Complementarities in the Diffusion of Personal Computers and the Internet: Implications for the Global Digital Divide

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This paper studies the cross-country diffusion of personal computers (PCs) and the Internet, and examines how the diffusive interactions across these technologies affect the evolution of the global digital divide. We adopt a generalized diffusion model that incorporates the impact of one technology's installed base on the diffusion of the other technology. We estimate the model on data from 26 developing and developed countries between 1991 and 2005. We find that the codiffusion effects between PCs and the Internet are complementary in nature and the impact of PCs on Internet diffusion is substantially stronger in developing countries as compared to developed ones. Furthermore, our results suggest that these codiffusive effects are a significant driver of the narrowing of the digital divide. We also examine the policy implications of our results, especially with respect to how complementarities in the diffusion of PC and Internet technologies might be harnessed to further accelerate the narrowing of the global digital divide.

Key words: IT penetration; IT diffusion; digital divide; global IT; diffusion model; codiffusion
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1. Introduction

There is considerable research interest in the cross-country diffusion of information technologies (see e.g., Dekimpe et al. 2000, Oxley and Yeung 2001, Quibria et al. 2003, Chinn and Fairlie 2006), motivated in part by the substantive issue of the global digital divide.[1] This research has identified a variety of factors, including country wealth, education levels, telecommunications infrastructure, and regulatory quality, that explain the existence or *widening* of the divide between developed and developing countries. In contrast to this prior work, we focus on a factor that we believe contributes to the *narrowing* of the global digital divide, which is the complementarity in the diffusion of focal information technologies. Specifically, we look at the diffusive interactions in the adoption of personal computers (PC) and the Internet, and address the following research questions: What is the nature of the global diffusion processes for PCs and the Internet, and how do the processes differ between developed and developing countries? What is the nature of the complementary interaction in the diffusion processes of PCs and the Internet? How will this interaction affect the future evolution of the digital divide, and what are some policy implications?

Given these questions, the innovation diffusion literature provides a natural theoretical framework for

[1] See Dewan and Riggins (2005) for a recent survey of current and future research directions pertaining to the digital divide.

our research. Although there is considerable prior work on the diffusion of IT innovations (see, e.g., Rai et al. 1998, Teng et al. 2002), we are not aware of research that has specifically examined the global cross-country diffusion of PCs and the Internet using a social contagion framework (Bass 1969) that incorporates complementarities in the diffusion of the two technologies.[2] Thus, in this research we develop a comprehensive framework for empirically examining the innovation, imitation, and codiffusive effects in the cross-country diffusion of PCs and the Internet, and examine the implications of our results for the future evolution of the digital divide.

With respect to the motivation for studying codiffusion of these technologies, Rogers (2003) recognizes the importance of understanding interactions across innovations, noting that "past diffusion research generally investigated each innovation as if it were independent from other innovations (p. 15)." He further observes that "in reality, the innovations diffusing at about the same time in a system are interdependent. While it is much simpler for diffusion scholars to investigate the spread of each innovation as an independent event, this is a distortion of reality. More scholarly attention should be paid to technology clusters." Motivated in part by this call for action, we examine the effects of cross-technology interactions between PCs and the Internet on the digital divide, by building on prior research on codiffusive interactions (Bucklin and Sengupta 1993, Kim et al. 2000, Mahajan and Muller 1996, Mahajan and Peterson 1978, Norton and Bass 1987, among others).

We find it useful to frame our theoretical development around basic elements from network economics, because network effects are a key economic force shaping the adoption of both PCs and the Internet. Indeed, the diffusion of these technologies is likely to be driven more by imitation or internal influence than by innovation or external influence, similar to the findings of Teng et al. (2002), who analyzed the diffusion of

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[2] An exception is Ladron et al. (2007), which also examines complementarities in the country-level diffusion of PCs and the Internet, but the analysis does not speak to the digital divide because the data is restricted to only the Organization for Economic Cooperation and Development (OECD) countries. We thank the senior editor for bringing this working paper to our attention in her acceptance letter.

Figure 1   Network Economics Framework for Diffusive Effects
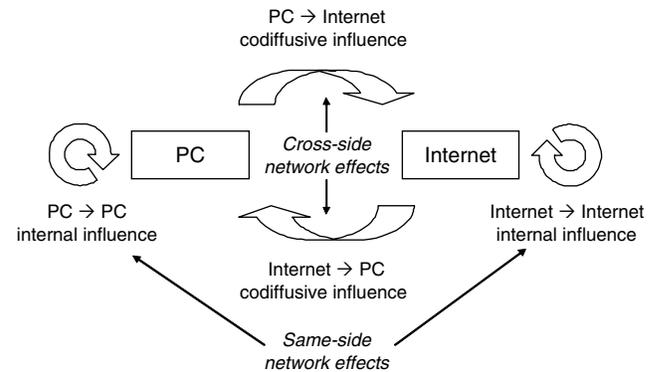
a broad set of IT innovations in a sample of large U.S. firms.[3] In our case, the network effects underlying the diffusion of PCs and the Internet are a function of the installed base of the same technology *and* the other complementary technology. As illustrated in Figure 1, there are two types of network effects, which we call "same-side" and "cross-side," borrowing terminology from the growing literature on two-sided network markets (see, e.g., Rochet and Tirole 2003, Parker and Van Alstyne 2005). The same-side and cross-side network effects represent the influence of the installed base of the same and other technology, respectively, and they characterize the imitation and codiffusion effects in the diffusion theory framework, respectively, as we discuss in §3.1.

We analyze data from 26 developed and developing countries over the period 1991–2005 and generate a number of interesting results. We find that imitation effects are stronger for Internet as compared to PC diffusion, and this internal influence is stronger in developing countries relative to developed countries. We further find significant codiffusive effects between PCs and the Internet, that are complementary in nature. Specifically, we find that the diffusion of the Internet receives a significant boost from the installed base of PCs. This complementarity is stronger in developing countries relative to developed ones—a force we believe is a significant contributor to the narrowing of the digital divide over time. The last

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[3] Teng et al. (2002) studied the contrasting diffusion processes for a number of IT innovations, including 4GL, CASE, client/server technology, electronic data interchange (EDI), Email, mainframe, and PC.

part of our analysis provides projections of the digital divide over time, in light of our results, and explores policy implications at the country level.

The plan of the paper is as follows. The next section provides a brief survey of the literature relevant to this research. Section 3 outlines the theoretical underpinnings of this research, and lays out our empirical hypotheses. Section 4 describes our empirical specifications and data. Section 5 presents our empirical results, and §6 explores policy implications and offers some concluding remarks.

2. Literature Review

We start with an overview of the literature on the diffusion of innovations, and specifically the work on multi-innovation interactions, followed by the relevant work on the global digital divide.

2.1. Diffusion of Innovations

We draw from the broad literature on the diffusion of innovations in our analysis of IT interactions in a cross-country diffusion context. The seminal Bass (1969) mixed influence diffusion model relates the rate of diffusion to forces of *innovation* and *imitation*, wherein the former captures the inherent tendency to adopt the innovation based on external influences, whereas the latter represents "social contagion" or the internal influence of the installed base of the innovation on the likelihood of new adoption—what we call same-side network effects in Figure 1. This approach has fed a long literature on the diffusion of innovations; see Chandrasekaran and Tellis (2006) and Teng et al. (2002) for recent surveys of diffusion research in the marketing and information systems literatures, respectively.

It has also been recognized that innovations do not spread in a vacuum, and that there often are interactions across overlapping innovations that affect the diffusion paths of the individual innovations. A number of papers have examined specific aspects of multi-innovation interrelationships. One stream of literature has focused on the process of *substitution* as older technologies are gradually replaced by new, more efficient technologies; see, e.g., Peterson and Mahajan (1978), Norton and Bass (1987), Islam and Meade (1997), Mahajan and Muller (1996), Danaher et al. (2001), and Meade and Islam (2006). Another stream of the literature, and one that is more relevant to

our research, has examined *complementarities* in the diffusion of multiple products or innovations—what we call cross-side network effects in Figure 1. Bayus (1987) examines complementarities in hardware and software sales data. Bucklin and Sengupta (1993) test complementary codiffusion effects between scanners and universal product code (UPC) symbols. Kim et al. (2000) further extend the framework to a dynamic market growth model, and estimate it on data for generations of wireless telecommunications services.

What is notable about this body of work on complementary codiffusion is the broad perspective it takes on the spread of seemingly disparate products or innovations that are tied together through customer-perceived functionality characteristics. As Bayus et al. (2000) assert, "inter-product relationships may extend across product categories since category boundaries are often defined for the convenience of industry participants rather than being based solely upon consumer perceptions of solutions to their problems" (p. 142). We take a similarly broad perspective to jointly examine the diffusion of PCs and the Internet, taking into account the diffusive interactions between them.

2.2. Global Digital Divide

The other foundation for our research is the literature on the country-level digital divide. The focus of this literature is on describing and explaining cross-country penetration of the Internet and other technologies, usually based on a variety of socioeconomic factors such as gross domestic product (GDP), human capital, trade, western orientation, telecom infrastructure, and computing and telecom costs, among others. Dewan and Riggins (2005) provide a comprehensive summary of how these factors have been shown to affect technology penetration, where a common finding is that all of these factors tend to systematically favor technology adoption in developed countries relative to developing countries, thereby *widening* the digital divide. In this body of work, however, there is very little that addresses the cross-technology interactions, which, we argue, lead to a *narrowing* of the divide.

The one paper we found that addresses cross-technology interactions at the country level is Dekimpe et al. (2000). It takes a coupled-hazard approach to

the global diffusion of a series of technological innovations, estimated on data for digital telecommunications switches across some 160 countries. Their hypotheses explicitly analyze the role of country wealth and the impact of installed base of an older technology on the rate of diffusion of a new one. Dekimpe et al. (2000) consider a narrow set of technologies (telecom switches) and focus exclusively on substitution effects. Our model covers a broader set of focal information technologies (PCs and Internet), characterized by complementary diffusive interactions. In another study obliquely related to our focus, Oxley and Yeung (2001) examine PC penetration at 30 countries, finding that Internet host penetration is positively associated with physical communication infrastructure (which included PC penetration) and negatively correlated with telephone service costs.

In addition, there are three studies that examine more than one technology concurrently, but cross-technology interaction is absent or limited to simple correlation analyses. Quibria et al. (2003) examines a data set of over 100 countries that includes counts of PC and Internet use per capita in 1999. They find that GDP, education levels, and infrastructure play critical roles in the levels of these and other information technologies. Chinn and Fairlie (2006) examine panel data from 161 countries over the 1999–2001 period, and find that telephone density and regulatory quality (as measured by an index assessing market-friendly policies) are important determinants of PC and Internet density. Dewan et al. (2005) examine the penetration of mainframes, PCs, and Internet, and find that mainline density and Internet costs are important determinants of penetration. These studies examine the cross-country penetration of information technologies using multiple regression specifications, without any consideration of cross-technology diffusive interactions.

2.3. Relation to the Prior Literature
Our analysis builds on the prior work described above to make a unique contribution at the intersection of three streams of research. First, we contribute to the literature on cross-country diffusion (see, e.g., Dekimpe et al. 2000, Ganesh et al. 1997, Rai et al. 1998, Takada and Jain 1991). This stream of research has focused on how the diffusion of new products and other innovations is affected by a variety of country characteristics, but it has not specifically examined

PCs and the Internet, which are the key technologies with a bearing on the future evolution of the digital divide.

Second, we contribute to the literature on IT penetration and the global digital divide (see, e.g., Dewan and Kraemer 2000, Caselli and Coleman 2001, Kiiski and Pohjola 2002, Corrocher and Ordanini 2002, Chinn and Fairlie 2006). This prior work documents how various country characteristics, such as country wealth, education levels, telecommunications infrastructure, and regulatory quality have contributed to the *widening* of the digital divide, but the thrust of our research is on understanding how complementarities in the diffusion of PCs and the Internet leads to the *narrowing* of the digital divide. It should also be noted that while some prior work (such as Chinn and Fairlie 2006) has looked at PC and Internet penetration, it has not studied diffusive interactions across these technologies.

Finally, our research is related to the marketing literature on the codiffusion of related products (see, e.g., Bayus 1987, Bucklin and Sengupta 1993, Mahajan and Muller 1996, Norton and Bass 1987), which has broadly focused on the substitution effects across multiple generations of a product or technology (Mahajan and Muller 1996, Norton and Bass 1987) or the complementary effects in the diffusion of products that are typically used together (Bayus 1987, Bucklin and Sengupta 1993). However, prior research has not examined the specific case of PC and Internet complementarity, which is the focus of our research, as it relates to the global digital divide.

3. Theory and Hypotheses

3.1. Diffusion Framework
Consider the diffusion of two overlapping focal information technologies, indexed by $i, j \in \{\text{PC, Internet}\}$. At any point in time t, let $F_i(t)$ denote the fraction of the total population that has adopted technology i, and let $f_i(t) = dF_i(t)/dt$ denote the instantaneous growth in the fraction of adopters. Then, the stereotypical diffusion model has the form $f_i(t) = h_i(t) \cdot [1 - F_i(t)]$, where $h_i(t)$ is the hazard rate of adoption, specifying the limiting probability that an individual member of the social system who has not yet adopted at time t will do so at time $t + \Delta t$, with

$\Delta t \to 0$. We take the hazard rate function to have the form:

$$h_i(t) = a_i + b_i F_i(t) + c_i^j F_j(t), \tag{1}$$

for a pair of overlapping technologies i and j, similar to that in Peterson and Mahajan (1978) and its extensions. In Equation (1), $F_i(t)$ and $F_j(t)$ are the fraction of adopters of technologies i and j, respectively; the parameter a_i is the *innovation* parameter, b_i is the *imitation* parameter, and c_i^j is the *codiffusion* parameter, representing the impact of the installed base of technology j on the diffusion of technology i. Note that the first two terms are the standard ones in the basic Bass (1969) model. The third term is added to capture codiffusive effects between the technologies, as in Peterson and Mahajan (1978) and Bayus et al. (2000). The codiffusion parameter c_i^j captures two types of codiffusive effects, with $c_i^j > 0$ indicating a *complementary* effect of technology j on technology i, and $c_i^j < 0$ reflecting a *substitutive* effect. Note that our framework allows for the codiffusive effects to be asymmetric so that, for example, the effect from technology i to j could be one of complementarity (i.e., $c_i^j > 0$), but the effect from technology j to i is one of substitution. Finally, $c_i^j = 0$ would be consistent with a lack of a significant codiffusion from technology j to technology i.

A complementary codiffusion effect, corresponding to $c_i^j > 0$, is one where increased adoption of technology j increases the likelihood of adoption, the rate of adoption of technology i, or both. This is a direct result of the technologies having increased value in use together. By contrast, a substitutive effect, $c_i^j < 0$, is one where increased adoption of technology j reduces the likelihood of adoption, the rate of adoption of technology i, or both.

3.2. Hypotheses

We now develop the hypotheses that we will test in our empirical analysis, referring to the network economics and diffusion theory frameworks described above. These hypotheses deal with the nature of diffusion forces for PCs and the Internet and how they differ between developed and developing countries. Referring to the framework of Figure 1, we start with predictions related to internal or imitation influence, driven by same-side network effects (Hypotheses 1A and 1B), followed by a discussion pertaining to codiffusive effects and how they relate to the nature of cross-side network effects (Hypotheses 2A–2C).

Imitation effects or internal influence are a key driver of the adoption of both PCs and the Internet because of the presence of same-side network effects. In the case of PCs, network effects arise from the ability of users to share data and applications with each other because of common standards and interfaces. There are also indirect network effects associated with the increasing number of applications available for the de facto standard Wintel platform. As strong as these network effects are, we believe the network effects underlying the diffusion of the Internet are even stronger. Whereas the PC has considerable standalone value, the Internet is almost entirely about communication, interaction, and sharing. The invention of the World Wide Web facilitated access to hyperlinked content, which is clearly increasing in the number of hosts and users on the Internet. This, combined with powerful search engines and Internet portal sites, not only made the Internet more user friendly, but greatly enhanced the value from interaction and sharing amongst users.

Another factor that contributes to stronger same-side network effects for the Internet as compared to PCs is the fact that the former is a relatively more recent phenomenon. As demonstrated by the analysis of Van Den Bulte (2000), there tends to be an acceleration in the diffusion speed of products introduced more recently as compared to earlier time periods. Although Van den Bulte (2000) focused on household durable goods, we believe the general arguments apply to PC (which is also a durable good) and Internet diffusion. Briefly, diffusion speed is faster for later products as compared to earlier products because of a systematic change in product design and environmental factors such as demographics and purchasing power. In our case, the most relevant factor is the steady increase in computer literacy over time, driven in part by PC adoption and use, which sped up the diffusion of the follow-on Internet innovations. For all of these reasons, we expect imitation effects to be higher for the Internet as compared to the PC.

We now turn to how imitation effects differ between developed and developing countries. In this regard, we learn from prior work that explained variations in these effects based on individual or country characteristics. It has long been established in the diffusion literature that innovators tend to have higher

incomes relative to population averages (Gatignon and Robertson 1985, Rogers 2003). Extended to the country level, this implies that the higher average wealth in developed countries would go along with higher levels of risk taking and externally driven innovation, whereas adoption in poorer developing countries would be driven more by internal imitation (or social contagion) and relatively less by external innovation (Dekimpe et al. 2000, Helsen et al. 1993). Researchers have also demonstrated a lead-lag effect between countries (Kumar et al. 1998, Takada and Jain 1991), wherein the later an innovation is adopted, the faster will be the rate of internal adoption. The reason for this is that lagging countries have greater time available to decipher the relative advantages and compatibilities of the new technology, while enjoying the benefits of lower cost, reduced risk, and enhanced opportunities to imitate because of learning effects (Kumar et al. 1998). These arguments lead to our first set of hypotheses:

HYPOTHESIS 1A (H1A). *Imitation effects will be stronger for Internet diffusion, as compared to PC diffusion.*

HYPOTHESIS 1B (H1B). *Innovation effects will be higher in developed countries, but imitation effects will be higher in developing countries.*

Turning now to the codiffusion effects between PCs and Internet, note that a PC provides a way of accessing the Internet, whereas an Internet connection enhances the value of investing in a PC—hence, the cross-side network effects in Figure 1. As such, the dominant nature of the relationship between PCs and the Internet is clearly one of complementarity. PCs are still the primary means of accessing the Internet across the globe. As Beilock and Dimitrova (2003) have identified, PCs exist as critical infrastructure for Internet users, and conversely, Internet use stimulates PC demand. For these reasons, we expect the codiffusive effects between PCs and Internet to be characterized by complementarity in both directions. Furthermore, analogous to the arguments of Bucklin and Sengupta (1993) for scanners and UPC symbols, both PCs and the Internet are much more valuable together than in isolation. That is, a PC offers standalone value even if is not connected to the Internet, but the value of a networked PC with Internet access is much more valuable than one without such access. Similarly, the

Internet can be accessed on cell phones and other Internet appliances, or through an Internet café or kiosk. However, the user is likely to derive more value when Internet access is integrated with other applications on a networked PC platform.

That being said, we expect an asymmetry in codiffusive effects: The codiffusion effect of PCs on Internet will be stronger than the corresponding effect of the Internet on PC diffusion.[4] That is, cross-side network effects will be stronger in the PC → Internet direction, as compared to the Internet → PC direction (see Figure 1). Access to the Internet has become a "killer application" on a PC, to the point that it is rare to find personal computers that are not connected to the Internet. Therefore, an increase in the installed base of PCs will provide a boost to the number of Internet users—in a one-to-many fashion if multiple users are sharing a PC. In the other direction (from Internet to PC), however, the linkage is a bit weaker because an increase in the installed base of Internet users will create added demand for Internet access, but this added demand is split across a multitude of Internet access methods, which includes PCs, but is not limited to them. Cell phones, Internet appliances, cafes, and kiosks are alternative ways of accessing the Internet.

This leads us to the question of how developing and developed countries compare in terms of the relative magnitudes of PC and Internet complementarity. In other words, in which type of country would the marginal consumer (i.e., a new consumer adopting the technology) derive a higher value from a system that combines a PC bundled with Internet access? We believe this to be the case in a developing country, for several reasons. First, at any point in time, developing countries are building onto a smaller installed base, so that by the "law of diminishing returns" the marginal value of an additional networked PC should be higher in a developing country. Second, there is a higher intensity of use in developing countries, with a larger number of users sharing PCs, Internet connections, or both. Whereas a new networked PC typically creates incremental value for a single individual in a developed country, it creates value for a household or a community of users in the developing world. This lowers the effective adoption cost for the technology.

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[4] We thank an anonymous reviewer for suggesting this line of thought.

This cost is further lowered by reinvention of the original PC, and Internet technology innovations by developing countries (e.g., lower-cost technologies, wireless local loop) makes each of these technologies more affordable in the developing world, enabling a faster rate of adoption (see, e.g., James 2002). Apart from cost reduction, there are demand-side externalities in the form of enhanced learning and sharing of information and resources within the social network of joint adopters, further increasing the value of technology adoption. A good illustration of this is provided by the HBS eChoupal case (Fuller and Upton 2004), which describes the transformation of the highly inefficient supply chain for soy bean products in India through the use of shared PC and Internet connections in village squares of the central Indian state of Madhya Pradesh.

Our arguments above lead to the following set of related hypotheses:

HYPOTHESIS 2A (H2A). *The codiffusion effects between PCs and the Internet will be that of complementarity in both directions.*

HYPOTHESIS 2B (H2B). *The codiffusion effect of PC on Internet diffusion is stronger than the codiffusion effect of Internet on PC diffusion.*

HYPOTHESIS 2C (H2C). *The codiffusion effects will be stronger in developing countries relative to developed countries.*

In the following section, we describe the empirical models and data that we use to test the above hypotheses.

4. Empirical Specifications and Data

4.1. Empirical Specifications

The theoretical diffusion model of Equation (1) was specified in continuous time. To translate to a discrete-time specification, to match our data, we need to introduce a bit of additional notation. Let N_i denote the maximum number of potential adopters of technology i and $S_{ik}(t)$ the number of adopters at time t in country k, so that the fraction $S_{ik}(t)/N_i$ in the discrete specification corresponds to $F_i(t)$ in the continuous one. Furthermore, let $s_{ik}(t)$ be the growth in the number of adopters between time periods t and $t + 1$ in

country k. Then, the basic Bass model (with just the innovation and imitation parameters) in discrete time is given by (see also Teng et al. 2002):

$$s_{ik}(t) = \left[a_i + b_i \frac{S_{ik}(t)}{N_i}\right][N_i - S_{ik}(t)]. \quad (2)$$

We can also calculate the time to inflection, t^*, defined as the number of years from the time of adoption to the point of maximum growth rate of the fitted diffusion curve, as follows:

$$t^* = \frac{1}{a + b} \ln \frac{b}{a}. \quad (3)$$

The lower the value of t^*, the faster the pace of diffusion.

One might wonder if the Bass model provides the best fit to the data, as compared to other models in the diffusion literature. In this regard, the Gompertz model has also been widely used in the literature (Mahajan and Peterson 1978, Teng et al. 2002).[5] It specifies the proportion of nonadopters in a logarithmic manner, as follows:

$$s_{ik}(t) = [b_i S_{ik}(t)/N_i][\log N_i - \log S_{ik}(t)].$$

We report the results from the model comparison test in §5, which indicate that the Bass model provides the better fit to the data. Accordingly, we use the Bass model as the basis of our empirical specifications, and extend it to include codiffusive effects, as described next.

The extended model with the codiffusion parameters—the codiffusion model—is characterized by the following equations, for a pair of overlapping technologies $i, j \in \{$PC, Internet$\}$:

$$s_{ik}(t) = \left[a_i + b_i \frac{S_{ik}(t)}{N_i} + c_i^j \frac{S_{jk}(t)}{N_j}\right][N_i - S_{ik}(t)], \quad (4)$$

$$s_{jk}(t) = \left[a_j + b_j \frac{S_{jk}(t)}{N_j} + c_j^i \frac{S_{ik}(t)}{N_i}\right][N_j - S_{jk}(t)]. \quad (5)$$

We also consider two extensions of the baseline codiffusion model of Equations (4)–(5). The first extension incorporates technology price (a key marketing mix

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[5] The logistic model is also used, but it is a special case of the Bass model focusing only on the imitation effect (i.e., the innovation coefficient is restricted to zero). Therefore, we only compare the Bass and Gompertz models.

variable) into the diffusion specification, following the original model of Robinson and Lakhani (1975), as summarized in Meade and Islam (2006):

$$s_{ik}(t) = \left[a_i + b_i \frac{S_{ik}(t)}{N_i} + c_i^j \frac{S_{jk}(t)}{N_j} \right]$$
$$\cdot \exp(d_i p_{ik}(t))[N_i - S_{ik}(t)], \qquad (6)$$

$$s_{jk}(t) = \left[a_j + b_j \frac{S_{jk}(t)}{N_j} + c_i^j \frac{S_{ik}(t)}{N_i} \right]$$
$$\cdot \exp(d_j p_{jk}(t))[N_j - S_{jk}(t)], \qquad (7)$$

for $i, j \in \{\text{PC, Internet}\}$, where $p_{ik}(t)$ and $p_{jk}(t)$ denote the unit price of technologies i and j in country k in year t, respectively. The second extension expands the baseline model of Equations (4)–(5) to include a cross-country effect, along the lines of Ganesh et al. (1997). That is, the specification allows an intercountry imitation effect, whereby diffusion in the lagging developing countries is affected by the installed base of the respective technology in the leading developed world. Thus, the diffusion specification for developing countries is given by

$$s_{ik}(t) = \left[a_i + b_i \frac{S_{ik}(t)}{N_i} + c_i^j \frac{S_{jk}(t)}{N_j} + cc_i \frac{\overline{S_{ik}^{DD}(t)}}{N_i^D} \right]$$
$$\cdot [N_i - S_{ik}(t)], \qquad (8)$$

where $i, j \in \{\text{PC, Internet}\}$ and $\overline{S_{ik}^{DD}(t)}/N_i^D$ denotes the average installed base in year t of technology i in the developed countries. The specification for developed countries remains unchanged.

Our preferred approach is to take the parsimonious baseline specification of Equations (4)–(5) as our baseline model and to treat the price and cross-country extensions of Equations (6)–(8) as robustness checks. As we discuss in §5, our empirical results indicate that the qualitative nature of our baseline model diffusion results remain unchanged under the model extensions, justifying our choice of the main model. The data used to estimate the above specifications is described next.

4.2. Data
The key data on penetration levels of PCs and Internet users were obtained from World Bank (2006) and ITU (2005). These agencies gathered the data from a variety of sources, including government reports, corporate estimates, and in-country surveys. The penetration level of PCs is defined by the ITU as the number of desktops, laptops, and notebooks installed in a country on a per capita basis, whereas the penetration of the Internet is defined by the ITU as the estimated number of per capita users of the Internet using any access method. The data for PCs runs from 1981 to 2004 for developing countries and from 1981 to 2005 for developed countries. Data on Internet users covers the period 1991 to 2005. To the best of our knowledge, these PC and Internet penetration data are the most reliable of those available, especially for the broad set of countries we are working with.

We also obtained price data from international data collection agencies. The price of PCs was obtained from the World Bank, and it refers to the average price of a midspecification PC, converted to U.S. dollars in a given year. Unfortunately, our data is available only on a regional basis, so we must first determine the region of a country to apply the proxy for the price of PCs. Despite this limitation, this is the best available data on global PC prices. The price of Internet usage is represented by the cost of monthly telephone access defined by the ITU, which is very common in this type of research (see, e.g., Dewan et al. 2005). The results were nearly identical when alternative costs of telephone infrastructure access were used.

We obtained data for a total of 54 countries, but we were forced to narrow down the list of countries to those with at least nine years of Internet data to support a robust estimation of our empirical specifications, and we also dropped a few outlier countries with very low penetration rates of PCs or Internet users. We assigned the countries to one of two categories (developed or developing) based on their World Bank designation level of economic development. We labeled the World Bank's High-Income category countries as *developed*, and the ones in the middle- and low-income categories as *developing*. To eliminate problems with countries that have changed designation over the time frame of our study, we truncated the group of developed countries at $24 K per capita in 2001, the last year a country in our data set changed its World Bank designation. This process resulted in a total of 26 countries, half of which are developed and the rest developing, with a clear separation between the groups that persists throughout the time period of our data set.

Table 1 Countries in Our Data Set

| Developed countries		Developing countries	
Australia	Japan	Argentina	Malaysia
Austria	Netherlands	Brazil	Mexico
Canada	Sweden	Chile	Poland
Denmark	Switzerland	China	S. Africa
Finland	UK	Czech Republic	Thailand
Germany	USA	Hungary	Venezuela
Hong Kong		India	

We present our final working list of 26 countries in Table 1 and offer some summary statistics on technology penetration in Table 2. The per capita GDP (measured in purchasing power parity terms) of developed countries is over three times that of developing countries, on average. The penetration levels of both PCs and Internet in developed countries in 2005 is four to six times the corresponding levels in developing countries. The table also shows the unit price of PCs and Internet use (proxied by the average monthly cost of telephone access), with the numbers suggesting a relatively larger price disparity, between developed and developing countries, for Internet access as compared to PCs.

Figure 2 displays the time trend in the digital divide, measured in terms of the differences in per capita penetration of PCs and the Internet between developed and developing countries. On the left axis (lines without markers) we plot the absolute difference in technology penetration, whereas on the right axis (lines with markers) we plot the percent differences in penetration, relative to the average penetration level in developed countries. Note that whereas the differ-

Table 2 Summary Statistics on IT Penetration

	Sample	Countries	Mean	St. dev.	Min	Max
GDP-PPP	Developed	13	33,441	2,767	29,461	41,889
($US, 2005)	Developing	13	10,942	4,509	3,452	20,538
PCs per KCapita[†]	Developed	13	648.2	100.6	481.0	826.2
(in 2004)	Developing	13	113.9	66.0	12.1	240.03
Internet users per	Developed	13	579.3	109.5	454.7	763.5
KCapita (in 2005)	Developing	13	190.2	104.1	54.8	434.6
Average PC unit price	Developed	13	1,571	194	1,538	1,585
($US, 2004)	Developing	13	1,486	419	1,413	1,544
Average monthly	Developed	13	14.1	1.6	12.2	17.7
cost of telephone	Developing	13	7.6	0.86	5.95	9.91
access ($US, 2005)						

[†]KCapita (short for Kilo Capita) stands for "per thousand population."

Figure 2 Global Digital Divide Over Time
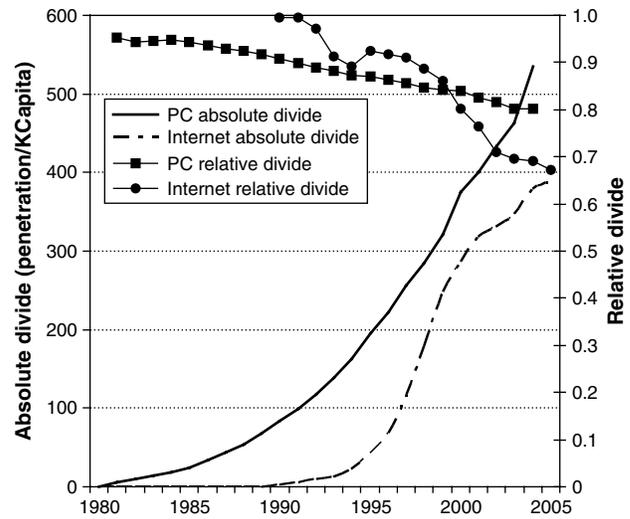
ences in penetration are growing in *absolute* terms, the *relative* magnitude of the divide is declining over time. Furthermore, the size of the Internet gap is noticeably smaller than the gap in PCs. Figure 3 displays the cross-sectional disparity in the penetration of PCs and Internet users across the countries in our data set (in the most current data year), where it is clear that there is a discrete jump in penetration levels as you transition from the developing countries to the developed countries in the figure.

4.3. Estimation Methodology

The estimation of our diffusion models is complicated by the nonlinearity of the specifications and the relatively large number of parameters to be estimated. Because the codiffusion model has more than three coefficients, previous researchers have advocated setting the value of the saturation level N before estimating the other parameters, exogenously based on reliable benchmarks (Kim et al. 2000, Mahajan et al. 1990) or using endogenous methods (e.g., Bucklin and Sengupta 1993). In our case, because of the lack of suitable exogenous sources for country-level saturation levels, we have chosen to endogenously estimate the values of N using the basic Bass model, along with other model parameters. These estimates are then fed into our estimation procedures of the extended diffusion model with codiffusion effects.

Thus, following the examples of Bucklin and Sengupta (1993) and Kim et al. (2000), we estimate the

Figure 3   Comparison of IT Penetration Levels Across Countries

Countries in ascending order of 2005 GDP/cap (PPP corrected, $US)
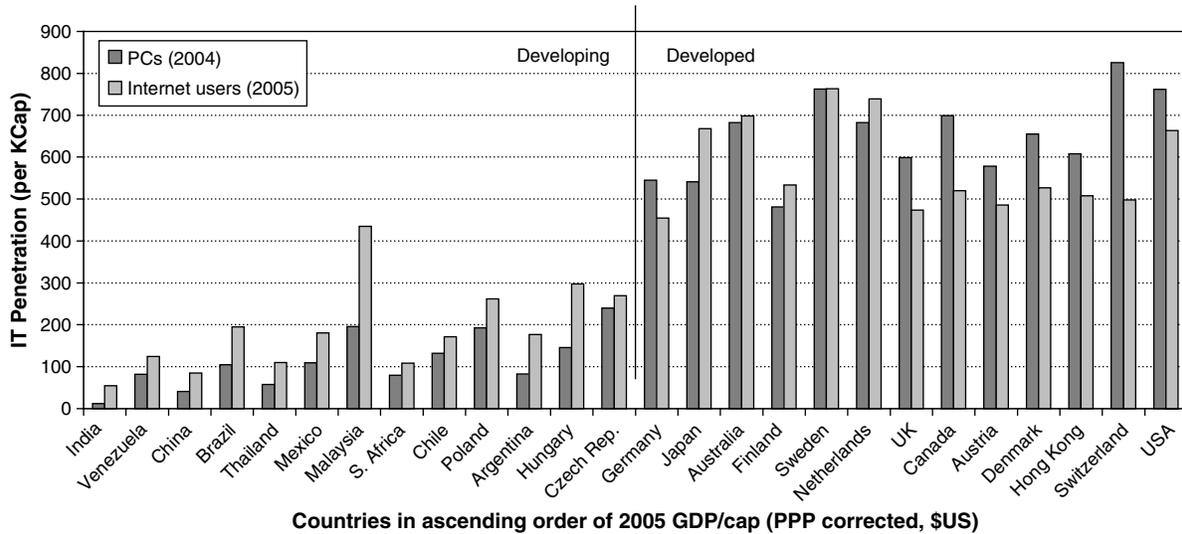
coefficients of the basic Bass Model (Equation (2)), for each of the developed and developing country subsamples in a simultaneous specification, for each focal IT, using nonlinear least squares (NLS). Our choice of NLS is consistent with much of the most recent work using similar diffusion models (e.g., Kim et al. 2000, Mahajan et al. 1990). The NLS technique produces a best-fit estimate of N, which we subsequently use in the estimation of the extended codiffusion models. To mitigate the concern that the Bass model tends to underestimate N, as noted by Van den Bulte and Lilien (1997), we reestimated the models using 20% higher values of N (see Table 8), and found the qualitative nature of the results to be unchanged (see §5.2).

In the second stage, we substitute the estimated saturation levels from the first stage into the nonlinear system of equations for the extended codiffusion model, and estimate the model parameters (of Equations (4) and (5)) using the NLS equations procedure in *Stata*. To account for correlated errors across the two groups of countries, we estimate the models for developed and developing countries simultaneously using seemingly unrelated regression (SUR), while incorporating corrections for any serial correlation and heteroskedasticity.[6]

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[6] *Stata* allows us to report robust variance estimates for our nonlinear models using the Huber/White sandwich estimator.

5.   Empirical Results

5.1.   Diffusion and Codiffusion Parameter Estimates

We start by evaluating the Bass and Gompertz models (described in §4.1) against the data and comparing relative measures of fit. Specifically, we derive the root mean square error (RMSE) and mean absolute error (MAE) from the nonlinear estimations, as reported in Table 3. The results suggest that the Bass model provides, by far, the better fit to the data, and therefore we use it throughout our analysis to follow. Table 4 presents the results obtained for the basic Bass model (Equation (2)), applied to the developed and developing subsamples. Note first that the estimated values of N are consistently higher for developed countries, consistent with prior research (e.g., Desiraju

Table 3   Measures of Fit for Bass and Gompertz Models

	Developed		Developing	
	Gompertz	Bass	Gompertz	Bass
PCs				
RMSE	26.55	25.44	7.66	6.58
MAE	17.47	15.19	5.57	3.99
Internet users				
RMSE	41.35	31.89	24.97	20.93
MAE	33.67	23.04	16.32	10.99

Note. RMSE = root mean square error; MAE = mean absolute error.

Table 4   **Basic Bass Model**

	Developed						Developing					
	a	b	N	t^*	No. of Obs.	Adj R^2	a	b	N	t^*	No. of Obs.	Adj. R^2
PCs	0.001	0.194	1,144.1	18.2	186	0.996	0.001	0.177	954.4	24.6	167	0.993
Internet users	0.021	0.359	666.5	6.8	194	0.990	0.020	0.292	384.3	13.1	172	0.966

Notes. These results correspond to the estimation of Equation (2). All estimated coefficients are significant at the 1% level or better. t-statistics comparing coefficients across groups indicated the differences are nonnull at the 1% level or better. t^* is the number of years from t_0 to point of maximum growth, where $t_0 = 1980$ for PCs, and 1990 for Internet Users.

et al. 2004). Diffusion is generally faster for the Internet as compared to PCs, as reflected in the lower time to inflection, t^*: The point of maximum growth of the Internet is reached over twice as fast as it was for PCs in both sets of countries. For both PCs and the Internet, developed countries reach their maximum growth rate distinctly earlier than developing countries, but subsequently experience a slowing in diffusion, whereas the growth rate in developing countries is peaking.

We turn now to the extended codiffusion model, starting again with model specification tests. We provide estimates of several types of forecasting errors, based on one-period-ahead forecasts of the last five years in each model specification we evaluated (see, e.g., Islam and Meade 1997), and the results are reported in Table 5. These help determine if the extended models fit the data more closely than the basic Bass model. RMSE and MAE evaluate the size of the predictive error of the model. Mean absolute percentage error (MAPE) evaluates the size relative to the actual variable measure, whereas Theil's U is a measure of the predictive error of the model relative to the error of a naïve model. We find that whereas the

precision of the Internet estimates are substantially higher for the extended codiffusion model relative to the basic Bass model, the precision of the estimates for PCs is somewhat lower. The codiffusion model does offer more insights into diffusive interactions, so we prefer to make it the main focus of our analysis.

The parameter estimates for the baseline codiffusion model of Equations (4)–(5) are presented in Table 6, with summary of hypothesis tests reported in Table 7. Note that the imitation parameters b are larger in the Internet model as compared to the PC model, and H1A is supported using a joint difference test with $p < 0.01$. With respect to H1B, the innovation parameter for PCs is larger for developed countries ($p < 0.01$), whereas the imitation parameter is slightly lower, although the difference is not statistically significant. However, the hypothesis is not supported for Internet users. That is, the data provide only partial support for H1B.

Turning to the codiffusion parameters, note that the sign on the coefficient of codiffusion c is consistently positive ($p < 0.01$ in all cases), indicating a complementary relationship between PCs and the Internet in both developed and developing countries, consistent with H2A. Furthermore, the codiffusion parameter c is larger in the Internet model as compared to the PC model, and H2B is supported using a joint

Table 5   **One-Step Ahead Forecast Errors**

	Developed				Developing			
	RMSE	MAE	MAPE	Theil's U	RMSE	MAE	MAPE	Theil's U
	Basic Bass model							
PCs	25.44	15.19	4.66	0.52	6.51	3.99	8.51	0.49
Internet users	31.89	23.04	7.73	0.59	20.93	10.99	19.27	0.76
	Extended model							
PCs/Internet	28.47	18.68	3.24	0.55	15.09	7.31	13.30	0.71

Notes. RMSE = root mean square error; MAE = mean absolute error; MAPE = mean absolute percentage error; Theil's U = the forecast RMSE divided by a naïve RMSE, and it ranges from 0 (perfect forecast) to 1 (no better than naïve estimator).

Table 6   **Baseline Codiffusion Model**

	Developed			Developing		
	a	b	c	a	b	c
PCs	0.007***	0.131***	0.035***	0.002*	0.135***	0.009**
Internet users	0.0001	0.261***	0.182***	0.0001	0.179***	0.730***
No. of obs.			719			
Adj. R^2			0.993			

Notes. See Table 7 below for a summary of hypothesis tests. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 7 **Summary of Hypothesis Tests**

Hypothesis	Support	Alternative hypothesis	Significance Level
H1A	Supported	$\{b^{DD}_{\text{Internet}} > b^{DD}_{\text{PC}}, b^{DG}_{\text{Internet}} > b^{DG}_{\text{PC}}\}$	$p < 0.01$ for the joint test
H1B	Partially supported	$a^{DD} > a^{DG}$	$p < 0.10$ for PC, $p > 0.10$ for Internet
		$b^{DD} < b^{DG}$	Not supported for PC or Internet
H2A	Supported	$c > 0$	$p < 0.01$ in all cases
H2B	Supported	$\{c^{DD}_{\text{Internet}} > c^{DD}_{\text{PC}}, c^{DG}_{\text{Internet}} > c^{DG}_{\text{PC}}\}$	$p < 0.01$ for the joint test
H2C	Partially supported	$c^{DD} < c^{DG}$	Not supported for PC
			$p < 0.05$ for Internet

Notes. The superscripts DD and DG correspond to developed and developing countries, respectively. All tests are two-tailed tests.

difference test with $p < 0.01$. There is partial support for H2C—although the codiffusion parameter for the impact of PCs on Internet diffusion is higher in developing countries as compared to developed countries ($p < 0.05$), the corresponding prediction for PCs is not supported.

Note the significant differences in the results across the development groups. The codiffusion parameter for the impact of PCs on Internet use is substantially larger for developing countries, as compared to developed countries. Indeed, the complementarity from PC to Internet diffusion for developing countries is the strongest effect in Table 6. The installed base of PCs in developing countries, although lower than that in developed countries, provides a strong boost to the diffusion of the Internet in these countries—much more so than in developed countries. Conversely, the effect of the Internet on PC diffusion is smaller and less significant in developing countries. Overall, the results suggest that the codiffusive impact of the PC-installed base on Internet adoption is stronger than the other way around, and this effect is stronger for developing countries than the developed ones, contributing to the narrowing of the digital divide in Internet penetration over time. We provide quantitative estimates of the rate of this narrowing in §5.3 below, but first we assure the robustness of our results.

5.2. Robustness Checks

We conduct several robustness checks to enhance our confidence in the results presented above. First, we estimated the codiffusion model with 20% higher values of the saturation levels N, to address the concern articulated by Van den Bulte and Lilien (1997) that nonlinear estimation of the basic Bass model results in

the underestimation of N. As can be seen from Table 8, the results are quantitatively and qualitatively similar to those in Table 6. Second, we estimated the codiffusion model with price effects (Equations (6)–(7)), with the results reported in Table 9. We find that the price variables are statistically significant and have negative signs; i.e., a higher technology price is associated with a slower rate of penetration growth, as expected. However, the qualitative pattern in the estimates of the diffusion and codiffusion parameters is similar to our baseline results of Table 6. Third, we estimated the extension of the codiffusion model with cross-country effects (Equation (8)), with the results presented in Table 10. As can be seen in the table, the cross-country diffusion coefficient has a positive sign, but it is insignificant. Furthermore, the qualitative nature of the diffusion and codiffusion results is unchanged.

Finally, we addressed a potential concern that the sample size might not be large enough to support the asymptotic distributional assumptions underlying our

Table 8 **Robustness Check: Codiffusion Model with Higher Saturation Level N**

	Developed			Developing		
	a	*b*	*c*	*a*	*b*	*c*
PCs	0.012***	0.073***	0.044***	0.001**	0.122***	0.011**
Internet users	0.001	0.157***	0.198***	0.0001	0.175***	0.671***
No. of obs.			719			
Adj. R^2			0.992			

Notes. These results correspond to the estimation of Equation (4), using a 20% higher value of the saturation levels N, as compared to Table 6. t-statistics comparing coefficients across groups indicated all differences are nonnull at the 10% level or better. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 9   Robustness Check: Codiffusion Model with Price Effects

	Developed				Developing			
	a	*b*	*c*	*d*	*a*	*b*	*c*	*d*
PCs	0.058***	0.235***	0.047***	−0.448***	0.033***	0.641***	0.019*	−1.070***
Internet users	0.001**	1.249***	0.674***	−0.101***	0.0001	0.338***	1.091***	−0.061***
No. of obs.				719				
Adj. R^2				0.993				

Notes. *t*-statistics comparing coefficients across groups indicated all differences are nonnull at the 10% level or better. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

hypothesis tests.[7] Specifically, we conducted Monte Carlo simulations to demonstrate that key parameter estimates are indeed distributed according to the Student *t* distribution, so that our hypothesis tests are valid. We generated multiple estimates of the model, sampling the data set with replacement, 100, 200, and 500 times—consistent with a bootstrapping estimation approach (see, e.g., Wooldridge 2002). The resulting data sets of coefficients were tested against a Student-*t* distribution using the Kolmogorov-Smirnov equality-of-distributions test. All tests resulted in accepting the simulated parameter distributions as from a Student-*t* distribution.

Based on these additional results and tests, we conclude that our baseline results (Table 6) are robust to alternative specifications and data issues.

5.3.   Implications for the Digital Divide
We now discuss what our codiffusion model results imply for the future evolution of the digital divide. For this purpose, we return to the simple metric of the relative digital divide, calculated as the difference in IT penetration between developed and developing countries, normalized by the penetration level in the former, and calculate the contribution of codiffusion to the narrowing of this metric of the divide. Our results are presented in Table 11, with the top panel providing projected technology penetration levels, and the bottom panel containing the percentage contribution of codiffusion to the narrowing of the divide. Starting with the former, columns (1) and (2) list the per capita penetration levels of PCs and Internet for developed and developing countries, respectively, during the year 2004. Based on our estimated

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[7] We thank an anonymous reviewer for urging us to examine this robustness check.

parameters in Equations (4)–(5), we generate projected penetration levels in 2010, and the resulting projected values of PC and Internet penetration levels are in columns (3) and (4). Comparing the actual levels in 2004 with the projections for 2010, we note that the relative divide appears to narrow over this time period. The relative divide in PCs goes from 0.82 in 2004 to 0.73 in 2010. However, the drop in the magnitude of the projected divide in Internet penetration shows a much sharper drop, from 0.69 in 2004 to 0.50 in 2010. Projections to 2015 suggest a further substantive narrowing of the relative divide to 0.61 for PCs and 0.44 for Internet, respectively.

The contributions from codiffusion in the diffusion paths are presented in the bottom panel of Table 11, where we calculate the percentage impacts of codiffusion on the penetration levels at the same forecasted points in time, using the following formula:

$$\frac{c_i^j(S_{jk}(t)/N_j)}{a_i + b_i(S_{ik}(t)/N_i) + c_i^j(S_{jk}(t)/N_j)}, \tag{9}$$

where $i, j \in \{PC, Internet\}$. In developed countries, on average, codiffusion contributes approximately 28%

Table 10   Robustness Check: Codiffusion Model with Cross-Country Effects

	Developed			Developing			
	a	*b*	*c*	*a*	*b*	*c*	*cc*
PCs	0.007***	0.129***	0.035***	0.002	0.139***	0.008**	0.001
Internet users	0.001	0.257***	0.187***	0.0001	0.217***	0.610***	0.002
No. of obs				719			
Adj R^2				0.993			

Note. *t*-Statistics comparing coefficients across groups indicated all differences are nonnull at the 10% level or better. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 11   Narrowing of the Digital Divide and the Contribution of Codiffusion

	Actual 2004 Penetration		Projected 2010 Penetration		Projected 2015 Penetration	
	(1) PCs	(2) Internet	(3) PCs	(4) Internet	(5) PCs	(6) Internet
Developed	648.2	549.6	1,024.7	732.3	1,278.2	854.6
Developing	113.9	170.2	302.2	377.4	523.8	478.1
Relative divide	0.82	0.69	0.73	0.50	0.61	0.44
Developed (%)	28	35	24	18	23	14
Developing (%)	16	49	35	54	37	61

Notes. For the "current path" estimates, saturation level is allowed 3% growth a year to minimize artificial capping.

to PC penetration in 2004, and 35% to Internet use, with these percentages reducing somewhat by 2010 to 24% and 18%, respectively, and to 22% and 13% in 2015. By contrast, in developing countries, codiffusion contributes 16% to PC penetration in 2004, and 49% to Internet use—these figures *rise* to a 35% for PCs and 54% for the Internet in 2010 and to 37% and 61% in 2015, respectively. Clearly, this model demonstrates the large and *increasing* importance of codiffusion to the narrowing of the digital divide.

6.   Conclusions

In this paper we have jointly examined the cross-country diffusion of PCs and the Internet, emphasizing the complementary codiffusive interactions across the technologies, and highlighting the implications for the evolution of the global digital divide. Our results show that developing countries have been on slower diffusion paths, but there are also indications that the digital divide will appreciably narrow in the future, driven in part by complementary cross-technology diffusion effects. Specifically, we find that the installed base of PCs provides a boost to the rate of diffusion of the Internet, and this effect is significantly stronger in developing countries as compared to developed ones. Whereas prior research on the digital divide has documented a number of factors that contribute to the *widening* of the divide, such as country wealth, infrastructure, and education, we show that the complementary codiffusive impact of the PC-installed base on Internet diffusion is a factor that serves to *narrow* the divide in Internet penetration over time.

Our findings have a number of policy implications, especially for developing countries. First of all, our

results clearly imply the importance of leveraging codiffusive effects across information technologies. We have found significant cross-technology diffusive effects between PCs and the Internet, which are stronger for developing countries relative to developed ones, perhaps reflecting a higher intensity of use (in terms of the average number of users per PC and Internet connection) and the deployment of lower-cost technologies in developing countries (Chopra 2005, James 2002).

The cross-technology codiffusive effects offer a mechanism for actively managing the digital divide, and driving it down further. Investments in technology infrastructure (including wireless and satellite technologies) and deregulation of the telecommunications sector not only provide an impetus to technology penetration, but they also fire up the codiffusion effects, which in turn provide a further boost to individual technology penetrations. Low-cost systems that combine computing with Web access and user-friendly applications would allow developing countries to internalize the complementarities inherent in codiffusive effects to accelerate the pace of reduction in the divide. Put differently, it is important for developing countries to take a "systems approach" to the promotion of technology access and use, instead of focusing on individual technologies by themselves. Rather than promote access to PCs and the Internet in isolation, our results indicate it would be more effective to push computers bundled with cheap access to the Internet.

Beyond the PC itself, there is a variety of low-cost personal computing technologies that can connect to the Internet. Technologies such as "network PCs" that failed to gain traction in the United States might well be ideal for the developing world, as also noted by James (2002). Low-cost PCs (about $175–$250) with Internet access, such as the OLPC Project's XO, Asus's eeePC, and Intel's Classmate are others that are gaining ground in developing countries. Over one million of these devices were deployed in 2007 and five million are projected for 2008 (Sharma and Kraemer 2008). Even these devices are too expensive for some countries and deployment in other countries frequently requires government subsidy not only for the hardware but also for user training and ongoing support.

Although our study did not include them, so-called "smart phones" and personal digital assistants (PDAs) with Internet access, as well as low-cost PCs, can enable faster transactions, help distribute critical market information, and generate new income. In India, locally manufactured public Internet kiosks called "eChoupals" led to a demand of 2.8 million rural farmers using them to check fair market prices for their crops (Kumar and Best 2006). In the rural areas of Bangladesh, where electricity is fitful and one gets around by walking through rice paddies, solar-powered cell phones financed by microloans are used by thousands of women who sell telephone services to villagers. In Zambia, local Coca-Cola distributors pay their American suppliers not in cash, but by sending payment orders to banks with text messages from their mobile phones (Mohiuddin and Hutto 2006).

In general, subsidizing access to PCs and other personal computing devices will boost demand not only for these devices, but also for Internet access. At the same time, the spread of Internet hosts and Web applications will accelerate the penetration of personal computing devices as well. For a case in point, the Simputer initiative in the Indian context is a good prototype of an integrated hardware, software, and Web portal solution that overcomes the hurdles of low affordability and illiteracy in providing usable systems to the mass population (Chopra 2005).

It should also be noted that codiffusive effects between PCs and the Internet can be amplified with appropriate technology infrastructure and cost policies. The Indian government, as a case in point, recognizes the crucial importance of building telecom infrastructure, with plans to increase telephone penetration from 10% in 2005 to 18% by 2010, calling for an investment of $75 billion over five years (Balakrishnan 2001). Wireless, microwave, and satellite technologies might actually be cheaper and more effective options, as compared to the terrestrial telephone network, for building out the telecom infrastructure (Chopra 2005). At the same time efforts need to be made to increase competition in the Internet service provider industry to bring down Internet access costs. More so than in developed countries, where access costs are not a significant impediment to technology diffusion, efforts in developing countries to provide more inexpensive access to the Internet will provide a noticeable boost

not only to Internet penetration, but to a variety of personal computing devices as well, which is also echoed in the findings of Kiiski and Pohjola (2002).

In these contexts, it seems that national government policy in developing countries might most effectively focus on stimulating infrastructure investments that enable connectivity at low prices. Moreover, some analysts argue that governments should pursue policies that promote exponential growth of the Internet, especially in those countries that are far behind their peers socially and economically because simple linear growth will never enable them to catch up (Best and Wilson 2006). In contrast, local governments might focus on deployment, training, and support of specific technologies appropriate to the unique features of their settings. Our results show that different technology generations can be strongly complementary to each other, especially in developing countries. Therefore, local policymakers may find that strategic investments in older generations of IT will bring greater diffusion benefits of the newer technologies than would efforts to directly stimulate diffusion of only the latest generation.

Turning to the limitations of our analysis, we start with the somewhat narrow composition of our data set, which excludes the poorest nations in the world, such as those in sub-Saharan Africa. Accordingly, the results should be interpreted with caution and may not apply for countries at the lowest end of the development continuum. Clearly, expanding our analysis to include such countries would present a worthwhile direction for future research. Another limitation of our analysis is that it is only focused on the digital divide as it applies to technology access; i.e., first-level digital divide (see Dewan and Riggins 2005). Researchers are highlighting the importance of looking at the second level of the divide in terms of technology use as opposed to just access (see, e.g., Hargittai 2006), which offers a rich direction for further research into the global digital divide. Finally, our analysis is limited to the direct effect of diffusion and codiffusion forces, but does not examine how these forces might interact with country characteristics such as culture or communication differences, as in Takada and Jain (1991). While these issues are beyond the scope of the present analysis because of data limitations, they are clearly productive areas for further research.

Acknowledgments

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