the model of demand for VCRs in 1978–1986 used in the study. The demand system is derived from a random-utility discrete choice model of consumer behavior. I estimate demand for VCRs at the brand level, incorporating important dimensions of VCR attributes. Since I do not observe the purchasing behavior of individuals or their socioeconomic backgrounds, I aggregate across individual buyers to obtain the demand for a VCR brand, while still allowing for heterogeneity across consumers.

3.1 Discrete Choice Model

This study uses the household as the purchasing entity. I also assume that a household has a unit demand for a VCR, that is, it buys either one VCR or none at all. Each consumer i is assumed to maximize the following indirect utility function at time t by choosing brand j among $J_t + 1$ alternatives, one of which is the option of not purchasing a VCR:

$$u_{ijt} = \beta_0 + \sum_k x_{jkt}\beta_k + \alpha p_{jt} + \varpi \ln N_{gt} + \xi_{jt} + \epsilon_{ijt}, \quad (1)$$

where u_{ij} is consumer i's utility from consuming brand j that belongs to format g (g is either VHS or Beta; the time subscript is omitted if there is no confusion). The vector x_j is brand j's observed attributes including time dummies. The kth component of this vector is denoted by x_{jk}. I allow x_j to include interaction and squared terms of the attributes. Let p_j be a real price (adjusted by the overall CPI), and ξ_j stand for an unobserved (by an econometrician) product quality of VCR brand j with $E(\xi_j) = 0$.

The presence of indirect network effects is a critical feature of the VCR market. The extent of the network effect depends on expectations of the number of available software varieties supplied with hardware. The feature of the indirect network effect is explicitly characterized by Church et al. (2002). Their model demonstrates that, when four assumptions mentioned below are satisfied, (i) the consumption benefit of hardware depends on the hardware installed base, and (ii) indirect network effects are technological. The first result was previously found by Chou and Shy (1990) and Church and Gandal (1992a, 1992b, 1993). The second result responds to Liebowitz and Margolis (1994), who argue that indirect network effects are only market-mediated effects, in that the network size depends solely on software price.

The four assumptions made in Church et al. (2002) are (a) increasing returns to scale in software production, (b) consumer prefer-

ences for software variety, (c) free entry into the software production, and (d) unsaturated hardware market. Each of the assumptions fits naturally in the VCR market: Software production costs are largely fixed with a small marginal cost of duplication and packaging; most movie titles during the study period were provided by unintegrated software companies for the platforms, which were made nonproprietary in 1978–1986; the VCR market experienced an increasing VCR adoption rate over the period. I thus use their finding to measure the extent of the network effects by incorporating the hardware installed-base variable, N_g. This treatment of network effects is particularly useful in our analysis of the VCR market, because software variety data, such as the number of movie titles circulated in the market, are hard to obtain for the study period.

In this study, we use the logarithm of N_g in the individual utility function. Since economic theory does not help determine the appropriate functional form for N_g, Section 5 discusses different specifications, such as a Box-Cox transformation and a second-order polynomial. The resulting estimation outcomes support specification (1). It should also be noted that what matters for hardware buyers is the expectation of the installed base. Section 5 thus uses different definitions of N_g, including one-year-lead and two-year-lead installed-base variables, and discusses how the baseline estimation results are robust to them.[10]

It is convenient, following Berry (1994), to decompose u_{ij} into ϵ_{ij} and δ_j:

$$\delta_j = \beta_0 + \sum_k x_{jk}\beta_k + \alpha p_j + \varpi \ln N_g + \xi_j.$$

The mean valuation in the population of consumers for brand j is denoted by δ_j, and the deviation in consumer i's taste from the mean is captured only by the mean-zero error, ϵ_{ij}. Here I impose assumptions on ϵ_{ij} that generate a standard nested logit structure, explained in the next subsection.

3.2 The Nested Logit Model

I consider the following simple nested logit model: On the first node, a TV household that does not have a VCR decides whether or not to buy a VCR. If the household decides to buy, it makes a format choice. On the second node, given the choice of format, the household decides

10. This paper does not focus on network effects at the stage of the wholesale market, especially that of OEM contracting, where technology licensing plays an important role. It was difficult to obtain such information.

which brand to buy. Since the VCR brands fall into one of the two formats at any given time, if consumers choose the format, such a choice will be made prior to the brand choice.

The nested logit gives a closed-form choice probability. The market share for brand j with format g (g is either VHS, Beta, or an outside option represented by 0) is given by (see McFadden, 1978, for example)

$$s_j = \frac{e^{\delta_j/(1-\sigma)}}{D_g^{\sigma} \sum_{g'} D_{g'}^{1-\sigma}},$$

where $D_g = \sum_{j \in \vartheta_g} e^{\delta_j/(1-\sigma)}$, and the set of brands with the format g is ϑ_g. The market share s_j is defined as the fraction of the total number of TV households that do not have VCRs. In theory the parameter σ lies between 0 and 1, and measures the correlation in unobserved (to the researcher) utility from different VCR brands with the same format. This parameter provides a test of whether it is appropriate to have a format-choice stage in the model. If σ is zero, it implies that the format choice is not important in explaining consumers' purchasing behavior, and the model collapses to a simple logit model with brand choice. If σ is close to one, format choice is important, and brands within a format are good substitutes. We normalize the standard error ϵ_{ij} to be one. This normalization is innocuous in that this standard error cannot be identified from the other utility parameters, as is common with other discrete choice models (see, for example, Johnston and DiNardo, 1997). We discuss an implication of this normalization in Section 5.1.

The market share of the outside option (i.e., the share of the people who choose not to buy) is denoted by s_0. Thus $s_0 + \sum s_j$ must be equal to one. Similarly, the market share of brand j given the choice of format g is

$$s_{j/g} = \frac{e^{\delta_j/(1-\sigma)}}{D_g}.$$

Following Berry (1994), a linear regression model for this two-stage nested logit is derived as follows:

$$\begin{aligned} \ln s_j - \ln s_0 &= \delta_j + \sigma \ln s_{j/g} - \delta_0 \\ &= \beta_0 + \sum_k x_{jk}\beta_k + \alpha p_j + \varpi \ln N_g + \sigma \ln s_{j/g} + \xi_j - \delta_0 \end{aligned} \tag{2}$$

for $j \in g$. I assume the mean utility of the outside option, δ_0, is zero. This assumption is the standard treatment in the literature, and does not affect the own and cross-elasticities resulting from the estimation.

However, the assumption does affect the welfare measures. I come back to this point in Section 7.

4. Data and Estimation

4.1 Data

The data set ranges from January 1978 to December 1986 on a monthly basis. Price data in satisfactory numbers are not available before 1978. I do not use the data after 1986 because the standards war (this paper's interest) was over long before.

Estimating a differentiated product demand system requires data on quantities sold, prices, and characteristics. The estimation also requires data on the installed base by format. The dataset covers more than 80% of the VCR market. Over the nine years, the dataset contains 696 models per year and 21 brands in total.[11] The frequent entry and exit of brands makes the dataset unbalanced. Table II shows summary statistics for VCR attributes, already examined in Section 2. Further explanations of the data sources are made in Appendix A.

Though the price and product characteristics are model-level data, the quantities are brand-level data. Most of the brands in 1978–1986 were multiproduct brands, carrying at least low-end and high-end models at the same time. As we find in Table II, a VCR brand comprised on average nine models in 1986. In order to match the brand-level quantity data, I aggregate the price and characteristics data to the brand level by taking an arithmetic mean over VCR models in each brand by month.[12] This data aggregation method substantially suppresses consumers' taste heterogeneity in price and characteristics dimensions. It is likely that some consumers preferred high-end models and others lower-end models, but the method and lack of disaggregated sales data do not allow me to identify such model-level substitution patterns.

4.2 Instruments

Following the literature (see, for example, Berry, 1994), I assume that x_j and ξ_j are not correlated with one another. This is a central identifica-

11. The brands in the sample are: Akai, Canon, Emerson, Fisher, General Electric, Hitachi, JVC, Magnavox, Mitsubishi, Panasonic, Quasar, Radio Shack, RCA, Sharp, Sylvania (all VHS), NEC (Beta until 1986, VHS since 1985), Sanyo (Beta until 1986, VHS since 1986), Sears (Beta until 1986, VHS since 1983), Sony (Beta), Toshiba (Beta until 1983, VHS since 1986) and Zenith (Beta until 1984, VHS since 1984).

12. As detailed in Appendix A, when a model received multiple price quotations, I take the median to get a model-level price index.

tion assumption for the demand estimation. This assumption may not be accurate in that observed characteristics may be positively correlated with brand image or other attributes that I do not have data for. Nevertheless the assumption helps greatly by reducing the number of instruments needed in the estimation.

Furthermore it may be that two explanatory variables in (2) are correlated with the error, ξ_j. One obvious variable is $\ln s_{j/g}$, since $s_{j/g}$ contains part of the dependent variable s_j. The other variable that is plausibly correlated with ξ_j is p_j. As we saw in Section 2, the observed characteristics may not cover all the important functions of VCRs. Brand image may also be an important concern for consumers. I thus interpret ξ_j as the unobserved quality error. If ξ_j is correctly perceived by consumers and sellers in the market, then this unobserved quality error is likely correlated with price: Better-quality products may induce higher willingness to pay, and sellers may be able to charge higher prices due to higher marginal costs or oligopolistic market power.

Traditionally cost variables that are excluded from x_j, such as input prices, are used as instruments in homogeneous-goods models, and continue to be appropriate here. I employ two kinds of instruments from the cost side. One is monthly exchange rates for Japanese yen per US dollar (the data are from the *International Financial Statistics Yearbook,* International Monetary Fund, 1997). During the sample period, virtually all the VCRs came from outside the US, mostly from Japan.[13] Thus the retail price of VCR brands would have been affected by exchange rates between Japan and the United States. I use the current exchange rates in the baseline estimation. Using a lag of one, three, or six months for the exchange rate does not change my estimation results much.

The other cost-side instrument is cumulative Japanese VCR output (the data source is *Production Statistics* by the Ministry of International Trade and Industry in Japan).[14] This instrument may capture learning effects and technological diffusion across VCR producers in Japan: As a firm manufactures more VCRs, it can achieve lower marginal cost by learning more efficient means of production. Furthermore, because all the manufacturing processes occurred in a geographically limited area (Japan), production techniques would probably

13. Japan's share in the US imports of VCRs was over 99% in 1978–1984, 96% in 1985, and 95% in 1986 (from the author's calculation using *Imports for Consumption* in *Tariff Schedules of the United States Annotated*).

14. I thank Tsuyoshi Nakamura for making the data available to me.

have diffused easily across VCR manufacturers.[15] Other conditions being equal, this effect would reduce VCR prices in the United States.[16] One problem in employing this instrument might be that cumulative VCR outputs could also be used as a proxy for VCR quality improvement. As a firm accumulates more experience in VCR production, it may be able to manufacture more reliable VCRs. Also, the knowledge and techniques accumulated at production sites could presumably feed back to R&D resources and eventually give birth to new models. Nevertheless, this type of feedback process takes time. The time lag significantly reduces concern about potential endogeneity. Note that the above two cost instruments are industry aggregates, and do not vary by brand. The use of the cost instruments thus helps identify the demand parameters only through the variations of the instruments over time.

In product differentiation models with exogenous characteristics, the characteristics of other firms (x_m, $m \neq j$) are also appropriate instruments. With market power in supply, the markup of each brand depends on the distance from its neighbors in the characteristics space. The characteristics of other products are thus related to p_j, but since characteristics are assumed to be exogenous, they are valid instruments. In the present study, I include in the set of instruments the sum of characteristics of other VCR brands in the same format. They may be negatively correlated with the price and the within-group market share.

Because of our unique data source detailed in Appendix A, we have another instrument available: The price data come from advertised prices in newspapers and mail-order catalogs. Each VCR brand normally generated more than one price quotation in these sources. The number of price quotations may indicate how accessible a brand was to consumers, because more price quotations for a specific brand indicate more vendors carrying that brand. I expect that a brand with more quotations achieved a larger within-format market share. Convenience in purchasing a brand, however, might be conceived by consumers as higher quality when they purchase a VCR. In particular, if retailers are more interested in selling and advertising brands with high unmeasured quality, this instrument may not be exogenous. Test

15. Itami (1989, p. 148) documents that VCR manufacturers in each format shared the same suppliers for quite a wide range of parts. Even VHS and Beta shared the same suppliers for several essential VCR components such as precision motors and connectors. These within- and between-format connections through parts suppliers may have facilitated technological diffusion rather efficiently.

16. I lag the instrument one year, because there must have been some passage of time before cumulative outputs influenced VCR prices in the United States.

statistics, however, show that this variable serves well as an instrument, and the endogeneity concern of using this instrument is minimal.[17] I found that the number of quotes helps identify the within-format coefficient lying within the theoretical range of the unit interval.

I assume that the installed base by format, N_g, is exogenous. If consumers took account of the effect of their purchase decision on the installed base, N_g would not be exogenous. The large size of the installed base, even in 1978, suggests that by that date VCR buyers no longer internalized the effect of their purchase on the installed base.

The installed base is, by definition, approximately equal to the sum of brand sales by format up to the previous period. Thus a concern for endogeneity arises if the unobserved quality term, ξ_j, has autocorrelation. In order to check how significantly autocorrelation would affect my results, I control N_g in two ways. One estimation uses the two-year lagged installed-base variable, and the other the cumulative sum of characteristics by format, as an instrument. The latter variable is an appropriate instrument because higher values of past format characteristics, which are already assumed exogenous above, would likely increase the past format sales. Both estimation results qualitatively maintain the rest of the results in this paper.

5. Estimation Results

5.1 Base Estimation

This section examines estimation results of the baseline model (2). The definitions of variables and summary statistics are presented in Table III.

The vector x_j includes observed characteristics, squared terms of PRG and DAYS (PRGSQ and DAYSQ), and an interaction term (PRGDAYS). It makes sense to include the interaction term because PRG and DAYS are related programming functions: The value of enhancing PRG by one event must depend on how many days ahead a VCR memorizes programmed contents.

The US VCR market in 1978–1986 was characterized by rapid turnover of models and fast upgrading of characteristics. Major brands introduced VCR models twice a year. Presumably, consumers' preferences for VCR attributes evolved with the changes in model attributes

17. The *J*-tests without the instrument reject the orthogonality condition, especially for the period 1980–1982. Furthermore, without the use of the instrument, the *t*-tests on residuals (discussed in detail in the next section) indicate significant serial autocorrelations in the period 1979–1983. This generates a concern for the endogeneity mentioned below.

TABLE III.
DEFINITIONS AND SUMMARY STATISTICS FOR THE VARIABLES

Variable	Descriptions	Mean	Std. Error	Min	Max
$\ln s_j$	Log of market share (=ln[(1 − out) × (inside brand market shares)])	−8.58	1.62	−15.31	−5.39
s_0	Outside market share	0.99	0.01	0.97	0.9998
CPI	The monthly CPI index (January 1978 = 100)	154	22	100	177
PRICE	CPI-deflated price (in January 1978 US dollars)	411	176	138	932
PRG	The number of programs preset in a machine	3.57	2.07	0.00	9.00
DAYS	The number of days preset in a machine	12	21	0	277
PRGSQ	Squared prg	17	17	0	81
DAYSQ	Squared days	599	4283	0	76868
PRGDAYS	prg × days	56	109	0	1400
WIRED	Availability of a wired remote control (0-1)	0.48	0.43	0	1
WIRELESS	Availability of a wireless remote control (0-1)	0.47	0.42	0	1
HIFI	Availability of a high-fidelity sound system (0-1)	0.17	0.28	0	1
HQ	Availability of a high-quality picture system (0-1)	0.08	0.24	0	1
$\ln s_{j/g}$	Log of within-group market share	−2.34	1.18	−6.38	0
N	Installed base by format (in millions of persons)	7.72	9.93	0.03	29.52
Ad expenditure	CPI-deflated advertising expenditure for TVs and VCRs (in thousands of dollars)	37.18	40.61	0.00	173.75
exch	Current nominal exchange rate, US$/Japanese yen	223	28	154	277
cumulative output	cumulative VCR output of production in Japan (in thousands of units)	35710	32195	436	105535
quote	The number of quotations for a VCR brand	8	11	1	90

Sample Mean of Dummy Variables

t78	0.06
t79	0.10
t80	0.08
t81	0.08
t82	0.09
t83	0.14
t84	0.15
t85	0.14
t86	0.16

Sample size: 1237

offered in the marketplace. I thus estimate demand in subsamples of adjacent pairs of years in order to mitigate the instability problem that would result from this type of demand evolution.[18]

Because of the small sample size and the presence of multicollinear regressors, I cannot test the assumption that the slope parameters are equal across the two adjacent years in each regression. Instead, a test is conducted to check whether a subset of critical variables, ln N and PRICE, has equal estimates in each two-year regression. The F-tests find that the equal-slope assumption cannot be rejected, with the exception of the 1981–1982 period, in which the price coefficient in 1981 is estimated to be not significantly different from zero; this result is, however, mainly due to the lack of price variation relative to the variation found in 1982.[19]

The estimation result for model (2) is shown in Table IV. The estimation finds that the specification fits the data moderately well. The model explains at least 70% of the variation in the dependent variable. The table also shows averaged first-stage F-statistics for the explanatory power of the instruments, conditional upon the included exogenous variables. The F-statistics indicate that the instruments are not weak. The statistics for overidentifying restrictions (the J-statistics) do not reject the hypothesis that the instruments are orthogonal to the error term. In order to check for the presence of autocorrelated errors and the resulting endogeneity problem discussed in Section 4.2, I supplement the estimation with more direct tests of whether the residuals are autocorrelated in each two-year subsample. The t-tests in the table are constructed by first getting a t-statistic on the coefficient of the lagged residual for each brand, and then aggregating all of them with brand market share as a weight. The t-statistics on AR(1) confirm the findings from the J-statistics that the endogeneity problem is not a serious concern.

We assume in Section 3.2 that the standard error of the nested logit error, ϵ_{ij}, is one. As is common with other discrete choice models, this standard error and the other structural utility parameters are not separately identified, and so the normalization assumption is not testable. If the assumption is not correct and the standard errors are indeed different across different years of the demand specifications, the estimates in Table IV should be viewed as being all scaled by the standard error ϵ_{ijt}. However, there is no problem in comparing the

18. Alternatively I can interact parameters with time dummies, and estimate the demand on the entire dataset at once. This method imposes the same error structure throughout the period, while the proposed method is free from such an assumption.

19. The F-test results are available from the author upon request.

TABLE IV.
DEMAND ESTIMATES

	1978–1979		1979–1980		1980–1981		1981–1982	
Variable	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.
PRG	−0.30	0.68	−0.15	0.45	0.40	0.23	0.69**	0.13
PRGSQ	0.05	0.07	−0.11**	0.04	−0.11	0.06	−0.21**	0.04
DAYS	6.60	4.22	3.18	2.56	0.63	0.59	0.30	0.41
DAYSQ	−0.66	0.37	−0.51	0.32	−0.19	0.10	−0.31**	0.07
PARGDAYS			1.43*	0.62	0.78*	0.39	1.43**	0.27
WIRED	0.33*	0.17	0.09	0.19	−0.24	0.57	−1.09**	0.25
WIRELESS							−1.84**	0.49
HIFI							−0.59	0.59
HQ								
ln N	0.63**	0.10	0.65*	0.32	1.03**	0.27	0.96**	0.19
PRICE	−0.51**	0.06	−0.65**	0.11	−0.58**	0.13	−0.84**	0.12
ln $s_{j/g}$	0.83**	0.10	0.84**	0.15	0.87**	0.21	0.78**	0.09
t79	−1.56**	0.22						
t80			−0.78*	0.38				
t81					−0.81**	0.18		
t82							−1.08**	0.12
Const.	−1.24**	0.11	−1.28**	0.36	−1.87**	0.38	−1.70**	0.26
No. observations	195		223		203		217	
R^2	0.92		0.88		0.86		0.77	
1st-stage								
F-statistics	14.63**		11.78**		30.75**		32.04**	
J-statistics (d.f.)	1.62 (4)		2.47 (4)		0.80 (4)		2.94 (6)	
t-tests on AR(1)	1.87		1.70		1.40		1.82	

	1982–1983		1983–1984		1984–1985		1985–1986	
Variable	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.
PRG	0.52**	0.11	0.44**	0.14	0.10	0.10	−0.24**	0.08
PRGSQ	−0.04**	0.01	−0.04**	0.01	−0.01	0.01	0.03**	0.01
DAYS	−0.50	0.57	0.89	0.83	−0.69**	0.23	0.10*	0.04
DAYSQ	0.03	0.03	−0.07	0.05	0.002	0.002	0.00004	0.0001
PARGDAYS	−0.05	0.08	0.09	0.11	0.10	0.05	−0.02**	0.01
WIRED	−0.28	0.35	0.42	0.27	−0.99*	0.46	−0.58	0.80
WIRELESS	0.17	0.42	0.98*	0.39	−0.47	0.45	0.26	0.79
HIFI	0.22	0.21	0.50*	0.20	0.66**	0.14	0.93**	0.19
HQ					0.24	0.39	0.08	0.11
ln N	1.04**	0.10	1.29**	0.13	1.28**	0.11	1.45**	0.10
PRICE	−0.70**	0.10	−1.20**	0.15	−1.00**	0.12	−0.84**	0.13
ln $s_{j/g}$	0.76**	0.05	0.78**	0.06	0.77**	0.06	0.94**	0.06
t83	−0.47**	0.10						

(continued)

TABLE IV (CONTINUED)

	1978–1979		1979–1980		1980–1981		1981–1982	
Variable	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.	Est.	Std. Err.
t84			−0.97**	0.14				
t85					−0.98**	0.13		
t86							−0.96**	0.09
Const.	−1.99**	0.12	−2.37**	0.15	−2.22**	0.15	−2.63**	0.18
No. observations	281		352		363		374	
R^2	0.75		0.65		0.73		0.85	
1st-stage *F*-statistics	35.03**		28.13**		27.66**		31.31**	
J-statistics (d.f.)	8.21 (6)		5.61 (6)		5.28 (7)		3.91 (7)	
t-tests on AR(1)	2.16*		1.76		1.78		1.71	

The dependent variable is the logarithm of brand market share minus the logarithm of the outside share. The brand market share is defined as the fraction of the total TV households that do not have VCRs by a given time. Heteroskedasticity-robust standard errors are used in the table. The DAYS, DAYSQ, and PRGDAYS coefficients are multiplied by 10, the PRICE coefficients by 100, and the intercept is divided by 10 for presentation. PRGDAYS is dropped in 1976–1979 due to multicollinearity. *N* refers to installed base. The unit is a household. First-stage *F*-statistics provide the average explanatory power of the instruments, conditional on the included exogenous variables. The *J*-statistic provides a test of overidentifications.
* Significant at the 95% confidence level.
** Significant at the 99% confidence level.

demand estimates (now adjusted by the standard errors) across years to discuss the evolution of the VCR demand.[20]

There are several points worth noting about the demand estimates. First, consider the characteristics coefficients. The coefficients for remote controls are generally insignificant. The hi-fi coefficients become significant in the last three years, whereas those of HQ are not significant. As seen in Table II, although hi-fi was introduced a year ahead of HQ, the diffusion rate of hi-fi was much slower than that of HQ. HQ was found in lower-end models by 1986, whereas hi-fi was still featured only in high-end and midrange machines. The coefficients for the interaction terms suggest the presence of positive complementarity between PRG and DAYS for about the first half of the period, and become generally insignificant thereafter. With a limited DAYS made available in earlier machines, consumers might have experienced the increase in the marginal value of PRG with more days for which a machine can memorize programmed content. As DAYS in-

20. It is inappropriate, however, to make an inference on the VCR utility of (1) from the demand estimates if the normalization assumption does not hold: The utility parameters in (1) are not scaled by the standard error [because (1) contains ϵ_{ij} in an additive term], whereas the demand estimates are scaled.

TABLE V.
MEAN OWN AND CROSS PRICE ELASTICITIES FOR THE SYSTEM SPONSORS, 1981–1982

	JVC	Sony
JVC	−18.84	0.0003
Sony	0.0011	−12.51

JVC and Sony were the system sponsors of VHS and Beta respectively. The estimates from 1981–1982 are used to calculate the elasticities. Cell entries *i, j*, where *i* indexes row and *j* column, give the percentage change in market share of brand *i* with a 1% change in price *j*.

creased to more than a week, the DAYS function may not have been a restriction any longer.

The installed-base coefficients are all significantly positive. Since both the dependent and installed-base variables are logged, the coefficient is interpreted as an elasticity of market share with respect to the installed base. The elasticity is estimated to have been fairly small and then become large, with a large increase in 1980–1981. It almost doubled in magnitude from the period 1978–1979 to 1985–1986. Cusumano et al. (1992) document that the rental video business began to grow in the early 1980s: Sales and rentals of prerecorded movie titles doubled each year from 1982 to 1986. The estimated installed base elasticity confirms the significance of indirect network effects in the US VCR market.

Theoretically, the coefficients of the within-group shares must lie between zero and one if consumers' behavior accords with the utility-maximization principle. This coefficient also indicates the degree of substitutability between the formats (relative to that among VCR brands within the format). All the estimated coefficients fall within the theoretical range. The estimates are between 0.8 and 0.9 in all years, implying that the VHS and Beta formats were substantially differentiated, or that brands within a format were good substitutes.[21] The estimated coefficients are significantly different from zero for the entire period, and thus a simple logit structure would be rejected as a specification: format mattered.

The price coefficients show that the VCR demand became elastic over time. This result accords with the general view that a new high-tech product is often first purchased by consumers with high willingness to pay, and then trickles down to price-sensitive consumers. Table V presents the own and cross-elasticities for the system

21. The large values of σ foreshadow the large own price elasticity of demand for Sony and JVC discussed below.

sponsors, JVC for VHS and Sony for Beta, in 1981–1982. This period is chosen because it is in the middle of our sample. The elasticities are evaluated at the mean values with the demand estimates from the same period. The own price elasticity of JVC was found higher than that of Sony, consistent with the evidence that Sony maintained higher prices. As the large estimate of the within-format coefficient shows, cross-elasticities between the brands in the different formats are quite small, implying that JVC and Sony were not close substitutes.

The coefficients of time dummies are all negative. This implies that, holding the VCR attributes (including price) fixed, brand market share should diminish in the second year. In a market with frequent introductions of new models with superior quality, market competition forces the valuations of all characteristics of incumbent models to obsolesce. The time dummy may capture such an effect. Increasing market competition is another possible explanation: Ohashi (2002) found that brand profit margins on the retail market generally declined during our study period.

5.2 Sensitivity Analyses

Several other specifications were used to check the robustness of the base estimation results. The whole sample period is discussed here, but in order to save space, the results only for 1981–1982 are presented in Table VI (the period is chosen simply because it is the middle of the sample). All specifications gave more or less similar results. The base result is copied from Table IV and presented in the column headed "Specification 1."

Our economic model does not determine how the installed-base variable should be included to capture the indirect network effects. The first four specifications in Table IV are thus used to check our assumption of using the logged installed-base variable as a proxy for the network effects. The first two examine other functional forms of the installed base variable, and the other two try different definitions of installed base.

Specification 2 adds a term in the square of $\ln N_g$. For most of the period, the coefficients on $(\ln N_g)^2$ are not significantly different from zero, and the other estimates are almost identical to the baseline estimates. Instead of adding the squared term, specification 3 incorporates a Box-Cox transformation for the installed base: $\varpi N_g^{(\lambda)} \equiv \varpi \cdot (N_g^{\lambda} - 1)/\lambda$, where ϖ and λ are parameters to be estimated. This transformation includes a linear form (when $\lambda = 1$) and a logarithmic form (when $\lambda = 0$, by the use of L'Hospital's theorem), and allows us to test if our use of $\ln N_g$ is relevant. We cannot reject the hypothesis that $\lambda = 0$ in the first half

TABLE VI.
SENSITIVITY ANALYSES, 1981–1982

	Specification 1: Baseline Model		Specification 2: Second-Order Polynomial for ln N		Specification 3: Box-Cox Transformation for N		Specification 4: One-Year-Lead Installed Base for N	
Variable	Est.	Std.	Est.	Std.	Est.	Std.	Est.	Std.
PRG	0.69**	0.13	0.70**	0.13	0.73**	0.13	0.70**	0.13
PRGSQ	−0.21**	0.04	−0.21**	0.04	−0.21**	0.04	−0.21**	0.04
DAYS	0.30	0.41	0.30	0.38	0.37	0.39	0.28	0.41
DAYSQ	−0.31**	0.07	−0.31**	0.06	−0.32**	0.07	−0.31**	0.07
PARGDAYS	1.43**	0.27	1.44**	0.26	1.47**	0.28	1.45**	0.27
WIRED	−1.09**	0.25	−1.10**	0.22	−1.08**	0.22	−1.11**	0.25
WIRELESS	−1.84**	0.49	−1.77**	0.47	−1.79**	0.49	−1.87**	0.49
HIFI	−0.59	0.59	−0.61	0.59	−0.78	0.61	−0.55	0.59
ln N (N for spec. 3)	0.96**	0.19	3.30	7.78	0.77**	0.25	0.60**	0.12
$(\ln N)^2$			−0.08	0.28				
PRICE	−0.84**	0.12	−0.81**	0.12	−0.84**	0.12	−0.84**	0.12
ln $s_{j/g}$	0.78**	0.09	0.75**	0.09	0.73**	0.10	0.77**	0.09
λ					1.05	1.02		
t82	−1.08**	0.12	−1.07**	0.12	−1.05**	0.12	−0.90**	0.11
Const.	−1.70**	0.26	−3.35	5.44	−0.40**	0.06	−1.24**	0.18
No. observations	217		217		217		217	
R^2	0.77		0.78		0.74		0.76	
J statistic (d.f.)	2.94 (6)		3.28 (6)		3.68 (6)		2.99 (6)	

Variable	Specification 5: Two-Year-Lead Installed Base for N		Specification 6: Adding Ad Expenditure as Exogenous		Specification 7: Adding Ad Expenditure as Endogenous		Specification 8: Treat Price as Exogenous	
	Est.	Std.	Est.	Std.	Est.	Std.	Est.	Std.
PRG	0.71**	0.13	0.69**	0.13	0.67**	0.15	0.33**	0.10
PRGSQ	−0.21**	0.04	−0.21**	0.04	−0.19**	0.06	−0.12**	0.03
DAYS	0.25	0.41	0.31	0.37	0.00	0.91	0.54*	0.22
DAYSQ	−0.31**	0.07	−0.31**	0.06	−0.27*	0.12	−0.21**	0.05
PARGDAYS	1.46**	0.27	1.44**	0.26	1.32**	0.39	0.79**	0.18
WIRED	−1.11**	0.24	−1.09**	0.28	−1.12**	0.32	−0.74**	0.18
WIRELESS	−1.83**	0.49	−1.83**	0.51	−1.99**	0.62	−0.23	0.25
HIFI	−0.50	0.58	−0.60	0.65	−0.55	0.62	−0.25	0.43
ln N	0.43**	0.09	0.96**	0.21	1.08**	0.37	1.26**	0.14
PRICE	−0.83**	0.12	−0.83**	0.13	−0.89**	0.17	−0.22**	0.03
Ad expenditure			−0.01	0.21	0.43	0.97		
ln $s_{j/g}$	0.76**	0.09	0.77**	0.12	0.83**	0.16	0.69**	0.09
t82	−0.83**	0.11	−1.07**	0.14	−1.11**	0.17	−0.74**	0.08
Const.	−1.04**	0.14	−1.70**	0.29	−1.82**	0.43	−2.40**	0.17
No. observations	217		217		217		217	
R^2	0.77		0.77		0.75		0.91	
J statistic (d.f.)	3.11 (6)		2.95 (6)		2.97 (5)		6.73 (6)	

The dependent variable is the logarithm of the brand market share minus the logarithm of the outside share. The brand market share is defined as the fraction of all TV households that do not have VCRs by a given time. Heteroskedasticity-robust standard errors are used. The DAYS, DAYSQ, and PRGDAYS coefficients are multiplied by 10, and the PRICE coefficients by 100, and the intercept is divided by 10 for presentation. N refers to installed base. The unit is a household, except that for specification 3 it is millions of households. See Table III for the definitions for the other variables. The J statistic provides a test of overidentifying restrictions.

* Significant at the 95% confidence level.

** Significant at the 99% confidence level.

of the sample, and we can accept $\lambda = 1$ in the latter half. Since the logarithmic transformation is nicely approximated by the linear one at large values of the installed base, I take this result as supporting the logarithmic assumption for the installed base.

Specifications 4 and 5 use different sets of installed bases to test the robustness of the base result. Specification 4 assumes that VCR purchasers correctly predict the size of the installed base one year ahead, and incorporate it into their purchasing decisions. Since VCRs are a durable good, consumers should be concerned about the future size of the installed base at the time of their purchase. The coefficients for the installed base are slightly smaller than the baseline estimates, but the other estimates are similar in the whole sample. For specification 5, I use a two-year-lead installed-base variable instead. The installed-base coefficients are smaller than those in specification 4, and the estimate is negative in 1979–1980 (-0.03). Nevertheless the main results in Sections 6 and 7 qualitatively hold in specifications 4 and 5.

Specifications 6 and 7 add, as an independent variable, overall CPI-deflated retail advertising expenditures for both TVs and VCRs by brand. I include the expenditure for TVs because promotions for VCRs tended to be made simultaneously with promotions for TVs. Since this advertising variable might be correlated with consumer perceptions of VCRs, I treat it as an endogenous variable in specification 7. The data are taken from the *Class/Brand Multi-Media Report* published by Leading National Advertisers, Inc. The data contain annual advertising expenditures by product and by brand, collected from a wide range of media sources, including magazines, newspapers, outdoor, network, and spot television and radio advertisements. I use the advertising data only for TVs and VCRs. The estimation results show that in general the coefficient for the advertising variable is not significantly different from zero in either specification (except in 1984–1985 for both specifications). This result suggests that advertising expenditure for VCRs may not have noticeably affected consumers' preferences at the time.

Finally, specification 8 treats price as an exogenous variable. I delete the cumulative outputs and exchange rate from the set of instruments. Although all the estimated price coefficients are negative, the magnitude of price responsiveness is reduced by at least one-third relative to the baseline model.[22]

22. This observation may confirm Trajtenberg's (1990) finding that price is likely correlated with the unobserved quality term. The result does not change if one omits using the number of price quotations as an instrument. This instrument is, however, crucial to identifying the between-format coefficient.

6. Evolution of Format Competition

6.1 The Model and Results

This subsection describes how the format competition between VHS and Beta unfolded in the period 1978–1986, and investigates the underlying economic factors behind the competition.

The nested logit structure presented in Section 3 provides the following format share:

$$s_g = \frac{D_g^{1-\sigma}}{\sum_g D_g^{1-\sigma}},$$

where $D_g = \sum_{j \in \vartheta_g} e^{\delta_j/(1-\sigma)}$. The set of brands with the format g is denoted by ϑ_g. Here I explore how changes in the relative market shares of VHS and Beta can be decomposed into different attributable factors. Taking the log of the group market shares and subtracting one from the other yields

$$\begin{aligned}\ln s_{\text{VHS}} - \ln s_{\text{Beta}} = \varpi(\ln N_{\text{VHS}} - \ln N_{\text{Beta}}) + (1-\sigma) \\ \times \left\{ \ln\left[\sum_{g \in \text{VHS}} \exp\left(\frac{\beta_0 + \sum_k x_{jk}\beta_k + \alpha p_g + \xi_g}{1-\sigma} \right) \right] \right. \\ \left. - \ln\left[\sum_{g \in \text{Beta}} \exp\left(\frac{\beta_0 + \sum_k x_{jk}\beta_k + \alpha p_g + \xi_g}{1-\sigma} \right) \right] \right\}. \qquad (3)\end{aligned}$$

The changes in the relative market shares can be decomposed into a network-effect factor (the first term) and a non-network-effect factor (the second term). Other conditions being equal, the non-network-effect factor favors VHS when the number of brands in VHS increases. This reflects consumer taste for "horizontal variety" inherent in the utility formulation. [For further discussion, see Trajtenberg (1990).]

I use the demand estimates in Table IV to explore the relative importance of the two factors in format competition between 1978 and 1986. The result is presented in Figure 2.[23] The network factor is shown with a dotted line, and the nonnetwork factor with a solid line.

As the above equation shows, the network effect is obtained by

23. The figures are constructed by the following procedure: Using the adjacent two-year demand estimates in Table IV, I calculate monthly indices and aggregate them using a proportion of monthly VCR sales as a weight. Note that there are two annual indices in each year except for 1978 and 1986, depending on which estimates are used from Table IV. Except for 1978 and 1986, I average out the two annual indices using a proportion of annual VCR sales as a weight to obtain yearly indices.

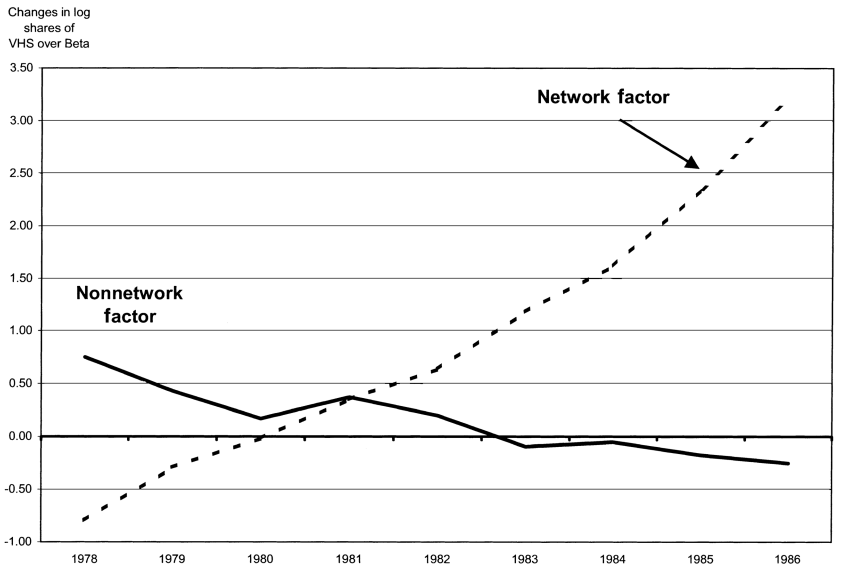

FIGURE 2. DECOMPOSITION OF THE DIFFERENCE IN THE FORMAT SHARES, $log(S_{VHS}) - log(S_{Beta})$

multiplying the difference in logs of format installed bases by the demand estimate ϖ. We already know from the data that the difference in the logs is increasing, as VHS was preferred by consumers throughout the sample (see Table I). However, ϖ is also allowed to change over time, as I estimate the demand by pooling subsamples of adjacent pairs of years. Thus, before obtaining the demand estimates, we do not know whether the product of the two terms looks like the dotted line in Figure 2. The trend is not obvious in the data. The sum of the dotted and solid lines must be equal to the difference in logs of the format shares.[24]

The figure confirms an explanation of how the format competition would have driven the Beta format toward exit. For the first three years in the sample, though Beta had a network-effect advantage due to the first-mover status, consumers perceived VHS as superior to Beta in VCR attributes. The latter nonnetwork factors outweighed the network effects, and thus, more consumers favored the VHS format. This contributed to the erosion of Beta's network advantage, and its eventual disappearance by 1981, when the rental video business was about to grow.

24. The sum does not match exactly with the second block of Table I, because our dataset does not cover the entire US VCR market (on average it covers about 88%).

The conventional wisdom in the VCR format war is that Beta featured a better picture, but VHS had longer recording time (see, for example, Cusumano et al., 1992). A close analysis of the estimates at the early stage of the competition confirms this common perception. The programming functions (PRG and DAYS), proxies for recording time, indicate that consumers preferred VHS to Beta: The utility rendered by the programming ($\Sigma\, x_k\beta_k$, in which k takes indices related to PRG and DAYS) is on average 0.91 for VHS, and 0.54 for Beta, in the period 1978–1981. For picture quality, the only variables we have are HQ and SuperBeta, which were introduced in the mid-1980s. We thus expect that the unobserved characteristics term would capture an important dimension of the picture quality in the earlier years. The estimated utility from the unobserved characteristics, ξ, indicates that Beta was superior in this dimension: The estimated ξ is on average 0.03 for VHS, and 0.07 for Beta. In the end, the VCR programming functions (PRG and DAYS) gave a competitive edge to VHS during 1978–1982. The other factors are found to have smaller effects on consumers' format choice in the first four years of the VCR introduction.

VHS remained superior in the characteristics domain until 1983, when Zenith, the second biggest Beta supplier in the US, started planning to drop the Beta format (*Japan Economic Journal,* July 19, 1983, p. 12). Zenith eventually OEM-contracted with JVC to market VHS in April 1984. This switchover dealt "a heavy blow to Sony" (*Japan Economic Journal,* January 10, 1984, p. 16), since Zenith had sold more than 15% of the Beta models each year. Beta quickly responded to this situation by moving towards high-end and midrange models as opposed to low-end models. As Table II shows, Beta established hi-fi and HQ systems at a much faster rate than VHS. In particular Sony introduced user-friendly features in its "EZ Beta" series, which first showed up in advertising in the *New York Times* in May 1983 (for the SL2400). Some of the "EZ Beta" machines (for example, SL2710) actually *talked* to users to guide them through the steps for programming. Beta also substantially reduced its prices to the point where they were $50 lower on average than those of the VHS models in that year.

Consumers enjoyed the consequence of Beta's move: Beta's characteristics led VHS's by 0.10 in 1983 and by 0.25 in 1986. The move, however, could not overturn the network advantage now held by VHS. The network factor snowballed in favor of VHS, beginning in 1981: from 0.35 in 1981 to 3.22 in 1986, a rate of growth of 57% per year. Network factors made the picture in 1986 completely different from that in 1980, while the magnitude of the nonnetwork factor remained almost unchanged. My analysis shows that systems competition is a

complex phenomenon whose outcome depends on endogenous strategic interaction between firms.

I have shown that firms in the VCR market differentiated their products along multiple dimensions. In addition, strategic decisions of firms about product prices and what models to offer significantly affected the outcome of competition. The endogenous strategic decisions by suppliers of complementary products, in this case firms providing videos in the two formats, also played a crucial role in establishing technological standards.

6.2 Simulation Exercises

For products with network effects, firms often compete aggressively to establish an installed-base advantage early in the product's life cycle. Heavy promotional spending and deep discount offers are frequently observed at product introductions in a network market. Notice in Table II that the average Beta VCR was especially expensive in the first three years, compared with the VHS models. The Beta VCR price was on average $60 higher than the VHS in 1978, and about $25 higher in 1979 and 1980.[25] We next explore what would have happened to the standards battle if Sony, the system sponsor of Beta, had sold its models at lower prices than it actually did during the early stages of competition. Such an exercise requires a supply model in order to analyze the equilibrium responses in the VCR format competition. This subsection first introduces such a model and then describes the simulation strategy.

6.2.1 Supply Model for the US VCR Market. Calculating the equilibrium under counterfactual scenarios requires a supply model describing VCR firms' behavior.[26] All VCR sellers in the market are assumed to compete in a Bertrand fashion. I focus on sellers' pricing decisions, and take the entry-exit process and choice of quality levels as exogenous to the analysis.

I assume that firms do not engage in dynamic pricing. That is, they do not take the installed base into account in their pricing decisions. This assumption on the VHS suppliers is reasonable. Because of its limited production capacity, JVC pursued both licensing and OEM agreements to form as large a VHS group as possible. A VHS supplier

25. It is not clear why Beta was more expensive than VHS. Gabel (1991, p. 88) explains that it was because of their premium pricing strategy, probably not because of royalty payments or R&D expenditures.

26. The discussion in this section relies on Ohashi (2002).

would have less of an incentive to price dynamically to grow the installed base, because the benefits were shared by the large number of licensees.[27] On the other hand, Sony, as the key Beta supplier, had a large market share of Beta, as shown in Table I, and might have pursued dynamic pricing. We argue in Section 7.2.1, however, that Sony actually faced weak network effects in the market, and thus that the static-supply assumption would be a reasonable description of Sony's behavior.

Some companies marketed more than one brand during the period. For example, Panasonic and Quasar (both VHS) were both sold by Matsushita.[28] The first-order condition for the short-run profit maximization problem with respect to price is derived as follows:

$$s(p) = -DB(p)(p - mc),$$

or

$$\begin{pmatrix} s_1(p) \\ \vdots \\ s_{n_t}(p) \end{pmatrix} = -D \begin{pmatrix} \frac{\partial s_1(p)}{\partial p_1} & \frac{\partial s_2(p)}{\partial p_1} & \cdots & \frac{\partial s_{n_t}(p)}{\partial p_1} \\ \frac{\partial s_1(p)}{\partial p_2} & \frac{\partial s_2(p)}{\partial p_2} & \cdots & \frac{\partial s_{n_t}(p)}{\partial p_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial s_1(p)}{\partial p_{n_t}} & \frac{\partial s_2(p)}{\partial p_{n_t}} & \cdots & \frac{\partial s_{n_t}(p)}{\partial p_{n_t}} \end{pmatrix} \begin{pmatrix} p_1 - mc_1 \\ \vdots \\ p_{n_t} - mc_{n_t} \end{pmatrix}. \tag{4}$$

The ownership matrix is D, in which the (i, j) element takes a value of 1 if brands i and j are marketed by the same firm, and 0 otherwise. Note that s_j is shown as a fraction of the total number of TV households, including non-VCR purchasers. The number of brands at time t is denoted by n_t, where t is the monthly frequency. The constant marginal cost of brand n at time t is denoted by mc_{n_t}. Entry and exit by brand make the size of B change over time. The components of B are as follows:

27. As discussed in footnote 10, it was difficult to obtain licensing information.

28. The other multibrand or multiformat firms were as follows: NEC (VHS and Beta) in 1986, RCA and GE (both VHS) since June 1986, Sears (VHS and Beta) in 1983–1986, Sanyo and Fisher (Beta and VHS, respectively) in 1984–1986, and Zenith (VHS and Beta) in 1984. JVC and Matsushita operated independently despite the ownership link (see Gabel, 1991).

$$B(i,j) = \begin{cases} \dfrac{\partial s_j(p)}{\partial p_i} = -\dfrac{\alpha}{1-\sigma} s_j[\sigma s_{i|g} + (1-\sigma)s_i] & \text{if } i \neq j \in g, \\ \dfrac{\partial s_j(p)}{\partial p_i} = -\alpha s_i s_j & \text{if } i \in g, j \in g', g \neq g', \\ \dfrac{\partial s_j(p)}{\partial p_j} = \dfrac{\alpha}{1-\sigma} s_j[1 - \sigma s_{j|g} - (1-\sigma)s_j] & \text{otherwise.} \end{cases}$$

Each element of B is calculated from the closed-form probability formula derived from the nested logit structure. Notice that the cross-derivatives differ, depending on which of the formats, g, a VCR brand belongs to. Each component of B consists only of market shares and demand parameters. Using the data and demand estimates presented in Table IV, I estimate brand marginal costs as explained in Appendix B.[29]

I use the demand equation (2) and the supply equation (4) along with the estimated marginal costs to solve equilibrium brand-level prices and market shares by month. Brand sales are calculated by using the potential market size for VCRs discussed in Appendix A.

6.2.2 Counterfactual Scenarios. I conduct the following experiment in brand-pricing strategies, leaving long-run strategies, such as product mix, constant. For the years 1978 and 1979, I assume that all Sony models were sold at the lowest market price in each month, and VHS brands behaved as actually observed in the data.[30] In the other years, VCR sellers are assumed to compete with one another over price, that is, I compute an equilibrium of the model by month, using the demand equation (2) and the supply equation (4). I take the installed base in January 1978 as given, compute the counterfactual sales by format for that month, and cumulate them respectively to obtain the format installed bases in the next month. I repeat this process in each month until the end of 1986, and compute monthly counterfactual network factors and the resulting monthly format market shares.[31]

Figure 3 shows how counterfactual network factors shift over the period. The bold line is the actual network factor taken from Figure 2. The broken line is the counterfactual network factor, assuming that Beta VCRs dropped their price only in 1978 and 1979. The average

29. Another way to obtain the estimates of marginal costs would be to just solve (4). This method, however, is not attractive, because we want the marginal costs (especially Sony's) to fall in response to the increases in outputs.

30. Sony's counterfactual prices would be lower if we used other VCR brands' best responses to Sony's strategic pricing. The current framework using the real VHS prices is a simplifying assumption.

31. The annual network factor is calculated as explained in footnote 23.

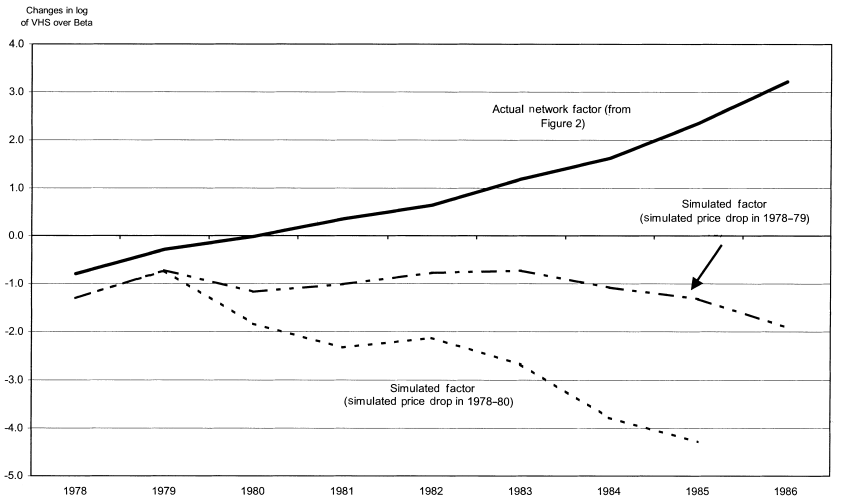

FIGURE 3. COMPARISON OF NETWORK FACTORS: ACTUAL AND COUNTERFACTUALS, 1978–1986

price drop would have been about $116. The broken line shows that Beta would have gained a network factor advantage in the entire period. Beta's network advantage appears to push its momentum in 1983: The network factor was at −1.90 in 1986. The Beta camp could not have achieved the same level of network factor just with its marketing push in 1983, even if it had given away its VCRs in that year. Its actual price cut was $103, far less than what they needed to catch up with VHS.

I redid the simulation under the assumption that Beta continued to match the lowest market prices through 1980. The real price drop would be $147 on average. The dotted line in Figure 3 shows the result. Since the simulation does not converge after November 1985 (presumably due to the large size of Beta's installed base), the dotted line stops short in 1985. Now it is clear that the network effects would have moved to the Beta side: Beta's advantage in the network factor was −4.2 in 1984, an order of magnitude larger than VHS's actual advantage in 1986.

I also calculate the market shares for Beta in the respective counterfactual exercises, as shown in Figure 4. The bold line is the actual Beta share, taken from Table I. The dotted and broken lines correspond to those in Figure 3. The distance between the dotted and broken lines is generated by the fictitious price cut by Beta in 1980. In contrast to its actual market share of 8.6% in 1986, under the counter-

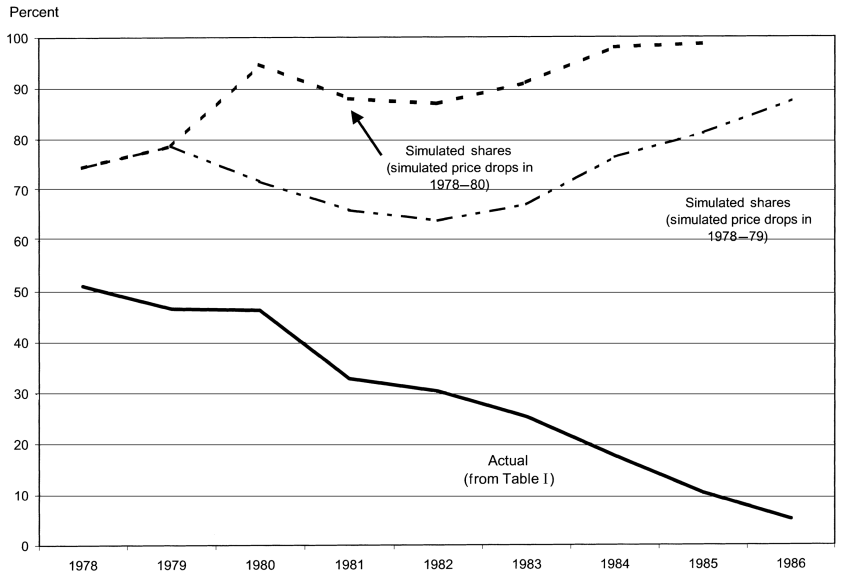

FIGURE 4. COMPARISON OF BETA MARKET SHARE: ACTUAL AND COUNTERFACTUALS, 1978–1986

factual scenarios the Beta format would have sustained a major market presence. In particular, if Beta had cut its price in the first three years of the VHS introduction, the format could have achieved more than 98% of the market by 1985.

It is interesting to ask why Sony did not pursue the above counterfactual strategies. These simulated strategies involve initial profit losses in order to reap future gains from the cumulated installed base. Thus an answer to the question may hinge on the value of Sony's discount factor. I calculate Sony's actual and counterfactual profits by year, using the estimated marginal cost described in Appendix B. Assuming Sony's discount factors are the same throughout the period, I compute the range of discount factors that support Sony's actual pricing strategies, that is, the present discounted value of actual profits is equal to or greater than that of the counterfactual profits. I find that Sony's subjective interest rate would have had to be quite high to rationalize the actual strategy: at least 48.9% for the simulated price drops in 1978–1979 (and 43.8% for those of 1978–1980). During the nine years, the average real rate of a US Treasury bill was 3.02%. Thus, according to the simulation results here, Sony would have had to have an interest-rate premium of at least 40% in order to justify its actual pricing scheme. One explanation of this high premium might be that it

reflected uncertainty faced by Sony regarding whether and how long the Beta format could survive in the cutthroat format battle during the period. An alternative explanation is that Sony did not understand the importance of strategic pricing in the market, which also provides support for our assumption of static pricing. I have shown that even though the non-network factor indicates that consumers preferred VHS over Beta from 1978 to 1982, if Sony had priced strategically, it would have become the de facto standard.

7. Value of Network Effects

This paper has so far discussed the importance of network effects with an emphasis on the supply side. The previous section analyzed how the network factor drove the Beta format out of the US VCR market. The simulation exercises confirmed that penetration pricing would have been quite effective in this market.

This section investigates the importance of network effects from the consumer's point of view. It first estimates the consumer surplus for the network effects in VCRs: How much consumers would have been willing to pay for the feature that enabled them to watch prerecorded tapes from rental video shops. This section also pursues another related issue on network effects: How much consumer surplus would have accrued if the two formats, VHS and Beta, had been compatible during the study period. This exercise may give us an idea why neither format seriously sought system compatibility.

7.1 Consideration for the Outside Option Value

In the demand estimation, it is not possible to distinguish between changes in the constant term in equation (2) and changes in the mean of the outside option value. As Pakes et al. (1993) point out, this does not affect the estimated own and cross price elasticities, since this merely changes the estimated constant term. The inability to distinguish between the two changes, however, creates some difficulty in deriving welfare implications.

An issue specific to the context of this problem concerns replacement demand for VCRs. The concern comes from the high frequency of VCR breakdowns and the high cost of repair at the time.[32] We can

32. *Consumer Reports* reported in 1985 that 20% of two-year-old machines experienced repairs, and older VCRs were more likely to need repairing. Moreover VCRs cost more to fix than TVs: The standard condition for manufacturers' warranties was twelve months on parts and three months on labor (*Consumer Reports,* various issues). Video heads were added to the coverage and extended warranties became available in later

think of two types of replacement buyers: (i) those who did not have working VCRs, and (ii) those who did have them. The first type of replacement buyers might have either bought a new VCR, or repaired an existing one. If they bought one, we do not need to worry about a potential bias in the welfare measurement: The consumers in this situation can be treated just like new buyers in the present framework. If they repaired, then their value of outside option would have been changed by the repair: Once the existing VCR was fixed, they began to enjoy a network effect, and thereby their value of not buying would be affected by the network effect. The second type of replacement buyers include individual households who had a functioning VCR and bought another, either because they wanted a second VCR or they wanted to upgrade because of new features (or some combination of the two). Even if they chose not to buy, since they had VCRs, they would have been able to enjoy a network effect. Therefore, for both types of replacement buyers, the outside options are a function of the network effect. Although I do not have data for replacement buyers, it is still helpful to appreciate the probable sign of any bias in the welfare measurements because of their presence.

Hence we measure the welfare of people who actually purchase VCRs. The welfare can be calculated as follows (for the derivation, see Trajtenberg, 1990):[33]

$$W(N_{\text{VHS}}, N_{\text{Beta}}) = \frac{\ln[\Sigma_{g=\{\text{VHS,Beta}\}} D_g^{1-\sigma}]}{-\alpha}, \tag{5}$$

where $D_g = \Sigma_{j \in \vartheta_g} e^{\delta_j/(1-\sigma)}$, and ϑ_g is the set of brands in format g. The marginal utility of income, $-\alpha$, represents the conversion between utility and money. Notice that equation (5) does not include consumers' heterogeneity in tastes. This welfare index should be viewed as the welfare of the mean consumer. To be rigorous, I use the true mean utility in equation (5), defined as

$$\delta_j^* = \beta_0 + \sum_k x_{jk}\beta_k + \alpha p_j + \varpi \ln N_g + \xi_j.$$

The asterisk indicates the true value. What is actually observed in the estimation, however, is

$$\tilde{\delta}_j = (\beta_0 - \delta_0^{A*}) + \sum_k x_{jk}\beta_k + \alpha p_j + \varpi \ln N_g + \xi_j.$$

---

years, but since about 36% of US households owned VCRs by 1986, more VCR households in the US might have sought replacement VCRs.

33. I omit an income term, which must be added to the right-hand side of (5).

The tilde indicates an estimated value, and δ_0^{A*} is the average value of outside options over the period of the pooled sample (two years in this case). The term $\beta_0 - \delta_0^{A*}$ is estimated as the constant term in equation (2). It is not possible to separate β_0 and δ_0^{A*} empirically. Using δ_0^{A*}, I expand the square bracket on the right-hand side of (5) in the following way:

$$\sum_g D_g^{1-\sigma} = \exp(\delta_0^{A*}) \cdot \left\{ \left[\sum_{j \in \text{VHS}} \exp\left(\frac{\tilde{\delta}_j}{1-\sigma} \right) \right]^{1-\sigma} + \left[\sum_{j \in \text{Beta}} \exp\left(\frac{\tilde{\delta}_j}{1-\sigma} \right) \right]^{1-\sigma} \right\}.$$

Thus the welfare of a mean consumer is represented by

$$W(N_{\text{VHS}}, N_{\text{Beta}}) = \frac{\delta_0^{A*}(N_{\text{VHS}}, N_{\text{Beta}})}{-\alpha} + \frac{\ln\left\{ \left[\sum_{j \in \text{VHS}} \exp\left(\frac{\tilde{\delta}_j}{1-\sigma} \right) \right]^{1-\sigma} + \left[\sum_{j \in \text{Beta}} \exp\left(\frac{\tilde{\delta}_j}{1-\sigma} \right) \right]^{1-\sigma} \right\}}{-\alpha}. \quad (6)$$

The welfare index consists of the value of the outside option (the first term) and the utility derived from consuming the inside good (the second term). The previous literature almost always assumes that δ_0^{A*} is zero. Notice now that the value of the outside option is a function of the installed bases. This addresses the concern that the outside option includes the network effect because of the presence of replacement buyers.[34]

7.2 Welfare Implication

7.2.1 Value of Network Effects. The value of the network effect can be measured by comparing the welfare of having the present size of the installed base with that calculated from a zero installed base: $W(N_{\text{VHS}}, N_{\text{Beta}}) - W(0, 0)$.[35] Table VII shows this value by year assuming the average outside option value is set to zero. Since $[\delta_0^{A*}(N_{\text{VHS}}, N_{\text{Beta}}) - \delta_0^{A*}(0, 0)]/(-\alpha)$ should be positive due to the presence of replacement buyers, the calculated value in Table VII may be biased downwards.

34. The welfare (6) can be negative. Some consumers buy VCRs and others do not because of differences in tastes. Our welfare measure is at best the welfare of the mean consumer.

35. I attempted to calculate equilibrium prices and market shares under zero installed base in the same manner as described in Section 6. Unfortunately, the simulation does not converge in most of the period. Thus, I used the actual prices and market shares in the welfare analysis.

TABLE VII.
VALUE OF NETWORK EXTERNALITIES

	Per-Household Welfare		Total US Consumer Welfare (US $1000)		Elasticity of Per-Household Welfare with Respect to Installed Base	
Year	US $	% of Average VCR Price	Estimate	Std. Error	VHS	Beta
1978	14.00	1.84	5,627	273	4.46	4.35
1979	15.37	2.20	7,305	651	3.91	3.35
1980	12.36	1.99	9,382	1,814	6.04	5.18
1981	26.23	4.95	30,717	2,573	3.73	1.84
1982	17.73	4.27	30,825	1,890	5.15	2.27
1983	21.91	6.28	80,591	2,913	4.37	1.49
1984	16.51	5.20	118,253	5,294	5.82	1.33
1985	21.93	8.25	244,807	11,508	6.15	0.69
1986	28.67	11.70	342,986	14,350	5.70	0.31

The values are in constant January 1978 US dollars. The network externality is measured by comparing the welfare obtained from the actual installed base with that obtained from a zero installed base.

In the welfare calculations, I compute both per-household welfare (in the second column) and the welfare for all US consumers (in the fourth column) by multiplying the total VCR sales volume by the per-household index.[36] Since the price is already deflated by the overall CPI, it is not necessary to deflate the welfare measures. The monetary unit is the January 1978 US dollar. The standard error for the total welfare, computed by the delta method, is shown in the fifth column. The unit of the total US consumer welfare measure is thousands of dollars.

The value of the network effect per household stagnates for the first three years: from $14.0 in 1978 to $12.4 in 1980. Then the value increases considerably, up to $26.2 in 1981, and stagnates again thereafter to $28.7 in 1986. The value of network effects accounts for 1.8% of the average VCR prices (taken from Table II), increasing to 11.7% in 1986. The value for all US consumers increases rather drastically due to the S-shaped diffusion curve in Figure 1: from $5.6 million in 1978 to $343 million in 1986.

VCR prerecorded tapes and video rentals were not widely available until 1980. Cusumano et al. (1992) document that VCR owners had

36. The index construction is same as in footnote 23. The calculation takes into account that the total VCR sales under zero installed base are different from the actual sales.

TABLE VIII.
VALUE OF FORMAT COMPATIBILITY

	Per-Household Welfare		Total US Consumer Welfare (US $1000)	
	US $	% of Average VCR Price	Estimate	Std. Error
1978	2.52	0.33	1,011	103
1979	4.20	0.60	1,995	219
1980	6.21	1.00	4,716	368
1981	6.71	1.27	7,857	175
1982	7.08	1.71	12,317	99
1983	6.88	1.97	25,307	470
1984	6.93	2.18	49,635	1,218
1985	8.54	3.21	95,281	2,563
1986	9.73	3.97	116,380	3,287

The values are in constant January 1978 US dollars. The value of compatibility is computed by comparing the welfare obtained from the actual installed base with that obtained from an installed base set at the total market level.

little opportunity in prerecorded movies in the late 1970s. Thus the small consumer welfare in 1978–1980 in Table VII indicates that direct network effects were not important for VCRs. With the weak direct network effects in the 1970s, Sony's pricing strategy would be similar to what we assumed in Section 6.2.1.

After 1980, sales and rentals of prerecorded tapes began to grow, as implied in Figure 1. The increase in the network value after 1980 may have been attributable to the popularity of prerecorded tapes. The last two columns of Table VII provide further evidence of the importance of indirect network effects. They show the elasticity of consumer welfare (per household) with respect to each of the format installed bases. The comparison in the elasticities between formats gives us the following interesting observation: In the late 1970s, the elasticity values were similar between the formats. As the supply of movies in rental video shops responded to the larger installed base of VHS in the 1980s, the elasticity for VHS gradually increased. On the other hand, the elasticity for Beta considerably declined as the advantage of indirect network effects was tipped away from Beta. The different paths of the format elasticities illustrate that it was indirect network effects that were important in the VCR market.

7.2.2 VALUE OF COMPATIBILITY

Table VIII computes the value of format compatibility by comparing the welfare of having the present size of the installed base with that

obtained from an installed base set at the total market level: $W(N_{\text{VHS}} + N_{\text{Beta}}, N_{\text{VHS}} + N_{\text{Beta}}) - W(N_{\text{VHS}}, N_{\text{Beta}})$. This experiment asks how much incremental welfare would have been generated if VHS and Beta had shared a compatible system, for given substitution patterns. One might want to further assume that $\sigma = 0$ because the format names, VHS and Beta, would have made no difference in this case. However, this assumption changes the underlying structure of consumers' preference from the one we found in the estimation.

Surprisingly, the value of compatibility turns out to be relatively small:[37] The value for all US consumers would have been $116 million in 1986, increasing from only $1.0 million in 1978. The value per household accounts for only 0.3% of the average VCR price in 1978 and 4.0% in 1986. There are three reasons why this estimate may be a conservative bound, apart from the considerations already noted above.

One is that we use the logarithm of the installed base in the demand estimation, and the log transformation gives diminishing returns to scale for the installed base. Reviewing the sensitivity analysis, however, it seems evident that our specification is correct.

Another possibility is that we are understating the equilibrium values of quantity under compatibility. The small welfare gains might be driven by the fact that there are no dynamics to this game. That is, the benefits from compatibility may be due to the faster diffusion of a product rather than just to the joining of installed bases at any given time. Though it is beyond the scope of this paper to incorporate dynamics into the model, as a sensitivity check I calculate the marginal welfare gain of compatibility. It is found to be small. Even if the installed base increased by 1000 households from our estimate, the compatibility gain would increase only by 0.1% per period on average during the study period. We thus believe that the magnitude of this potential bias would not be large.

Lastly, though we do not consider the supply side in the welfare calculation, the software industry might have saved on the costs of making duplicate titles for the formats if the two formats had been compatible. This gives another reason why our estimate is probably conservative.

The total advantage of standardization is the sum of the value of network effects and that of compatibility. The advantage ranged from

37. As in footnote 35, we could not calculate equilibrium prices under format compatibility. Thus we use the actual prices in this analysis. The welfare calculation, however, takes into account that the VCR sales under compatibility are different from the actual sales.

$7 million in 1978 to $460 million in 1986 for all US households. The consumer welfare accrued by standardization in the 1980s would be the value of the indirect network effects, which was mostly attributable to the VHS network, plus the additional value of compatibility if the Beta network had been compatible. The fact that Sony, the sponsor of Beta, did not act unilaterally to establish compatibility with VHS indicates that the construction cost of an adapter exceeded Sony's increased profit through compatibility: An upper bound on Sony's compatibility benefit by year is provided by the value of compatibility in Table VIII.

8. Conclusion

The last three decades have witnessed a dramatic diffusion of high-tech consumer electronics products. The successful proliferation of these products often depends on the availability of complementary products and services. Computers require application software, DVD players require movie software, and video game consoles require game cartridges in order for consumers to value the whole system. This phenomenon of indirect network effects has attracted significant attention in recent years, and there is a rich theoretical literature that examines it (see, for example, Church and Gandal, 1992a, b). Empirical work in this area has been slow to respond to this growing importance of new product characteristics.

This paper has focused on a classical anecdote illustrating the critical role of indirect network effects: the format battle between VHS and Beta in the US VCR market. The market for VCRs during the period was one of the fastest-growing markets in the United States: The household penetration rate grew 78% annually on average. The substantial market growth was fueled by fast upgrades in quality, the high rate of model turnovers, and emerging replacement demand. These characteristics of the market had a direct bearing on the estimation strategy pursued in the present paper. The obtained demand estimates witnessed the history of the US VCR market during the period. In particular, the paper found a significant effect of indirect network effects on end users' demand.

The paper conducted three analyses using the demand estimates. It first gave an *ex post* explanation of why the Beta format faded out of the market despite being the first mover in the United States. We found that network effects played a crucial role in the format competition between VHS and Beta. By the time Beta realized that the bandwagon

had started rolling in favor of VHS, it was too late for Beta to close the gap.

The paper next analyzed what would have happened to the Beta market share if Sony had introduced its VCRs aggressively at the initial stage of the competition. We found that, in contrast to its actual market share of 8.6% in 1986, if Sony had cut its price in the first three years of the VHS introduction, Beta would have achieved as much as 98% of the market. We examined Sony's discount factor and discussed why Sony did not pursue other available strategies.

Finally, the paper measured the value of the network effect for consumers. It found that the value of network effects grew dramatically, to $29 per capita and $343 million for all US households in 1986 (in constant January 1978 US dollars). The substantial increase in the value in the 1980s along with higher marginal value of the network effect for VHS provides evidence of the importance of indirect network effects in the US VCR market.

Appendix A. Data

A.1 Quantities

Two different data sources were used to construct the VCR sales market-share data for 1978–1986. Data from 1981 to 1986 were estimated annual brand sales market shares from *Video Book,* 1st–6th editions. Market shares for 1978–1980 were computed by the author using the VCR penetration and ownership surveys conducted by Media Statistics (documented in *Economic World,* February, 1980). Data on the VCR unit sales by month came from *Appliance* (April 1978–March 1988). The data were sales from factories to dealers.

I obtained the monthly quantities sold by brand by multiplying VCR sales by brand market shares. Notice that the market-share data were at the brand level; quantities sold by VCR model were not available. Also, the data were annual; I assumed that brand market shares in each month did not fluctuate much from the annual level.

The installed-base data required the VCR sales and format share data in 1976 and 1977. The sales data for this period were factory shipment units estimated by the Electronics Industry Association (*Fortune,* July 19, 1979). Beta had been the only format until September 1977, when JVC introduced VHS machines. I used Media Statistics's share estimate (also available in *Fortune,* July 19, 1979) to calculate the format market share for the last four months of 1977.

A.2 Price

The price data were advertised prices in the *New York Times* (*NYT*) and mail-order prices in the *Sears Catalog*. I used the *Sears Catalog* because in 1978–1986 the *NYT* did not advertise Sears, a brand with the tenth highest average sales market share. The advertised prices in the *NYT* were collected from Sections 1 and 2 on all Sundays in 1978–1981, and the last Sunday of each month in 1982–1986. Quoted retail VCR prices and brief attribute descriptions of some major brand models were obtained, in addition to model names and their brand names. The advertisers were vendors (including discount shops) operating in New York City. I also studied all sections of the *Los Angeles Times* and the *Chicago Tribune* on the last Sunday of June and July for the nine years. The price levels and the brand coverages found in the two newspapers were mostly in the range of those in the *NYT* in the period 1978–1986. Since the *Los Angeles Times* and the *Chicago Tribune* did not seem to provide significant additional information, I did not further consider these newspaper sources.

The *Sears Catalog*, a semiannual mail-order pamphlet, started listing VCRs in the fall of 1978. I assumed that the VCRs in the spring catalogs were available from February to July, and that those in the fall issues were available from August to the next January at prices listed in the catalogs. The *Sears Catalog* included primarily the Sears brand. The total number of collected mail-order prices was 380.

A total of 10,440 observations on quoted prices were collected for this study. Some VCR models disappeared and then reappeared again in the sources. In such cases, I assumed that the models had been on the market during their disappearance and I linearly interpolated the missing prices. Most of the models had more than one price quotation from vendors. When more than one vendor quoted prices on the same model, I picked the median of them.[38] Thus the number of observations used in the paper is 1,237, not 10,440. Lastly, the VCR prices were deflated by the monthly overall CPI with January 1978 as the reference period.

38. There were two reasons why the median price was used. One was to avoid the bias from loss-leader models. The other came from consideration of remote-control units. Some discount shops had removed remote-control units from the boxes and sold them separately, regardless of the manufacturers' intention to sell them with VCR machines. Although I could not identify which vendors had done this, taking the median price might remove a fair amount of the problem.

A.3 Characteristics

The characteristics data were the most difficult part of the data work in this project. Unfortunately, there existed no sources that gave complete information on VCR characteristics.[39] Moreover, some series of characteristics data differed from one source to another, which added another layer of difficulty to data collection. To increase the reliability and consistency of the dataset, I used three external sources to resolve conflicting information.

One was information on the OEM relationship. Because there were no US VCR manufacturers, US companies sold Japanese-made VCRs through OEM contracts. For example, RCA was selling Hitachi VCRs under the RCA brand name in 1984. So even though they were in the market under the RCA brand name, the RCA VCRs were identical to the Hitachi VCRs at this time. The OEM relationships during the sample periods were as follows (OEM suppliers in parenthesis): Akai (JVC in 1978–1984), Canon (Matsushita), General Electric (Hitachi, Matsushita), Magnavox (Matsushita), RCA (Matsushita in 1978–1982 and Hitachi in 1983–1986), Sears (Hitachi, Sanyo), Sylvania (Matsushita), and Zenith (Sony from 1978 to March 1984, and JVC from April 1984).

The second external source was information on multibrand models. This information applied only to Panasonic and Quasar models. The same VCR models were marketed by Matsushita under different brand names.

The final outside source was information hidden in the VCR model names. The VCR model names consisted of two or three letters of the alphabet, followed by a two- to five-digit number. The first letters showed the brand that a model belonged to. For example, a Sony model name always began with "SL," and a JVC began with either "HR" or "HRD." The number normally showed the quality level within the brand. If several models of a brand came out in the same year, a model with a larger number corresponded to a higher-quality model. An exception clearly observed in the dataset was Panasonic's model name construction. Panasonic models began with "PV" followed by a four-digit number. This four-digit number contained two data. The first two digits indicated the level of quality, and the last two the introduction year of the model. For example, if a model showed up in the market in 1983, its name ended with "20." Although some exceptions were observed, especially after 1985, this rule of thumb in

39. The main sources used here were various issues of: *Consumer Reports, Dealerscope Merchandising, Mart Magazine, Merchandising,* the *NYT, Popular Electronics,* the *Sears Catalog,* and *Video News.*

the construction of model names confirmed and enhanced the accuracy of the characteristics data. The six characteristics variables were thus discovered; these characteristics are listed in Table II.

A.4 The Outside Option and Installed Base

I defined the potential VCR market as the number of people who had a TV but did not have a VCR prior to their purchase. The annual numbers of TV and VCR households for 1978–1986 were available in *Trends in Television* (December 1996). The outside market share, s_0, indicated those who did not buy VCRs, as a fraction of the potential VCR market. Since the majority of the TV households did not purchase VCRs in a given month, the outside market share varied only from 0.97 to 0.99 in Table III.

97.6% of US households owned TVs in 1978, and this number grew slightly to 98.1% in 1986, whereas the percentage of TV-owning households that owned VCRs increased drastically, from 0.3% in 1978 to 36.0% in 1986, as we saw from Figure 1. Note that about half of TV-owning households had more than one TV set during our sample period; however, it was rare to observe households with two or more VCR sets, even in 1986. Thus, I assumed that each household had only unit demand for a VCR. Replacement demand might have been a concern toward the end of the sample. It was, however, impossible to read the magnitude of replacement demand from the dataset, since I did not have information on depreciation and new purchasers. I adjusted the annual potential market size and installment base to a monthly frequency, using monthly VCR sales.

Appendix B. Estimated Marginal Cost

Using the demand estimates in Table IV and the data, I derived brand marginal costs from equation (4). The reason we estimated marginal costs, instead of using the estimates directly calculated from (4), was provided in footnote 29. Since prices were already deflated by the overall CPI, the obtained marginal cost was in terms of January 1978 US dollars. Note again that there were two cost estimates in any particular year, except for 1978 and 1986, depending on which estimates were used in Table IV. I pooled all the marginal cost estimates together, ignoring the effect of double counting. In the end, there were 2,208 observations, not 1,257. Since almost all VCRs in the US were manufactured in Japan, I converted these marginal costs into Japanese yen by using the monthly exchange rate introduced in Section 4.2.

I then estimated the VCR marginal cost in Japan, using the

TABLE IX.
Cost Estimates

Variable	Est.	Std. Err.
PRG	63.38**	2.07
DAYS	13.80	18.19
WIRED	−10.51	18.99
WIRELESS	48.76	25.45
HIFI	79.84**	15.26
HQ	−103.74**	19.62
Demand error	182.32**	6.99
Total output	−337.80**	15.58
Const.	59.55**	2.12
No. Observations	2208	
R^2	0.90	

Estimation method is described in Appendix B. Estimates of time and brand dummies are omitted from the table. Heteroskedasticity-robust standard errors are used. The DAYS coefficient is divided by 10 and the intercept is multiplied by 10 for presentation. Demand error represents the estimated unobserved quality of the VCR.
* Significant at the 95% confidence level.
** Significant at the 99% confidence level.

following independent variables: cumulative Japanese VCR output, VCR characteristics (PRG, DAYS, WIRED, WIRELESS, HIFI, HQ, and the unobserved characteristic ξ_j), and year and brand dummy variables.[40] Unlike studies on automobiles done by, for example, Berry et al. (1995), it was not clear to what extent my observed characteristics had been important components of VCR unit cost. I believe, however, that the observed and unobserved characteristics would have been strongly correlated with major VCR cost components, such as the number of video heads or the cost of VCR large-scale integrated (LSI) microchips, data that were hard to obtain.

OLS estimation result is shown in Table IX. The estimation fitted the data moderately well. I found that the coefficient of the cumulative Japanese output was significantly negative, indicating strong industry-wide economies of scale on the cost side, as discussed in Section 4.2. The unobserved characteristic had a significantly positive coefficient. Using the result from Table IX, I performed the Sony simulation exercises in Section 6.2.

40. Cumulative Japanese VCR output by OEM group was also tried but found not significantly different from zero. Ohashi (2002) found a supply disruption in the US VCR market in late 1982 to early 1983. I used a dummy variable to control for this shock. The result was not different from that without the dummy. Thus the estimation here did not include these two variables.

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