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Indirect Network Effects in New Product Growth

Indirect network effects are of prime interest to marketers because they affect the growth and takeoff of software availability for and hardware sales of a new product. Although prior work on indirect network effects in the economics and marketing literature is valuable, there are two main shortcomings. First, empirical analysis of indirect network effects is rare. Second, in contrast to the importance prior literature credits to the "chicken-and-egg" paradox in these markets, the temporal pattern (i.e., Which leads to which?) of indirect network effects remains unstudied. Based on empirical evidence of nine markets, this study shows that (1) indirect network effects, as commonly operationalized by prior literature, are weaker than expected from prior literature and (2) in most markets examined, hardware sales "lead" software availability, whereas the reverse almost never happens, contrary to existing beliefs. These findings are supported by multiple methods, such as takeoff and time-series analyses, and fit with the histories of the markets studied herein. For academia, the study identifies a need for new and more relevant conceptualizations of indirect network effects. For public policy, it questions the need for intervention in network markets. For management practice, it downplays the importance of the availability of a large library of software for hardware technology to be successful.

> A familiar high-tech variation on an age-old conundrum is stalling acceptance of the much-heralded computer storage medium known as DVD-ROM: Which comes first, affordable hardware or a wealth of software? The installed base or the content providers? (Pescovitz 1997)

Economists regularly claim that markets such as those for television sets, CD players, and DVD players exhibit "indirect network effects."[1] The expected utility of the primary product, and thus its sales, increases as more complements become available; in turn, this availability of complements depends on the installed base of the primary product (Caillaud and Jullien 2003; Church and Gandal 1993, 1996; Cottrell and Koput 1998; Hill 1997; Katz and Shapiro 1994).[2] Prior research has typically referred to the primary product, such as a television set, a CD player, or a DVD player, as "hardware" and to the product that complements the primary product, such as programming (television), compact discs (CD player), and DVD movies (DVD player), as "software" (Church and Gandal 1992a; Ducey and Fratrik 1989; Gandal, Kende, and Rob 2000; Gupta, Jain, and Sawhney 1999).

Indirect network effects give rise to the "chicken-and-egg" paradox; that is, consumers wait to adopt the hardware until enough software is available, and software manufacturers delay releasing software until enough consumers have adopted the hardware (Caillaud and Jullien 2003; Gandal 2002; Gupta, Jain, and Sawhney 1999). A recent example is the high-definition television (HDTV) market. The expected utility of HDTV sets to consumers (and thus HDTV set sales) increases as more HD broadcasting becomes available. Conversely, broadcasters will make more HD broadcasting available as the number of con-

[1]The phenomenon of indirect network effects is different from the possible interdependence between hardware sales and software sales, such as CD player sales and CD sales (Bayus 1987; Peterson and Mahajan 1978).

[2]The literature is inconsistent in terminology. Scholars have used the term "availability" (e.g., Dranove and Gandal 2003; LeNagard-Assayag and Manceau 2001), "variety" (e.g., Church and Gandal 1992a, 1993), or both interchangeably (e.g., Basu, Mazumdar, and Raj 2003; Frels, Shervani, and Srivastava 2003; Gandal, Kende, and Rob 2000; Katz and Shapiro 1985; Nair, Chintagunta, and Dubé 2004) in theory development. Most, if not all, of the empirical studies that have used the term "variety" operationalize this construct by counting the total complements available (e.g., Basu, Mazumdar, and Raj 2003; Gandal, Kende, and Rob 2000; Nair, Chintagunta, and Dubé 2004). In this study, we consistently use the term "availability" because it corroborates with our measures.

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sumers who own HDTV sets increases. For HDTV to succeed, this chicken-and-egg paradox must be resolved (Farrell et al. 1992; Gandal 2002; Pope 1999).

In the previous two decades, several economists have researched various aspects of indirect network effects, including (1) coordination between software and hardware industries (Church and Gandal 1992a; Economides and Salop 1992; Farrell et al. 1992), (2) standard setting (Church and Gandal 1992b; Clements 2004; Economides 1989; Katz and Shapiro 1985, 1986a, 1992, 1994), and (3) buyers' technology adoption decisions (Gandal, Kende, and Rob 2000; Saloner and Shepard 1995; Shy 1996). Although most research in the first two streams is related to choice between rival incompatible systems, the third studies why consumers adopt a given system (Majumdar and Venkataraman 1998). Our study fits into this third research tradition.

Marketing researchers have only recently begun to study indirect network effects (Basu, Mazumdar, and Raj 2003; Gupta, Jain, and Sawhney 1999; LeNagard-Assayag and Manceau 2001; Nair, Chintagunta, and Dubé 2004), though the discipline has had a relatively longer tradition of studying direct network effects (e.g., Brynjolfsson and Kemerer 1996; Majumdar and Venkataraman 1998; Sun, Xie, and Cao 2004; Xie and Sirbu 1995).[3] In addition, some marketing studies have focused on network effects per se, independently of whether they are direct or indirect (e.g., Shankar and Bayus 2003; Srinivasan, Lilien, and Rangaswamy 2004; Van den Bulte and Stremersch 2004).

Tables 1 and 2 summarize the prior economics and marketing literature streams. Table 1 contains all empirical papers on indirect network effects and stipulates whether they study demand-side or supply-side indirect network effects or both; whether they define indirect network effects from only the demand side, only the supply side, or both; what the focal dependent and independent variables in their inquiry are; whether they use proxies to measure focal constructs; how many markets they study; whether they have data from the introduction of the new technology; and which markets they study. Table 2 contains a selection of nonempirical papers on indirect network effects. It illustrates what the main focus of this prior work is (whether on indirect network effects specifically or on network effects in general); what the method is (whether mathematical or conceptual); whether they define indirect network effects from only the demand side, only the supply side, or both; and which focal dependent and independent variables are included. Although this prior literature is valuable and insightful, it also shows some limitations.

First, empirical analysis of indirect network effects is rare and, as Table 1 shows, is mostly limited to the study of one market. Of the 18 empirical studies of indirect network effects, 17 examine only one market, and only 1 (Gandal 1995) examines two markets. This situation is probably due to a lack of data on both hardware sales and software availability. Some authors even claim that such data are unavailable (Putsis et al. 1997); others (6 of the 18 studies) use distant proxies, such as the amount of advertising (Gandal, Greenstein, and Salant 1999); and still others have modeled indirect network effects as if they were direct network effects (Hartman and Teece 1990; Ohashi 2003; Park 2004; Shankar and Bayus 2003). Authors often also do not use data from the introduction of the new technology (rare exceptions are Dranove and Gandal 2003; LeNagard-Assayag and Manceau 2001), leading to potential left-censoring biases. Frequently, authors have modeled only one side of indirect network effects, most often the effect of software availability on hardware sales (demand-side indirect network effects). Moreover, the literature is diverse and inconsistent as to the definition of indirect network effects. Many papers do not even explicitly state a definition of indirect network effects, and others provide (inexplicitly) multiple definitions (see the variation on the definition of indirect network effects in Tables 1 and 2). The literature is also inconsistent as to the empirical models employed (see the list of dependent and independent variables in Table 1). Thus, we conclude that the literature lacks a unifying framework to examine indirect network effects empirically.

Second, although the chicken-and-egg paradox is cited a lot, it is unclear how it is resolved. Many business analysts (e.g., Midgette 1997; Tam 2000; Yoder 1990; Ziegler 1994 [all in *The Wall Street Journal*]) and academics (Bayus 1987; Bucklin and Sengupta 1993; Clements 2004; Frels, Shervani, and Srivastava 2003; Sengupta 1998) have casually observed that a critical mass of software titles is required for hardware sales to take off. Takeoff is the point of transition between the introduction stage and the growth stage of a growth curve (Golder and Tellis 1997). Several academics (e.g., Church and Gandal 1992b) have made similar arguments based on theoretical models. However, to our knowledge, no one has empirically examined whether software availability leads hardware sales, or vice versa.

In this article, we aim to fill these voids. To do so, we examine the temporal pattern of indirect network effects across multiple markets using secondary data and based on prior theories developed in economics and marketing. We constructed a database on both hardware sales and software availability for nine markets dating back to their inception: black-and-white television, CD, CD-ROM, color television, DVD, Game Boy, i-mode, Internet (World Wide Web [WWW]), and laser disc (for a detailed description of the data, see the Appendix).

The next section of the article develops the theoretical background of this study. Then, we detail the data used. This is followed by our empirical analysis. We conclude by summarizing the results, presenting the implications and limitations of our study, and discussing avenues for further research.

Theoretical Background

The essence of indirect network effects theory is the understanding that software and hardware form a system (Chou and Shy 1996; Economides 1989; Katz and Shapiro 1994). As they form a system, the supply of software and the demand for hardware may affect each other in accordance with a specific temporal pattern. Both may also be affected

[3]In direct network effects markets, the utility of the product depends directly on the number of others using the same product (Katz and Shapiro 1985).

TABLE 1
Overview of Empirical Literature on Indirect Network Effects

	Demand or Supply Side	Definition of Indirect Network Effects				Dependent Variable		Independent Variable		Uses Proxies	Number of Markets	Data from Intro-duction?	Markets
		Demand Side	Supply Side	Both	Other	In Hardware[a] Equation	In Software[a] Equation	In Hardware[a] Equation	In Software[a] Equation				
Basu, Mazumdar, and Raj (2003)	Demand	V				HP		SA		No	1	No	CD
Clements and Ohashi (2005)	Both			V		HMS	SA	SA	HIB	No	1	Partial	Video game
Cottrell and Koput (1998)	Demand			V		HP		HMS, SA		No	1	No	Micro-computer
Dranove and Gandal (2003)	Demand			V		HS		SA		Yes	1	Yes	DVD player
Frels, Shervani, and Srivastava (2003)	Demand	V				RA		SA		No	1	No	Computer
Gandal (1995)	Demand			V			SP		C	No	2	No	Spread-sheet and DMS
Gandal, Greenstein, and Salant (1999)	Both			V		HS	SA	SA	HS	Yes	1	No	CP/M and DOS
Gandal, Kende, and Rob (2000)	Both			V		HIB	SA	SA	HIB	No	1	No	CD
Gupta, Jain, and Sawhney (1999)	Both			V		CD	CR	SA	CD	No	1	No	Television
Hartman and Teece (1990)	Demand		V			HMS		HMS, HIB		Yes	1	No	Minicom-puter
LeNagard-Assayag and Manceau (2001)	Both			V		HIB	SA	SA	HIB	No	1	Yes	CD (France)
Nair, Chintagunta, and Dube (2004)	Both			V		HS	SA	SA	HIB	No	1	No	Personal digital assistant

TABLE 1
Continued

	Demand or Supply Side	Definition of Indirect Network Effects				Dependent Variable		Independent Variable		Uses Proxies	Number of Markets	Data from Intro-duction?	Markets
		Demand Side	Supply Side	Both	Other	In Hardware[a] Equation	In Software[a] Equation	In Hardware[a] Equation	In Software[a] Equation				
Ohashi (2003)	Demand			V		HMS		HIB		Yes	1	No	VCR
Park (2004)	Demand			V		HMS		HMS, HIB		Yes	1	No	VCR
Rysman (2004)	Both			V		CD	SP	SA	CD	No	1	No	Yellow Pages
Saloner and Shepherd (1995)	Supply				V		SD		HS	Yes	1	No	ATM
Shankar and Bayus (2003)	Demand			V		HS		HIB		No	1	No	Video game console
Shurmer (1993)	Demand		V			CD		SA		No	1	No	Personal computer sofware (United Kingdom)
This study	Both			V		HS	SA	SA	HIB	No	9	Yes	Black-and-white televi-sion, CD, CD-ROM, color televi-sion, DVD, Game Boy, i-mode, Internet, laser disc

[a]C = compatibility, CD = consumer demand, CR = complementor response, HIB = hardware installed base, HMS = hardware market share, HP = hardware price, HS = hardware sales, RA = resource allocation, SA = software availability, SD = software deployment, and SP = software price.

TABLE 2
Overview of Nonempirical Literature on Indirect Network Effects

	Main Focus[a]	Method[b]	Definition of Indirect Network Effects: Demand Side	Supply Side	Both	Other	Dependent Variable Model: Hardware[c]	Software[c]	Independent Variable Model: Hardware[c]	Software[c]
Bental and Spiegel (1995)	NE	C		V						
Bonardi and Durand (2003)	NE	C			V					
Caillaud and Jullien (2003)	INE	M			V		CU	CP	SA	HMS
Choi (1994)	NE	C	V							
Chou and Shy (1990)	INE	M	V				CU	CP	SA	SA
Chou and Shy (1993)	INE	M	V				CU	SA	SA	HMS
Chou and Shy (1996)	INE	M	V				CU	SA	SA	HIB
Church and Gandal (1992a)	INE	M	V				CU	CP	SA	SA
Church and Gandal (1992b)	INE	M	V				CU	CP	SA	HMS
Church and Gandal (1993)	INE	M			V		CU	SE	SA	HIB
Church and Gandal (1996)	INE	M			V		CU	CP	SA	SA
Clark and Chatterjee (1999)	NE	M			V		CU		SA	
Clements (2004)	NE	M			V			SE		HIB
Conner (1995)	NE	C	V							
Dhebar (1995)	INE	C			V					
Economides (1996)	INE	C				V				
Economides and Himmelberg (1995)	NE	C	V							
Economides and White (1994)	NE	C				V				
Esser and Leruth (1988)	NE	C	V							
Farrell and Saloner (1985)	NE	C		V						
Farrell and Saloner (1986)	NE	M	V				CU		HIB	
Gandal (2002)	NE	M			V		CU		SA	
Garud and Kumaraswamy (1993)	NE	C		V						
Hahn (2003)	NE	C				V				
Hill (1997)	O	C			V		CU	SA	SA	HIB
Katz and Shapiro (1985)	NE	C		V						
Katz and Shapiro (1986a)	NE	M		V			CU		HIB	
Katz and Shapiro (1986b)	NE	M		V			CU		HIB	
Katz and Shapiro (1992)	NE	C		V						
Katz and Shapiro (1994)	INE	C		V						
Koski and Kretschmer (2004)	NE	C			V		CU	SA	SA	HIB
Kotabe, Sahay, and Aulakh (1996)	O	C			V					
Kristiansen (1996)	NE	C			V					
Kristiansen (1998)	NE	C	V							
Lee and O'Connor (2003)	NE	C			V		CU	SA	SA	HIB
Loch and Huberman (1999)	NE	C		V						
Matutes and Regibeau (1988)	O	C		V						
Matutes and Regibeau (1992)	O	C		V						
Postrel (1990)	NE	C	V							
Rohlfs (2001)	NE	C			V					
Schilling (1999)	O	C			V		HIB	SA	SA	HIB

TABLE 2
Continued

			Definition of Indirect Network Effects				Dependent Variable Model		Independent Variable Model	
	Main Focus[a]	Method[b]	Demand Side	Supply Side	Both	Other	Hardware[c]	Software[c]	Hardware[c]	Software[c]
Schilling (2002)	O	C			V					
Shapiro and Varian (1998)	NE	C			V					
Sheremata (2004)	NE	C			V					
Shy (2001)	NE	M			V			SA		HIB
Srinivasan, Lilien, and Rangaswamy (2004)	NE	C			V					
Thum (1994)	NE	C		V						
Valente (1995)	O	C	V							
Viswanathan (2005)	NE	C		V						
Wade (1995)	NE	C			V					
Xie and Sirbu (1995)	NE	C			V					

[a]NE = main focus on network effects, INE = main focus on indirect network effects, and O = main focus on other.
[b]C = conceptual method (containing verbal or graphical logic), and M = mathematical method (containing a mathematical formulation).
[c]CU = consumer utility, CP = complementor profit, HIB = hardware installed base, HMS = hardware market share, SA = software availability, and SE = software entry.

by other variables. For example, the supply of software may be affected by the supply of software in previous periods, and hardware sales may be affected by its price and previous hardware sales.

Indirect Network Effects

The theory of indirect network effects argues that the supply of software and the demand for hardware affect each other. The amount of software that is available for a certain technology has a positive influence on the utility of the entire hardware–software system to the consumer (Church and Gandal 1992b; Katz and Shapiro 1985), drawing more new adopters to adopt the new hardware (Rogers 1995) and thus increasing hardware sales and the installed base of hardware. In turn, the hardware installed base positively affects software companies' decisions to make software titles available (Church and Gandal 1993; Gandal 2002). The more consumers who adopt the hardware product, the larger is the market potential for software products for that particular hardware product, and thus the larger is the impetus for software companies to provide software titles for the hardware.

Our in-depth review of the literature of indirect network effects (see Tables 1 and 2) suggests at least three forms of indirect network effects, depending on the conditions authors have imposed to define them. We call these forms "demand-side indirect network effects," "supply-side indirect network effects," and "demand- and supply-side indirect network effects." Demand-side indirect network effects mean that software availability significantly and positively affects hardware utility of an individual consumer and, therefore, at the aggregate level, hardware sales. Supply-side indirect network effects imply that the hardware installed base significantly and positively affects the software provision by software manufacturers and, therefore, at the aggregate level, software availability. Demand- and supply-side indirect network effects imply that both characteristics exist.

Temporal Pattern in Indirect Network Effects

The temporal pattern in indirect network effects is important because it can indicate how the chicken-and-egg paradox is resolved. Prior literature has not covered this issue in detail. At the same time, academic scholars and business analysts have expressed different opinions about this temporal pattern.

A first opinion expressed is that given the extensive coordination between hardware and software manufacturers, growth of software availability coincides with growth in hardware sales (e.g., Katz and Shapiro 1994). Government intervention may coordinate the actions of market participants—both software and hardware—to achieve this. The guidelines of the Federal Communications Commission regarding new broadcasting and radio technologies are an example. Hardware manufacturers may also give subsidies, kickbacks, and side payments to software manufacturers to fine-tune software availability to the hardware sales evolution. In extreme cases, hardware manufacturers may even vertically integrate into the software industry. An example is RCA's ownership of NBC (when color television was introduced).

Others have argued that growth in software availability may precede growth of hardware sales (Bayus 1987; Bucklin and Sengupta 1993; Clements 2004; Frels, Shervani, and Srivastava 2003; Sengupta 1998). Church and Gandal (1992b) and several business analysts (Midgette 1997; Tam 2000; Yoder 1990; Ziegler 1994) claim that software availability needs to achieve a critical mass for hardware to become a viable alternative and for hardware sales to take off. The reason is that consumers need a sign of sufficient software availability before they adopt the hardware. Moreover, software companies may invest in software provision before any marked hardware sales occur. For example, Microsoft invested in the CD-ROM long before any significant sales of CD-ROM hardware occurred. Because the CD-ROM was the first mass-market high-capacity medium that might prove useful in copyright protection, Microsoft envisioned the dramatic advantages it might have for software delivery and installation.

Still other economists (e.g., Dranove and Gandal 2003) argue that software companies may balk at making software available for new hardware that has not yet taken off. In the early years of most new technologies, the benefits of the new technology are unclear to the software industry. Moreover, different standards may be fighting for dominance, generating even more uncertainty for the software industry. The future mass acceptance of the hardware and, thus, the future profitability of software for the new technology are highly uncertain. Faced with such uncertainty, software companies are unlikely to commit substantial resources to making software available for the new hardware, especially if it requires a high, up-front, lump-sum investment (Ducey and Fratrik 1989). Software providers may make such investments only after hardware sales have taken off and grow rapidly, thus signaling the viability of the new hardware.

At the same time, a critical mass of consumers who adopt the new hardware may develop before a sizable library of software is available; this may happen for several reasons. First, early adopters may like the "snob appeal" of owning new hardware (Tellis, Stremersch, and Yin 2003). Second, cascade effects may prompt consumers to buy new hardware because of their popularity among "opinion leaders" rather than their intrinsic utility (Golder and Tellis 2004). Third, early adopters may create their own content (e.g., i-mode, Internet [WWW], VCR) after buying the hardware.[4] Fourth, a "killer" application (a single software application of high quality and popularity) may be available, and as such, a sizable consumer segment "must own" the hardware, regardless of the sheer number of applications available (Frels, Shervani, and Srivastava 2003).

Other Effects

When indirect network effects are empirically examined, other considerations come into play as well on both the hardware and the software side. On the hardware side, it is

[4]We thank a reviewer for this insight.

also necessary to account for the price of the hardware and prior hardware sales.[5] Hardware price affects the affordability of the new technology, which may affect consumers' adoption of the hardware and, thus, future sales (Golder and Tellis 1998). Prior hardware sales may affect future hardware sales for several reasons. The most salient reason is probably social contagion, in that prior hardware adoptions influence future hardware adoptions through either learning under uncertainty or status considerations (Van den Bulte and Stremersch 2004). However, there can be several other reasons as well, such as market inertia.

On the software side, two variables may affect software availability. First, prior software availability may have an influence on future software availability, though the direction of the influence may be unclear a priori (Chou and Shy 1996; Church and Gandal 1992b). It may be positive because higher prior software availability is likely to increase the utility of the new hardware, increasing the future sales software that providers may expect and, consequently, encouraging them to make more software available (the "network" effect). It may also be negative because higher prior software availability yields more intense competition among software providers, decreasing the margins that software providers can make on their software and, consequently, discouraging them from making more software available (the "competition" effect). Second, software costs may affect software availability decisions by software providers. High costs involved in providing software for a new technology may discourage software provision by software companies.

Data

Data Collection

To collect data for this study, we conducted extensive archival research. The data collection took a great deal of time and effort because for each market, we needed data on hardware sales (and/or hardware installed base), software availability, and hardware prices from the time of introduction. As Table 1 shows, prior empirical research has most often examined the effect of software availability on hardware sales to test for demand-side indirect network effects and the effect of hardware installed base on software availability to test for supply-side indirect network effects. We attempted to obtain these variables rather than any other proxies, as some prior scholars have done (again, see Table 1).

We used the following procedure to obtain our data: First, we examined the published literature on consumer electronics (e.g., Ducey and Fratrik 1989; Golder and Tellis 1997). Second, we examined statistical yearbooks (e.g., *Broadcasting and Cable Yearbook*, *TV Factbook*, *Broadcasting Yearbook*, *International TV and Video Almanac*, *CD-ROM Directory*) in the libraries of two large U.S. research universities. Some of these sources are also available electronically but only for more recent years. Third, we contacted organizations directly to assess and access their data archives. Our search led us through approximately 30 public institutions and their libraries (e.g., the United Nations, the U.S. Federal Communications Commission, U.S. Senate Committees, recording and broadcasting associations, consumer electronics manufacturers' associations) and approximately 20 private companies, such as market research companies, media consultants, and manufacturers or software providers. For example, NPD, a leading research company for marketing and sales information, graciously provided us with hardware sales data and software availability data for Game Boy. In addition, we tried to combine different sources to check for consistency in the data series.

Characteristics of the Sample

For this study, we focused on consumer electronics because economic and marketing researchers claim that this class of products shows substantial indirect network effects (Church and Gandal 1993; Ducey and Fratrik 1989; Farrell et al. 1992; Gupta, Jain, and Sawhney 1999). Although we tried to gather data on all consumer electronics markets post–World War II, we were able to gather annual data on only the following nine network markets: black-and-white television, CD, CD-ROM, color television, DVD, Game Boy, i-mode, Internet (WWW), and laser disc. The markets we have data on vary widely from music to video entertainment and information and communications technology to broadcasting. These markets also have the feature of diversity in market structure, for example, in the number of manufacturers (from one, Nintendo, for Game Boy to many for television sets and Internet [WWW]) and in the amount of government involvement (from relatively high in television broadcasting to low in CD or DVD).

All data are from the United States, except for three markets: CD, laser disc, and i-mode. Data on CD and laser disc title availability were unavailable for the United States from their introduction (even after many consultations with the industry and leading publishers), but data were available for CDs in the United Kingdom (which is also a lead market in music) and for laser disc in Japan (which is a lead market in the most popular laser disc applications, such as Karaoke).[6] Data on i-mode were not available for the United States, but they were available for the lead market for i-mode, Japan.

The precise measures for all our variables and their sources appear in the Appendix. For some markets, we

[5]It could also be argued that software price affects consumers' utility and, thus, hardware sales. Although this argument is valid, in most cases, software prices are small (or even equal to zero, such as in broadcasting or Internet content) compared with hardware prices. Furthermore, in most cases, it is more difficult to obtain information on average software price than on average hardware price. Moreover, variation over time may be less in software price than in hardware price. The production of software is likely characterized by high up-front investments and low reproduction costs. Combined with intense competition, software prices are likely to be low (Shapiro and Varian 1998).

[6]For the CD market, the main problem with the U.S. data is that the number of CDs released by independent labels is unavailable, which is approximately one-third to one-quarter of the CD market.

derived hardware installed base from hardware sales by taking the cumulative sales, because data on the hardware installed base were unavailable. Such derivation assumes that there are no replacement sales, which is likely in many of our markets because we study the early diffusion process, in line with prior literature (Clements and Ohashi 2005; Dranove and Gandal 2003; Gandal, Kende, and Rob 2000; Hartman and Teece 1990; Nair, Chintagunta, and Dubé 2004; Shankar and Bayus 2003).

Our measures for software availability are consistent with measures that other scholars have used. For example, Nair, Chintagunta, and Dubé (2004) use the number of software titles available for different personal digital assistant platforms. Basu, Mazumdar, and Raj (2003), LeNagard-Assayag and Manceau (2001), and Gandal, Kende, and Rob (2000) use the number of available CD titles.

Our measures for hardware prices are the average prices across brands, again similar to prior literature (LeNagard-Assayag and Manceau 2001; Shankar and Bayus 2003). For three markets, our measure for price shows specific limitations. In the CD market, we were unable to obtain hardware prices from the United Kingdom. Because we assume that the U.K. market has undergone a similar CD player price pattern as the United States (e.g., because CD player brands are global players with global manufacturing capacity that determines their prices), we included the U.S. CD player price as a proxy. In the i-mode market, we included the average price of i-mode handsets; this does not include access fees, for which we could not obtain data. In the Internet (WWW) market, we included the average price of a (fax) modem because this is the hardware component, and we made abstraction of the average price of Internet access.

We display all our data graphically in the subsequent results section, in which we normalized the series by dividing the values by the maximum value in the series. This normalization enables better comparison and graphic conclusions while also retaining the confidentiality required to obtain some of the data.

Empirical Analysis

There are two ways the theoretical framework we presented can be empirically analyzed. First, the focus can be on the concept of takeoff, and the takeoff of hardware sales can be contrasted with the takeoff of software availability. Second, a time-series model based on the notion of Granger (1969) causality can be conceptualized. We apply both techniques and discuss each in turn. We end by relating our findings to the historical industry development, lending further credence to the pattern we found.

Takeoff Analysis

This section explores takeoff in indirect network effects markets. First, we derive the concept of takeoff and develop its usefulness in empirically examining the previously derived theory. Second, we present the measurement of takeoff, after which we discuss the findings.

Conceptual. Initially, sales of a new product are typically flat. After some time, a critical mass of adopters may develop, causing sales to show a distinct takeoff (Golder and Tellis 1997; Rohlfs 2001; Shapiro and Varian 1998).[7] The concept of critical mass has its roots in physics, in which it refers to the point of no return after which nuclear fusion becomes self-sustaining, and it has subsequently been adopted in sociology, in which it refers to the minimum level of activity needed to make an activity self-sustaining (Schelling 1978). Thus, new product takeoff is followed by rapid self-sustaining growth, in which additional consumers adopt the new technology until the market is saturated and sales show a decline (Golder and Tellis 2004). Hardware sales takeoff has been recognized as an important phenomenon in the marketing literature (Agarwal and Bayus 2002; Golder and Tellis 1997; Tellis, Stremersch, and Yin 2003).

Scholars have argued that the critical mass concept, and thus takeoff, is pronounced in markets that are strongly influenced by interdependence of players, as is the case in system markets (Andreozzi 2004; Granovetter 1978; Valente 1995). This fits the diffusion literature in marketing, which has found that diffusion curves are more pronouncedly S shaped in markets with competing standards (Van den Bulte 2000; Van den Bulte and Stremersch 2004).

In markets with direct network effects, the utility of the product to consumers depends on the number of prior adopters. Thus, the critical mass is a certain number of adopters (Katz and Shapiro 1986a). In markets with indirect network effects, there is interdependence between the utility an adopter derives from the system and the number of other adopters of the system because of the availability of complementary products (Katz and Shapiro 1986a; Srinivasan, Lilien, and Rangaswamy 2004). Thus, markets with indirect network effects exhibit critical mass not only in consumer adoption of hardware (i.e., the demand side) but also in the amount of available software (i.e., the supply side). Therefore, software availability may show a pattern similar to hardware sales. At first, software companies may balk at providing software because they doubt the viability of the new technology. After some time, a critical mass of software availability may develop, and software availability will show a distinct takeoff. Prior business analysts (e.g., Midgette 1997; Tam 2000; Yoder 1990; Ziegler 1994) and academics (e.g., Church and Gandal 1992b) have made reference to such phenomenon without examining it in depth.

In terms of the chicken-and-egg paradox, the takeoff in both hardware sales and software availability is an important event in indirect network effects markets. The order of takeoff of hardware sales and software availability may provide insight into the temporal pattern of indirect network effects. As we stipulated in our theoretical framework, prior theory is *ex ante* indeterminate as to what the temporal pattern may be, or in popular terms, What came first, the chicken or the egg? The empirical study of the temporal order in which takeoff of software availability and hardware sales occurs may provide a preliminary answer.

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[7]"Threshold" and "critical mass" are terms that are used interchangeably in the sociology and economics literature (Macy 1991; Witt 1997). For clarity, we consistently use the term "critical mass."

Measurement. Most prior research has identified takeoff using heuristics, such as the rules developed by Golder and Tellis (1997), Stremersch and Tellis (2004), and Tellis, Stremersch, and Yin (2003). For an exception, see Agarwal and Bayus (2002). The spirit of these rules was to call takeoff the first time hardware sales crossed a boundary growth percentage, after the base sales were taken into account (past sales, as in Golder and Tellis [1997], or penetration, as in Stremersch and Tellis [2004] and Tellis, Stremersch, and Yin [2003]). The reason is that growth of 400% is not that significant when it entails unit sales growth from 100 to 500 units, but it is significant when it entails unit sales growth from 50,000 to 250,000.

We face two issues in applying these rules to our data, which encompass hardware sales and software availability. First, there is no natural base against which to benchmark growth of software availability. For example, 10,000 i-mode sites may be high, whereas 10,000 Internet hosts may be extremely low. Second, we have no prior guidance on whether the growth percentages set forth by these prior studies actually make sense for software availability, because they were developed as heuristics for consumer durable sales.

We define takeoff of hardware sales as the year in which the ratio of change in the growth of sales relative to base sales reaches its maximum before the inflection point in hardware sales. To clarify, change in sales growth is akin to acceleration in sales and is equal to the second difference in sales. Thus, takeoff is the year in which the ratio of the second difference in hardware sales to hardware sales itself is at its maximum. Note that this rule is similar in spirit to the rule that Golder and Tellis (1997) provide in their Appendix. Analogously, we define takeoff in software availability as the year in which the ratio of change in the growth of software availability relative to base software availability reaches its maximum before the inflection point in software availability.

Prior studies on takeoff contain four of our nine series on hardware sales. Our identification of the year of takeoff is identical or at least similar to that of prior studies in three of the four cases: For CD player sales, it is identical to that of Tellis, Stremersch, and Yin (2003); for CD-ROM sales, it is identical to that of Golder and Tellis (1997); and for black-and-white television set sales, it is one year earlier than that of Golder and Tellis (1997). These results provide face validity to our method. For color television set sales, our identification of takeoff is six years earlier than that of Golder and Tellis (1997). These prior studies also find that takeoff identified through their heuristic coincided with that from visual inspection in more than 90% of the cases. In our case, the heuristic rule for takeoff matches visual inspection in all cases (see Figure 1).

Findings. Table 3 provides an overview of the takeoff in all markets, and Figure 1 displays them graphically. A comparison of Columns 4 and 7 of Table 3 with the arrows in Figure 1 shows that for five of the nine markets (black-and-white television, CD, i-mode, Internet [WWW], and laser disc), hardware sales take off before software availability does. For three of the nine markets (color television, DVD, and Game Boy), hardware sales take off at the same time as software availability does. For one of the nine markets (CD-ROM), hardware sales take off after software availability does. Columns 5 and 8 of Table 3 show the amount of available software when hardware sales took off and the level of hardware sales when software availability took off.

We conclude that for the nine markets we examined, hardware sales takeoff leads or coincides with software availability takeoff (except in the case of CD-ROM). Moreover, Table 3 shows that hardware sales can take off at low levels of software availability. For example, we find that sales of television sets took off with only seven stations on air. This level is low compared with the more than 1000 television stations today. It is also low compared with the 2000-plus radio stations in 1947 (the year of takeoff for black-and-white television sets). Color television took off with even remarkably less software (again, admittedly judgmental); namely, there were only 560 hours a year of broadcast in color for the entire United States.

However, the analysis of takeoffs provides only a limited picture on indirect network effects in these markets for several reasons. First, although we find a clear temporal pattern between takeoffs, it does not prove that indirect network effects actually exist in these markets. Second, caution must be used regarding the temporal pattern we find. As our research and prior research shows (e.g., Tellis, Stremersch, and Yin 2003), uncertainty of several years may surround the identification of takeoff. Thus, a difference of one year between the takeoff in hardware sales and the takeoff in software availability is statistically not very meaningful. Third, although drops in hardware prices seem to coincide with takeoff in hardware sales (similar to Golder and Tellis 1997), our takeoff analysis is a pure bivariate exercise into the temporal pattern of takeoffs. Given all these limitations, our takeoff analysis should be interpreted with caution. To address these limitations, we next develop a more sophisticated econometric time-series model to examine indirect network effects. This time-series analysis provides other benefits. It enables us to examine the temporal pattern of indirect network effects, while accounting for the entire history of a market rather than merely one point that is the takeoff. Furthermore, it enables us to include other variables that may affect hardware sales, such as prior hardware sales and hardware price.

Time-Series Analysis

This section develops a time-series analysis to examine indirect network effects and their temporal pattern. First, we conceptualize the modeling framework, after which we turn to the model specification. Second, we present the findings from estimating the model and discuss some additional analyses we conducted.

Conceptual. To examine the temporal pattern in indirect network effects empirically with aggregate-level secondary data, several considerations should guide the model specification. First, because we test the model on actual aggregate-level market data, we need to make some further simplifications to the theory. We do not have data on consumer utility, because such data can be obtained only through experiments, surveys, or panels. We also do not have data on the profits software companies expect. Such

FIGURE 1
Graphical Illustration of the Sample

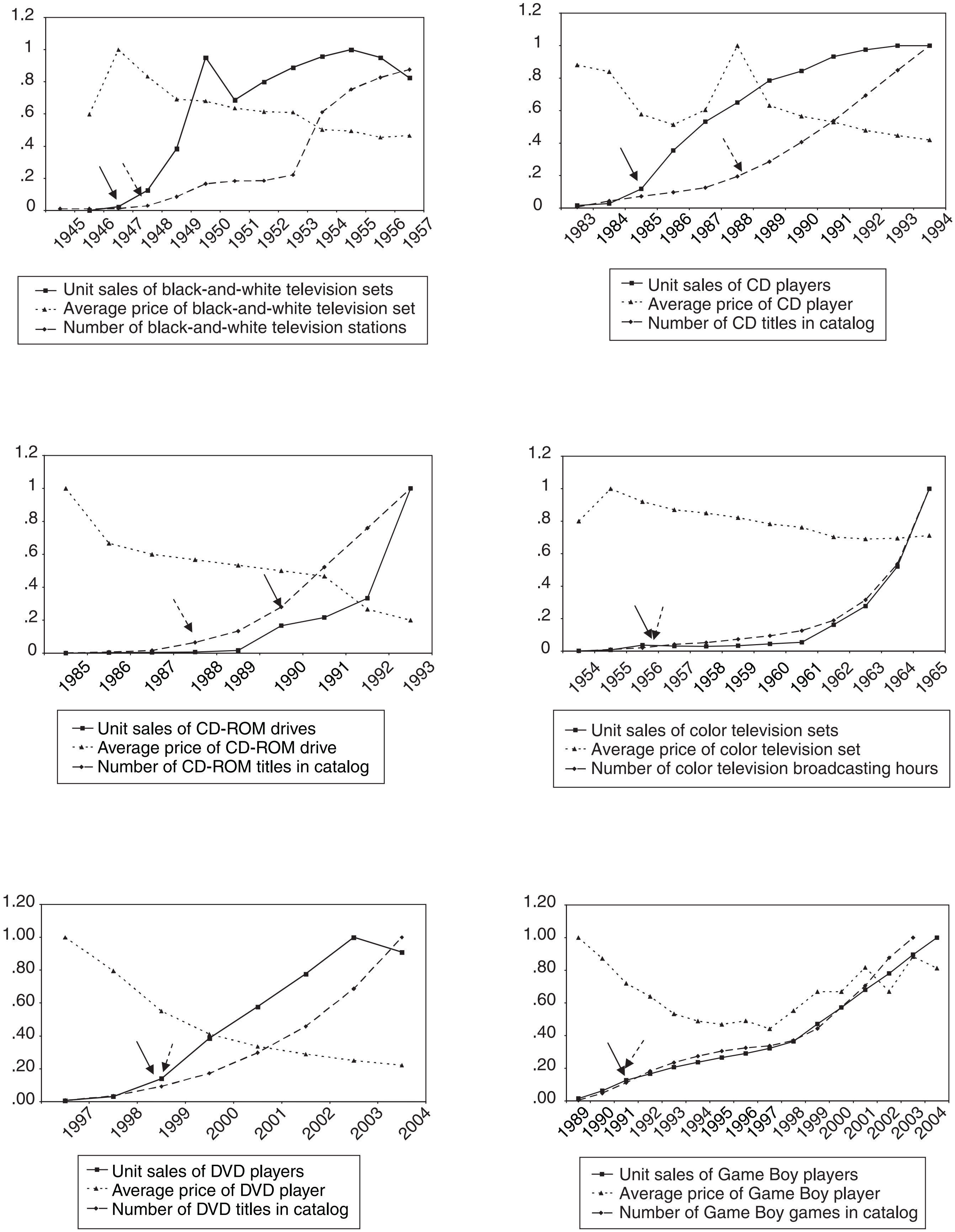
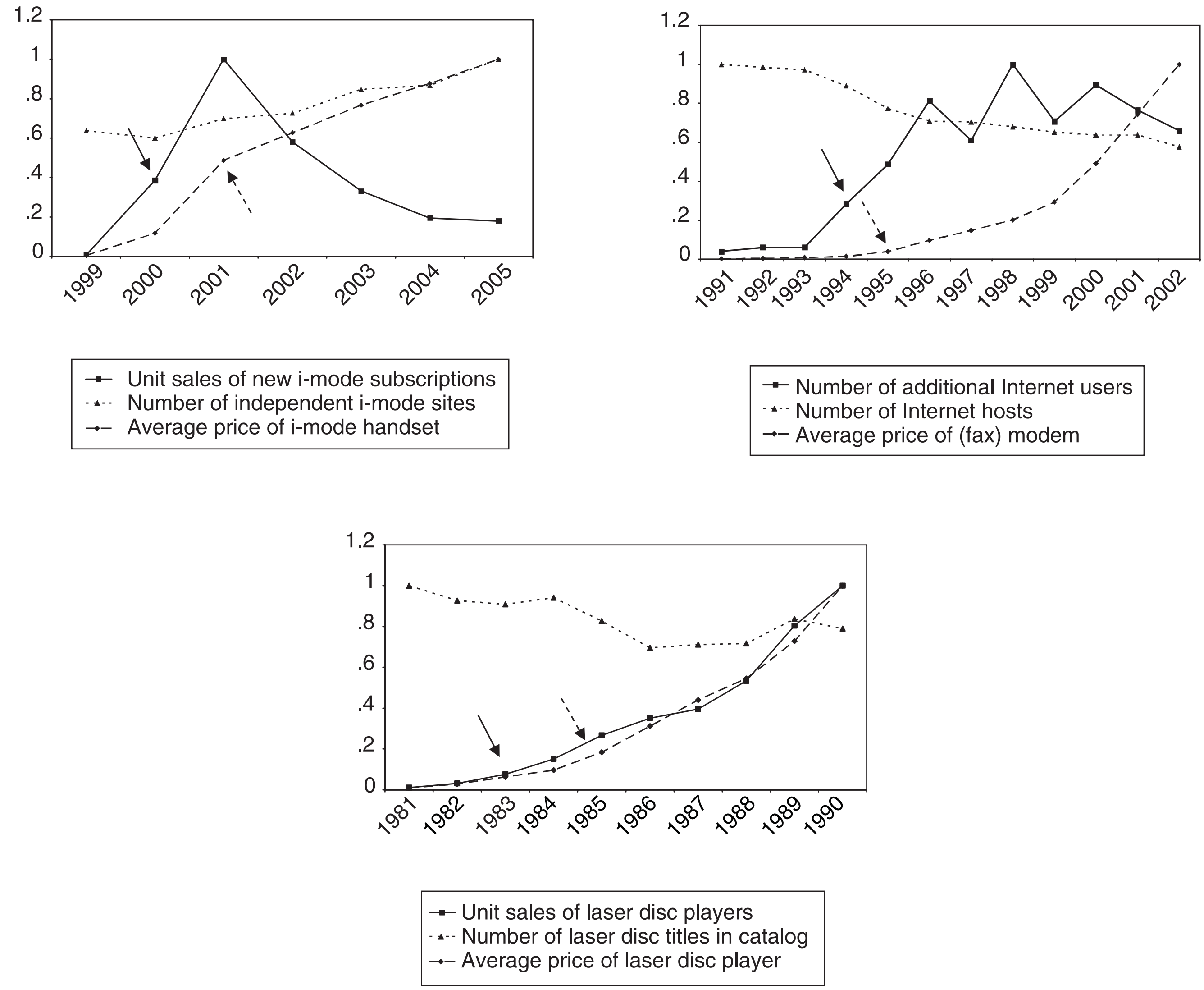


FIGURE 1
Continued



Notes: The full lines with squares indicate hardware unit sales. Dashed lines with diamonds indicate software availability. Dotted lines with triangles indicate the hardware price evolution. A full arrow indicates hardware sales takeoff. A dashed arrow indicates software availability takeoff.

data would be difficult to gather using any empirical methodology. Regarding price, there are often data on only the hardware price and not the software price. Software price is often complex, and thus it is difficult to obtain reliable software price information. However, it is often of minor importance, and its omission may not seriously compromise the conclusions of the model. We also do not have information on software costs, because it is proprietary to software firms. Thus, the ideal empirical model to examine the indirect network effects on secondary data reduces to the model in Figure 2. This model assumes, rather than tests, that the influence of software availability and hardware price on hardware sales occurs through consumers' utility considerations; it also assumes, rather than tests, that the influence of previous hardware installed base and software availability on future software availability occurs through software providers' profit considerations. In addition, it makes abstraction of both software costs and software prices.

Second, given our interest in the temporal pattern of indirect network effects, we refer to the notion of Granger (1969) causality. A process x_t is said to Granger cause a process y_t if future values of y_t can be better predicted using both the prior values of process x_t and process y_t than merely the prior values of the process y_t. In mathematical formulation, x_t does not Granger cause y_t if

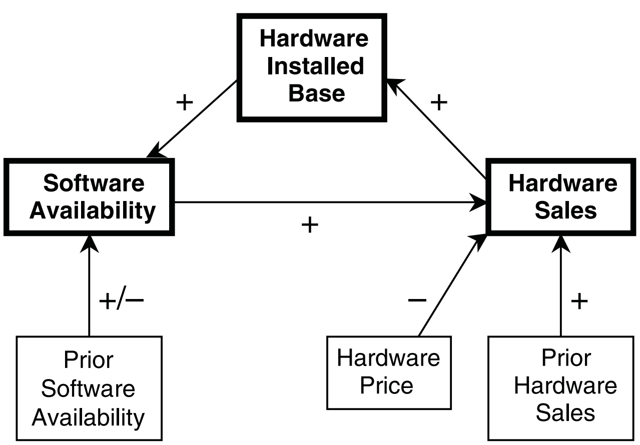
$$f(y_t | y_{t-1}, x_{t-1}) = f(y_t | y_{t-1}). \tag{1}$$

In such a case, lagged values of x_t do not add any information to the explanation of the movements in y_t beyond the

TABLE 3
Takeoff Analysis Results

		Hardware Sales			Software Availability		
Market	**Introduction Year**	**Takeoff Year**	**Time to Takeoff (in Years)**	**Software Availability at Hardware Sales Takeoff**	**Takeoff Year**	**Time to Takeoff (in Years)**	**Hardware Sales at Software Availability Takeoff**
Black-and-white television	1939	1947	8	7 stations on air	1948	9	970,000 unit sales
CD	1983	1985	2	5000 titles	1988	5	770,000 unit sales
CD-ROM	1985	1990	5	1522 titles	1988	3	20,000 unit sales
Color television	1954	1956	2	560 hours in color	1956	2	100,000 unit sales
DVD	1997	1999	2	3084 titles	1999	2	3,095,654 unit sales
Game Boy	1989	1991	2	156 games	1991	2	4.4 million unit sales
i-mode	1999	2000	1	10,000 sites	2001	2	23,039,000 subscribers
Internet (WWW)	1991	1994	3	2,217,000 hosts	1995	4	25 million subscribers
Laser disc	1981	1983	2	649 titles	1985	4	229,012 unit sales

FIGURE 2
Graphical Overview of Empirical Model



prior value y_t itself. The principle of Granger causality rests on the extent to which a process x_t leads a process y_t. To include this notion of Granger causality in our model specification, we lag all independent variables in our models.

Third, nonlinearities may be expected (see Figure 1). Therefore, we should use a log-transformation to linearize the model in most, if not all, cases.

Fourth, our model is a growth model, and thus, as time passes, the processes we study might be expected to approach a certain maximum value (Franses 1998). For this reason, our model also needs to capture a nonlinear trend, which we can easily obtain by including a linear trend in log-transformed data. Prior network effects models also include a trend (e.g., Basu, Mazumdar, and Raj 2003; Gandal 1994; Shy 2001). Next, we formally specify our model on the basis of these considerations.

Model. We specify the following model:

$$\log(S_t^H) = \alpha + \beta \times \log(S_{t-1}^H) + \gamma \times \log(A_{t-1}^S) + \rho \times \log(P_{t-1}^H) + \delta \times t + \varepsilon_t, \text{ and} \tag{2}$$

$$\log(A_t^S) = \upsilon + \lambda \times \log(A_{t-1}^S) + \eta \times \log(IB_{t-1}^H) + \tau \times t + \zeta_t, \tag{3}$$

in which S_t^H is hardware sales at time t, A_t^S is software availability at time t, P_t^H is price of the hardware at time t, IB_t^H is hardware installed base at time t, α and υ are intercepts, and δ and τ capture the time trend. This model specification is a flexible time-series model, which we estimate for each market separately, using seemingly unrelated regression.

Findings. Table 4 shows the results from estimating Equations 2 and 3. The fit statistics for all models are satisfactory. The adjusted R-square ranges from .75 to .99. The models also seem to behave well because there is only one effect that seems implausible—namely, the negative coefficient for prior software availability on future hardware sales in the Game Boy market.

Theoretically, the most notable result is that we find that prior hardware installed base significantly and positively affects (or "leads" in Granger terminology) future software availability in five of the nine markets we examined: black-and-white television, CD, Game Boy, Internet (WWW), and laser disc. Only one of these markets shows the presence of both demand- and supply-side indirect network effects: CD. None of the markets we study show only demand-side indi-

TABLE 4
Time-Series Analysis Results

	Black-and-White Television		CD		CD-ROM		Color Television		DVD	
	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$
Intercept	13.38***	–.71	1.40**	6.15***	3.10	1.41	–7.92	4.41***	–2.69	4.57***
	(4.05)	(.62)	(.57)	(.38)	(10.21)	(1.62)	(13.18)	(1.00)	(14.89)	(.42)
Time	.00	.17*	–.24***	.23***	.97	–.13	.51**	.19***	–.19	.19***
	(.07)	(.09)	(.02)	(.02)	(.58)	(.35)	(.20)	(.06)	(.31)	(.04)
$\log(S_{t-1}^H)$	.69***		.51***		–.09		.54*		.58	
	(.11)		(.03)		(.11)		(.28)		(.44)	
$\log(A_{t-1}^S)$	–.39	.15	.77***	.08	.13	.95***	–.87	–.07	.83	.38*
	(.32)	(.24)	(.05)	(.07)	(.65)	(.25)	(.60)	(.40)	(.47)	(.18)
$\log(IB_{t-1}^H)$		.22***		.09*		.03		.14		.01
		(.07)		(.05)		(.25)		(.19)		(.10)
$\log(P_{t-1}^H)$	–1.28		–.04		.54		2.69		.72	
	(.87)		(.08)		(1.37)		(2.38)		(1.88)	
Adjusted R-square	.96	.95	.99	.99	.91	.96	.91	.92	.99	.99
Number of observations	11	11	11	11	8	8	11	11	7	7

	Game Boy		i-mode		Internet (WWW)		Laser Disc	
	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$	$\log(S_t^H)$	$\log(A_t^S)$
Intercept	7.04***	–10.65*	51.54	1.60***	–60.16	–.43	–4.69	.33
	(1.88)	(5.13)	(46.25)	(.22)	(50.58)	(1.92)	(4.90)	(.69)
Time	.13***	.02	–.30	.01	–.36	.17	.03	.13***
	(.03)	(.03)	(1.70)	(.01)	(.48)	(.11)	(.05)	(.03)
$\log(S_{t-1}^H)$	.66**		–.25		.86*		.47*	
	(.26)		(2.08)		(.48)		(.23)	
$\log(A_{t-1}^S)$	–.42**	–.32	3.95	.74	1.34	–.04	.30	–.28
	(.18)	(.24)	(20.99)	(.69)	(1.25)	(.41)	(.30)	(.25)
$\log(IB_{t-1}^H)$		1.11**		–.06		.96**		.70***
		(.41)		(.09)		(.36)		(.19)
$\log(P_{t-1}^H)$	–.13		–4.11		8.57		.75	
	(.61)		(4.21)		(6.94)		(.43)	
Adjusted R-square	.77	.99	.82	.98	.75	.99	.99	.99
Number of observations	15	15	6	6	11	11	9	9

*$p < .10$ (two-sided tests).
**$p < .05$ (two-sided tests).
***$p < .01$ (two-sided tests).

rect network effects. This result also allows us to conclude that on the basis of the operationalization of indirect network effects commonly used in the literature and applied in our model through the quantity of available software, demand- and supply-side indirect network effects are less pervasive in the markets we examined than is commonly assumed. We graphically represent our results in Figure 3.

These results are consistent with our prior findings on takeoff. Of the five markets in which we found supply-side indirect network effects (again in Granger's terminology, in which hardware installed base leads software availability), four (black-and-white television, CD, Internet [WWW], and laser disc) show an earlier takeoff of hardware sales than of software availability. Conversely, in markets in which the time-series analysis did not show evidence of indirect network effects, the pattern is diverse; the takeoff of hardware sales of CD-ROM lagged the takeoff of CD-ROM software availability, the takeoff of hardware sales and the takeoff of software availability coincided in the cases of color television and DVD, and the takeoff of hardware sales preceded the takeoff in software availability in the case of i-mode.

We next discuss the effects of the other variables we included. As would be expected, many of our markets (black-and-white television, CD, color television, Game Boy, Internet [WWW], and laser disc) show a positive influence of prior hardware sales on future hardware sales, either because of contagion or other effects, such as inertia. Contrary to what would be expected, hardware price does not play a major role in hardware sales growth. However, prior research has presented similar findings (Bayus, Kang, and Agarwal 2007). The explanation for these results may be that in many of the markets we study, hardware price is typically not prohibitive. The average hardware price at introduction for the markets we study was \$570. When more expensive devices are considered, the impact of price will likely be more pronounced. Finally, we find that in two markets (CD-ROM and DVD), the effect of prior software availability on future software availability is positive and

FIGURE 3
Indirect Network Effects in Nine Markets

Supply-Side Indirect Network Effects	Demand-Side Indirect Network Effects: No	Demand-Side Indirect Network Effects: Yes
Yes	Black-and-white television Game Boy Internet Laser disc	CD
No	CD-ROM Color television DVD i-mode	

significant, consistent with the network effect hypothesis. In the other markets, the coefficient is not significant, because prior software availability does not affect future software availability, because prior software availability affects future software availability both positively (the network effect) and negatively (the competition effect), or because prior software availability affects future software availability in a much more complex pattern than we modeled.

Further analyses. We conducted several other analyses to examine how changes to the model might affect our conclusions. First, it could be claimed that it would be better to work in first differences. However, econometric theory cannot offer clarity as to whether this approach is appropriate in our case, because conducting unit root tests is not informative given the limited number of data points (Elliott, Rothenberg, and Stock 1996; Franses 1998). The estimates for the lagged terms of the models in Equations 2 and 3 (see Table 4) indicate that differencing may be inappropriate. The reason is that these estimates are far from 1, whereas differencing would impose these parameters to be equal to 1. Prior authors in the indirect network effects literature typically do not difference either, with the exception of Gandal, Kende, and Rob (2000), who use it to check the robustness of their model. Nonetheless, we decided to conduct these analyses and compare the estimates with our own from estimating the model in Equations 2 and 3.

Our findings were as follows: First, we found weaker (nonsignificant or negative) evidence of indirect network effects for supply-side indirect network effects in the cases of black-and-white television and Internet (WWW) and for demand-side indirect network effects in the case of the CD player. We found stronger evidence of indirect network effects for supply-side indirect network effects in the case of color television and for demand-side indirect network effects in the case of CD-ROM. Second, we found many effects to be implausible. We found one additional case (CD) in which indirect network effects were negative and two cases (CD-ROM and Internet [WWW]) in which prior hardware sales growth had a negative effect on future hardware sales growth. These findings hint that working in first differences is inappropriate.

Second, we conducted many checks common in time-series analysis. Because Franses (2005) would categorize our model as a descriptive model, we focused our diagnostic tests on residual autocorrelation, heteroskedasticity, and omitted variables. These tests revealed relatively few problems, considering the complexity of our model and the small number of observations. Thus, none of these tests revealed a need for revisions to our model specification.

Historical Industry Analysis

CD. We found strong demand- and supply-side indirect network effects in the CD market. This market has also been empirically examined the most. Our findings are in line with prior findings. LeNagard-Assayag and Manceau (2001) find that software availability has a positive, significant effect on consumers' utility, and the hardware installed base has a positive, significant effect on software availability. Basu, Mazumdar, and Raj (2003) find that software availability has a positive, significant effect on hardware prices. Gandal, Kende, and Rob (2000) find that software availability has a positive, significant effect on hardware sales and that hardware sales have a positive, *non*significant effect on software availability.

Black-and-white television. In both the takeoff and the time-series analyses, we found that in this market, hardware leads software. The reason for these effects may lie in the massive investments that were involved in starting a television station. It required large outside revenue during the initial years of massive losses. Therefore, many of the early stations were owned by television set manufacturers (e.g., General Electric, RCA). The revenues they used to sponsor these early television stations were generated by the sales of television sets (Sterling and Kittross 2002). Therefore, the positive, significant effect of hardware installed base on software availability need not come as a surprise. Conversely, the sales of television sets were not affected much by the quantity of software available (as our time-series analysis shows) but rather by the technological appeal of television. Television was such a revolutionary new product that families gave their new television set a dominant location in their living room, and for the first couple of weeks, all members of the family marveled at the phenomenon (Sterling and Kittross 2002).

Game Boy. We found that in the Game Boy market, hardware leads—though the takeoff analysis shows simultaneous takeoffs in hardware sales and software availability, and the time-series analysis shows that prior hardware installed base positively affects future software availability—and positively affects software availability. Independent software providers respond strongly to the adoption of hardware (Nair, Chintagunta, and Dubé 2004), as was the case with Game Boy. Therefore, our finding that the availability of Game Boy games grew as more consumers adopted the Game Boy seems logical. However, why did consumers not react to a growing catalog of Game Boy games? The answer: Tetris. Tetris is considered a killer application for the Game Boy (Allen 2003; Rowe 1999). Tens of millions of copies of Tetris have been sold since it was introduced simultaneously with the introduction of the Game Boy. It was often bundled with the Game Boy hardware itself. Thus, rather than the evolution in the full catalog of titles available for Game Boy, the availability of one game, Tetris, fueled the Game Boy growth.

Internet (WWW). In both the takeoff and the time-series analyses, we found that in the Internet (WWW) market, hardware leads software. Again, these findings seem logical when the industry evolution is considered. Internet users can easily become a software provider by the provision of online content (e.g., Web pages). Therefore, a growing installed base of users also automatically leads to a growing base of software providers and, thus, to more Internet hosts (e.g., Web servers providing Web pages). Conversely, why do we not find that Internet content stimulates growth in Internet (WWW) adoption? In the first year, the WWW already had 80,000 hosts that provided millions of Web pages to consumers, more than a single human can possibly read in a lifetime. Furthermore, people used the Internet for other types of communication. E-mail predated the birth of the WWW and was already an important application at the start of the WWW.

Laser disc. In both the takeoff and the time-series analyses, we found that in the laser disc market, hardware leads software. The reason may be similar to the history of the black-and-white television. The most important provider of laser disc titles was the leading manufacturer of laser disc players (Pioneer) because laser disc publishing entailed a substantial start-up investment (McClure 1992, 1993a, b; McGowan 1994). Pioneer used hardware sales as a measure for how strong or weak the laser disc market was, and accordingly, it released a fitting number of titles on laser disc. Therefore, we find that prior hardware installed base positively affects future software availability. Conversely, the number of titles available does not affect future hardware sales. This is likely because most laser disc titles released in the 1980s (the period we study) were not very different from their VHS counterpart, lacking digital sound, widescreen, and "extras" (Dick 1990). The provision of such titles did not provide would-be laser disc owners with an opportunity to exploit laser disc players to their fullest potential. Thus, it gave would-be consumers little reason to purchase a laser disc player. Until 1993, laser disc titles could only be bought and could not be rented (McClure 1993a), which also made consumers less likely to react to an increase in title availability.

CD-ROM. We found no evidence of a significant relationship between software availability and hardware sales in the CD-ROM market. We also found that it is the only market in which software availability takes off before hardware sales take off. These findings are in line with the historical development of the CD-ROM market. The early support of Microsoft for the CD-ROM is well known, and the outcry of Bill Gates—"I have no idea what the future will bring for the CD-ROM, but I am willing to invest $1 billion just to find out!"—is notorious. Microsoft also hosted the first CD-ROM conferences and developed networks with other content and software providers to write for the CD-ROM medium. Microsoft did all this before a substantial hardware installed base developed. Conversely, the evolution in hardware sales has been independent from that of software availability, probably because of technological compatibility issues. The first multimedia personal computer specifications were announced at the start of the 1990s—CD-ROM was introduced in 1985—which also set a standard for connecting CD-ROM drives to IBM-compatible personal computers. This eased customers' fears about incompatibility. After years of anticipation, the CD-ROM was finally making its way into homes (Alpert 1992).

Color television. We found no evidence of a significant relationship between software availability and hardware sales in the color television market. There may be two major reasons for this result. First, during the first ten years of color broadcasting, NBC was the only vivid supporter of color broadcasting among the major networks. In 1961, CBS and ABC provided their viewers with zero hours of color broadcasting (Ducey and Fratrik 1989). In 1964, NBC still delivered 95% of all color broadcasting (Ducey and Fratrik 1989). Because NBC was the only supporter among the main national broadcasters, expansion in color broadcasting (by NBC alone) may not have had a major effect on consumers. Second, networks needed to invest a massive $30–$40 million (1960 dollars) to purchase the required color equipment, which still excluded additional investments in new graphics, costumes, sets, and so on, that were needed as well when going color (Sterling and Kittross 2002). Conversely, broadcasters did not perceive a major upside of color television that would match this massive investment. Broadcasters, such as ABC and CBS, did not expect it to expand the installed base of viewers or to increase the number of hours viewers watched television. Therefore, there was little incentive to react to growing color television set sales, with increasing color broadcasting, even more as the technology was backward compatible with black-and-white broadcasting. It was only when the majority of advertising was recorded in color that broadcasters began to invest in color broadcasting equipment (Sterling and Kittross 2002).

DVD. For DVD, we found no evidence of a significant relationship between software availability and hardware sales. In addition, Dranove and Gandal (2003) examined the DVD market empirically. They used two proxies for software availability in the DVD market: (1) when a particular studio committed to releasing movies on DVD and (2) the percentage of U.S. box-office top 100 movies released on DVD. Only one (percentage of U.S. box-office top 100 films released on DVD) of the two proxies had a positive, significant effect on hardware sales. Thus, the reason we do not find significant demand-side indirect network effects may be because of the killer application phenomenon we cited previously in our discussion of the Game Boy history. Consumers may care only about the top titles and the format on which they appear rather than the entire catalog of movies supporting a format. The reason we do not find supply-side indirect network effects may be due to the immense and early support the DVD technology received from the movie studios (Gandal 2002). Within 18 months after the introduction of the DVD format, all the major movie studios had adopted the DVD format (Dranove and Gandal 2003), and therefore additional hardware sales no longer had any impact on the major movie studios' decisions to adopt the new DVD technology, making the supply of software largely independent of hardware sales.

i-mode. For i-mode, we do not find any demand- or supply-side indirect network effects. NTT DoCoMo, the parent of i-mode, positioned i-mode essentially as an extension of preexisting mobile phone services (Ratliff 2002); this may well have contributed to the finding that consumers do not seem to react to increases in the availability of i-mode services. New hardware characteristics, such as a built-in camera and i-mode's "always-on" feature, may have been the main drivers behind hardware sales rather than the total number of i-mode sites. i-mode uses C-HTML (compact hypertext markup language), a form of HTML with a reduced instruction set, which eases the transition for content providers from their already existing HTML Web sites to i-mode-ready content (Ratliff 2002). This low barrier to entry makes it easy and relatively profitable for content providers to render their services on i-mode handsets. With the required up-front investment to provide i-mode services being so small, service providers need only a small number of i-mode users to turn a profit. This may make their decision to provide i-mode services largely independent of consumers' hardware adoption.

Discussion

Summary of Findings

This study has two main findings. First, we find that indirect network effects as commonly operationalized are less pervasive in the examined markets than expected on the basis of prior literature. This finding contrasts sharply with the "current wisdom" that the amount of available software is of critical importance to hardware sales growth (e.g., Church and Gandal 1992b; Gupta, Jain, and Sawhney 1999; Katz and Shapiro 1986a, 1994).

Second, in most of the markets we examined, hardware sales lead software availability, whereas the reverse almost never happens. These findings illuminate the temporal pattern of indirect network effects, underlying the chicken-and-egg paradox, which has never been empirically examined. They contradict the widely held view that software availability should lead hardware sales (Bayus 1987; Bucklin and Sengupta 1993; Clements 2004; Frels, Shervani, and Srivastava 2003; Midgette 1997; Sengupta 1998; Tam 2000; Yoder 1990; Ziegler 1994).

Although there may be many reasons underlying our results, including sampling issues and method artifacts, given the variation in the markets we examined and the consistency of our findings across methods (takeoff, time series, and historical case detail), the most credible is that a considerable segment of consumers makes decisions to buy hardware relatively independently of the quantity of software available. Thus, a critical mass of hardware adopters may gather before a critical mass of software titles is available. A probable reason may be the snob appeal of owning new hardware (Tellis, Stremersch, and Yin 2003). Other reasons may be cascade effects that prompt consumers to buy new hardware because of its popularity rather than its intrinsic utility (Golder and Tellis 2004) or because users can create their own content after buying the hardware. It may also be that a killer application is available, which impels a sizable consumer segment to own the hardware regardless of the sheer number of applications available (Frels, Shervani, and Srivastava 2003; Williams 2002).

Implications

To firms, the most important implication is that hardware manufacturers should not overstate the importance of software quantity. Rather, hardware manufacturers should take their fate into their own hands and produce high-quality technology with a few (not necessarily many) exciting applications rather than aiming for wide availability of a huge library of software. For example, our results contradict previous calls for hardware manufacturers to pay a lot (in the form of kickbacks and subsidies) to get software companies to provide a huge library of titles.

In terms of public policy, our study is relevant to government intervention in indirect network effects markets. Often, governments or public institutions are under pressure to intervene in indirect network effects markets to improve coordination between hardware and software companies. Critics claim that the lack of coordination, especially in terms of availability of software, can slow down the takeoff of the new technology. This claim is difficult to maintain in view of our findings. In contrast, we find that in many markets, hardware sales take off before software availability does and, in some markets, at limited quantities of available software. In our time-series analysis, we also found that hardware sales mostly lead software availability rather than software availability leading hardware installed base. Therefore, an important argument for government intervention fades. Conversely, if intervention were necessary, it might take the form of subsidizing the cost of new hardware. Although such subsidies may not be reasonable for entertainment products, they might be appealing for products with social benefits, such as electric or hydrogen-powered cars.

For academics, the weak evidence we found using traditional operationalizations of indirect network effects and based on a long tradition in economics (Church and Gandal 1992a, b; Gandal, Kende, and Rob 2000) fits into new conceptualizations of indirect network effects that may prove more powerful. A first conceptualization is to examine software quality rather than quantity. Our case detail illustrates that in some cases (e.g., Tetris in the case of Game Boy), quantity does not matter, but the presence of killer applications does. There is little scholarly research that examines the role of killer applications, though the phenomenon is deemed to be important, especially in certain industries, such as the video game console market. A second conceptualization may revolve around the notion that network effects may be more restricted in scope than previously assumed (Tucker 2006). As such, the entire catalog of software may not be relevant to consumers, but only a small selection of it may be (e.g., a genre). A third conceptualization may revolve around the notion of thresholds. Software availability may need to cross a threshold at introduction to make the technology credible. Research that extends indirect network effects in these directions may be impactful.

Limitations

This article examines a complex phenomenon in an area in which data are scarce. It is easy to point to its limitations, which we hope further research will address. First, because of data limitations, we could not include other important explanatory variables, such as software price, software costs, or software and hardware entry, nor could we address possible threshold effects (see also Bayus 1987). We were also unable to test the underlying theoretical mechanisms of our model, such as consumers' utility considerations and software providers' profitability considerations.

Second, we study only nine network markets. Although this is a relatively small sample, it compares favorably with prior studies in this area that examine only one or two markets.

Third, we study only surviving technologies. Further research that studies the role of indirect network effects in new technology failure would be worthwhile.

Fourth, we focused on countries that can be considered lead countries in the given technology. It would be worthwhile to examine whether uncertainty from indirect network effects is lower in lag countries than in lead countries. Research that focuses on indirect network effects in an international setting would be most fruitful.

Fifth, the role of consumer expectations is of great importance in indirect network effects markets. However, we do not include it in our model because of data limitations. Incorporating consumer expectations in future models might provide new insights.

APPENDIX
Detailed Overview of the Data

Network Market	Series	Operationalization	Period	Country	Data Source
Black-and-white television	Hardware sales	Retail unit sales of black-and-white television sets to consumers	1946–1957	United States	*The Broadcasting Yearbook*
	Hardware installed base	Cumulative retail unit sales of black-and-white television sets to consumers	1946–1957	United States	Own derivation
	Hardware price	Average price of black-and-white television set	1946–1957	United States	eBrain Market Research
	Software availability	Number of television stations on air	1945–1957	United States	*The Broadcasting Yearbook* and Federal Communications Commission
CD	Hardware sales	Retail unit sales of CD players to consumers	1983–1994	United Kingdom	Philips Consumer Electronics
	Hardware installed base	Cumulative retail unit sales of CD players to consumers	1983–1994	United Kingdom	Own derivation
	Hardware price	Average price of CD player	1983–1994	United States	eBrain Market Research
	Software availability	Number of CD titles in catalog	1983–1994	United Kingdom	The British Phonographic Industry Ltd.
CD-ROM	Hardware sales	Retail unit sales of CD-ROM drives to consumers	1985–1993	United States	Peter Golder
	Hardware installed base	Cumulative retail unit sales of CD-ROM drives to consumers	1985–1993	United States	Own derivation
	Hardware price	Average price of CD-ROM drive	1985–1993	United States	Peter Golder
	Software availability	Number of CD-ROM titles in catalog	1985–1993	United States	*CD-ROM Directory*
Color television	Hardware sales	Retail unit sales of color television sets to consumers	1954–1965	United States	Consumer Electronics Association
	Hardware installed base	Cumulative retail unit sales of color television sets to consumers	1954–1965	United States	Own derivation
	Hardware Price	Average price of color television set	1954–1965	United States	eBrain Market Research
	Software availability	Number of hours broadcasted in color (all stations)	1954–1965	United States	Ducey and Fratrik (1989)
DVD	Hardware sales	Number of DVD players shipped to dealers	1997–2004	United States	Consumer Electronics Association
	Hardware installed base	Cumulative number of DVD players shipped to dealers	1997–2004	United States	Own derivation
	Hardware price	Average price of DVD player	1997–2004	United States	eBrain Market Research
	Software availability	Number of DVD titles in catalog	1997–2004	United States	http://www.hometheaterinfo.com/
Game Boy	Hardware sales	Retail unit sales of Game Boy to consumers	1989–2004	United States	NPD
	Hardware installed base	Cumulative retail unit sales of Game Boy to consumers	1989–2004	United States	Own derivation
	Hardware price	Average price of Game Boy player	1989–2002	United States	NPD and Nintendo
	Software availability	Number of Game Boy games available to consumers	1989–2003	United States	Nintendo

APPENDIX
Continued

Network Market	Series	Operationalization	Period	Country	Data Source
i-mode[a]	Hardware sales	Number of new i-mode subscribers	1999–2005	Japan	Own derivation
	Hardware installed base	Total number of i-mode subscribers	1999–2005	Japan	NTT DoCoMo
	Hardware price	Average price of advertised i-mode handset	1999–2005	Japan	Ascii24.com
	Software availability	Number of independent i-mode sites	1999–2005	Japan	OH!NEW i-search (www.ohnew.co.jp)
Internet (WWW)	Hardware sales	Number of additional Internet (WWW) users	1991–2002	United States	Own derivation
	Hardware installed base	Total number of Internet (WWW) users	1991–2002	United States	Internet Software Consortium
	Hardware price	Average price of (fax) modem	1991–2002	United States	eBrain Market Research
	Software availability	Number of Internet (WWW) hosts	1991–2003	United States	International Telecommunication Union
Laser disc	Hardware sales	Number of laser disc players shipped to dealers	1981–1990	Japan	Philips Consumer Electronics
	Hardware installed base	Cumulative number of laser disc players shipped to dealers	1981–1990	Japan	Own derivation
	Hardware price	Average manufacturer suggested retail price of released laser disc player in year t	1981–1990	Japan	Various sources
	Software availability	Number of laser disc titles in catalog	1981–1990	Japan	Philips Consumer Electronics

[a]i-mode is a high-speed mobile Internet service (2.5G) introduced first in Japan by NTT DoCoMo.

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