[[Draft. Incomplete]]

# The Digital Divide

by

Danny Quah[*]
LSE Economics Department
January 2007

---

[*] The Digital Divide is one of 32 original problem areas identified and targeted for study by the Copenhagen Consensus. Chrisanthi Avgerou, Robin Mansell, and Christine Qiang have provided helpful suggestions. I thank Vinayak Nagaraj for assistance.

# The Digital Divide

by

Danny Quah
LSE Economics Department

January 2007

## ABSTRACT

*(How would I spend US$50bn?) This paper presents dynamic welfare calculations to evaluate costs and benefits on the Digital Divide, the unequal distribution of digital technologies across countries and people. It provides, among other things, an explicit analytical model of technological dissemination, producing, from feedback and contagion effects across society and individuals, Verhulst-equation distribution dynamics in a logistic curve. Calibrating a range of models to recent data, the benefits to spending US$50bn to close the Digital Divide range from US$...*

**Keywords:** contagion, convergence, digital technology, dissemination, distribution dynamics, growth, inequality, information technology, Internet, mobile telephony, population dynamics, Verhulst equation

**JEL Classification:** D30, D61, D90, O33, O47

**Communications to:** Danny Quah, Economics Department, LSE, Houghton Street, London WC2A 2AE

Tel: +44.20.7955.7535, Email: `dq@econ.lse.ac.uk`
(URL) `http://econ.lse.ac.uk/staff/dquah/`

The Digital Divide
by
Danny Quah*
LSE Economics Department
January 2007

## 0 Summary

The time is not long since observers in the development community asked why a computer wired up to an Internet connection might matter for anything, given that in the developing world the most pressing economic and social problems included infant mortality, starvation, lack of clean water, inadequate infrastructure, or epidemic and debilitating illness.

Those problems have not gone away. But awareness has grown that information flows can help mobilize political action, build institutions, and foster accountability and governance. And all these latter certainly do matter for economic growth. Information and communications technologies (ICT) can aid such flows of information.

Beyond these potential channels of influence, there is of course also the prosaic possibility that ICT, or digital technologies more generally, might directly raise productivity in the workplace. Through appropriate application, digital technologies might guide human capital accumulation, lower poverty, deliver information to schools and hospitals, improve public-services provision, and make patterns of production more efficient. By increasing community outreach and enlarging the size and diversity of one's contact network, digital technologies might overcome obstacles to trade and thereby raise the degree of competition, making more efficient entire societies, not just individual workplaces.

---

*The Digital Divide is one of 32 original problem areas identified and targeted for study by the Copenhagen Consensus. Chrisanthi Avgerou, Robin Mansell, and Christine Qiang have provided helpful suggestions. I thank Vinayak Nagaraj for assistance.

All these reasons make important understanding how and why digital technologies differ across societies and across people. The Digital Divide is the gap between those who have regular and effective access to digital technologies and those who do not. We use this term uniformly to refer to a divide across people, communities, or entire countries.

Digital technologies refers, in the first instance, to personal computers, the Internet, and mobile telephony, i.e., traditional information and communications technology. But, more usefully, we can take it to mean all tools that transmit, receive, create, and manipulate digital goods, i.e., strings of 1s and 0s that allow communication, enhance worker productivity, or raise consumer welfare. Thus, digital technologies will include not just computer software and hardware; personal digital assistants; and email, mobile, and instant messaging telecommunications; but also digitized music and video entertainment; Internet-transmitted medical, engineering, and scientific publications; digital-networked advertising and financial transactions; and Web-based civic engagement and social networking.

Call *digital attainment* the level of access to digital technologies. Digital attainment is multi-attributed, and thus difficult to quantify. A meaningful measure of digital attainment takes into account not just availability but quality: Simply being able to access the Internet does not automatically imply a high-speed, wireless connection with sufficiently broad bandwidth to allow reorganizing production processes.

Worse, the term digital attainment alone conflates supply and demand. On the supply side digital attainment incorporates, among others, those factors arising from the cost of computer hardware and software, and the availability of high-speed Internet and telecommunications infrastructure. On the demand side it includes the income, literacy, education, and skills in a population. High-speed fiber-optic cable connections might not be used effectively by technology-averse workers and consumers.

The Digital Divide is inequality in digital attainment. Therefore, it is a special case of inequality more generally, and it can be analyzed using those economic tools for studying the dynamics of income distribution. However, novel issues arise.

Inequality is rife in, among other things, ice-cream consumption across people and between countries. But hardly anyone flags that particular Divide as a global concern. First, inequality in ice-cream consumption likely has no implication for any other important measure of economic performance. Second, such inequality is easily explicable: people and countries have different income levels, and expenditures on ice-cream vary with income according to well-understood elasticities of consumption. The observed distribution of ice-cream consumption across people and countries is a result of consumer choice, and any explanation—if one were necessary—rests solely on understanding the underlying income distributions. Ice-cream inequality passively reflects income inequality.

The Digital Divide is generally thought to differ on both accounts. The suspicion is that the Digital Divide is not just explained by income differences, say, but that the Divide might itself drive the dynamics of yet other inequalities, including those in income itself. Does the Digital Divide over time exacerbate social polarization and worsen income inequality? If so, what mechanism enables that? Conversely, does convergence eventually take place, because the Digital Divide allows growth from rapid imitation and learning, so that any initial inequality tends to vanish over time?

Improving the digital attainment of those relatively deprived to close the Digital Divide is costly to society:[1] How do benefits compare to costs? In light of the earlier discussion, to address this question of costs and benefits, this paper models potential simultaneity and dynamic feedback, and calibrates the relative strengths of the opposing effects.

This paper finds that significant improvements in welfare can be brought about by appropriate investment to close the Digital Divide. The benefit to cost ratios can be high. However, the implication is

---

[1] To be clear, subsequent references to closing the Digital Divide means raising the bottom part of the distribution of digital attainments, not lowering the top, which logically of course would be another way of reducing inequality.

not generally unambiguous. Cost-benefit ratios are favorable under certain conditions, but are less so under other no less plausible assumptions. Strict vanishing of the Digital Divide is unlikely, and is probably undesirable in any case. Contagion effects potentially figure prominently in dissemination patterns for digital technologies (as they do in many others). If so, the resulting pattern of logistic diffusion gives an increasing and then declining Digital Divide, from the momentum of the dissemination alone.

Empirically

[[...]]

## 1 Introduction

In March 2000 the technology-heavy NASDAQ stock market index reversed dramatically, after a seven-year period when it had inexorably risen seven-and-a-half-fold. In the 18 months that followed, the NASDAQ plunged 77% off its peak. Many observers took this to vindicate skepticism they had all along had about the so-called New Economy.[2]

Much of the rise in the NASDAQ over the 1990s stemmed from computing and telecommunications sectors most closely linked to the Internet and electronic commerce. The equity markets' subsequent sharp retreat took with it much activity in those sectors as well as many then-emerging ideas. Since then, many have acknowledged as embarrassing hyperbole terms such as the New Economy, dot-com's, the information superhighway, the all-importance of mindshare and of eyeballs on webpages, and others.

Paradoxically, however, this cringe factor arises from success as

---

[2] From 1993 until March 2000 the NASDAQ increased at an average annual rate of 28%. By comparison, the Dow Jones Industrial Average grew at only 17% annually over this period, or in total 330% by March 2000. But, correspondingly, in the 18 months following March 2000 the Dow Jones average fell only 30%, less than half of the 77% decline in the NASDAQ index.

much as it does failure. Those ideas that have caught on have embedded so deeply in how societies operate that they are no longer remarkable, and thus suggest naivete in anyone who deems them noteworthy. No high-school or university student in the West now stops to think *information superhighway* given that a high-speed, broadband Internet connection has been always and invisibly available to them. No child in the West can now imagine a world where Google is not a verb. The fibre-optic cables and business process reorganization that came out of digital technologies developed in the 1990s are now just quietly-accepted facts allowing, among much else, Bangalore India to grow its software exports 36% a year between 2000 and 2003.

Still unclear if useful insight or unfortunate hyperbole, however, is the notion of a Digital Divide, i.e., that people have unequal access to Internet connections, cellphones, PCs, and other digital technologies, and that this inequality then excludes those deprived—who might also be poor, illiterate, ethnic minority, or living in a low-income country—rendering them unnecessarily worse off.

This paper examines a number of hypotheses related to the Digital Divide. Does the Digital Divide only passively reflect inequality in, say, incomes and literacy? Or is the Digital Divide itself a cause of inequality more generally? How quantitatively important—in welfare and other terms—is the Digital Divide? What are the costs and benefits to closing the Digital Divide?

The remainder of this paper is organized as follows. Section 2 presents some basic facts on the Digital Divide. This Section looks at the dynamics of inequality in digital attainment, across people and across countries, and compares it to inequality dynamics in incomes and other economic variables.

Section 3 provides a technical discussion of the costs and benefits, and the dynamics, of the Digital Divide—across countries and communities, and across individuals within countries. The exposition uses models of infinitely-lived economies, evolving in continuous time in both deterministic and stochastic environments, to develop the dynamics of technology dissemination.

Section 4 calibrates these models against data and previous econometric estimates. It shows

[[ . . . ]]

Section 5 concludes. The appendix, Section 6, collects for completeness the more technical discussion, all mathematical proofs (6.2), and notes on the data used in the calibrations. A supplementary Section 7 contains additional, more qualitative material not easily fit in the relatively quantitative discussion of the body of paper.

## 2 Basic Facts

In 2004 the world had population 6.36 billion; average income per person came to \$8187 (measured in PPP-adjusted 2000 International\$). Internet users worldwide numbered 874 million; mobile phone users, 1778 million; PCs, 786 million. Mobile phone users thus numbered more than double both Internet users and PCs, while there were 88 million (6%) more Internet users than PCs.[3]

### 2.1 Across economies

Table 1 illustrates gross features of the Digital Divide across countries grouped according to categories of per capita income. Of course, what high income or low income means is arbitrary. Any division into discrete income groups potentially produces inappropriate inference, especially around the defining thresholds. But without some such organizing device one ends up either looking at hundreds of numbers individually, or using simply a smoothed distribution function across countries. Neither extreme is necessarily insightful and unproblematic.

Here, for ease of replication I use the 2005 income thresholds described in World Bank (2007, p. 285). Low-income economies are those with Gross National Income per capita no greater than \$875; middle-income economies, Gross National Income per capita at

---

[3] Numbers are the author's calculations from World Bank (2006b).

**Table 1** Digital Divide 2004, across economies grouped by per capita income. Each entry in the Table is the percentage located in the particular group of economies of the world total for that variable. The numbers were calculated from World Bank (2006b).

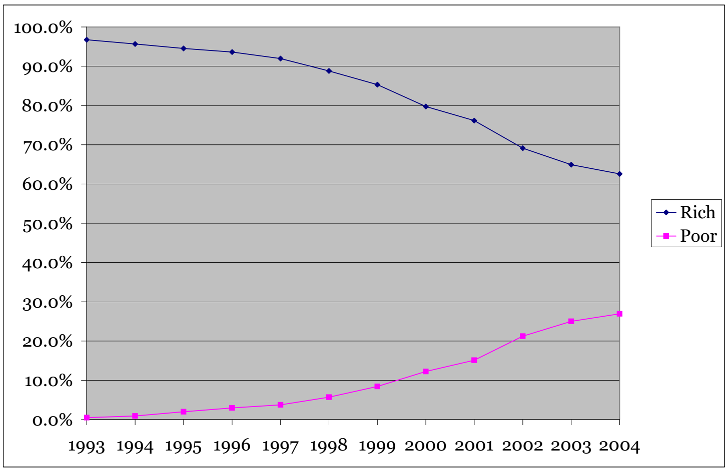
| | High | Upper Middle | Lower Middle | Low |
|---|---|---|---|---|
| Population | 16 | 9 | 38 | 37 |
| Income (PPP) | 55 | 11 | 25 | 9 |
| Internet users | 63 | 10 | 21 | 6 |
| Mobile users | 44 | 16 | 34 | 6 |
| PCs | 73 | 9 | 15 | 3 |

least $876 but less than $10,725; and all the remainder, high-income economies. Within the group of middle-income economies, partition lower-middle-income and upper-middle-income economies at $3,465 Gross National Income per capita. To put these figures in perspective, call *rich* those economies that are high-income: A rich economy is one where the average person earned at least $29.40 a day. Call *poor* those economies that are lower-middle-income and low-income: a poor economy is one where the average person earned no more than $9.50 a day. For comparison the average person on Earth earned $22.40 a day. Roughly, then, the thresholds for rich and poor are $30 and $10 a day, respectively; with world average at the midpoint $20 a day.

Table 1 brings out some key facts on world distribution. Of 208 economies in the world, 56—more than one quarter—are classified to be rich. On average, rich economies have relatively small populations, containing in sum only 16% of the world's people. They, however, received 55% of world income and held 63% of the world's Internet users and 73% of the world's PCs, both latter fractions notably exceeding rich economies' income share. Rich economies also contained 44% of the world's mobile phone subscribers, this number now falling *below* income share.

Poor economies are not just poor; they are populous. The 112 economies in this category contain 75% of the world's population.

**Figure 1 World Internet users** Percentage located in rich and poor economies



They received only 35% of world income and held 27% of the world's Internet users and 18% of the world's PCs. But they also contained 40% of the world's mobile phone subscribers, almost as many as in rich economies.

The dynamics driving Table 1 confirm this conclusion. Figures 1–3 show the evolution over time of the fraction of Internet users, mobile phone subscribers, and PCs across rich and poor economies. The gap between rich and poor economies in Internet users remains large, as seen in Figure 1, but also has narrowed considerably, from 96% (96.8% Internet users in rich economies compared to 0.5% in poor) in 1993 to 36% (62.6% versus 26.9%) only a decade later. For PCs (Figure 3), however, that gap remains considerable at 56% of the world's PCs (73.4% in rich versus 17.7% in poor) in 2004, with the gap as large as 84% (89.6% versus 5.5%) in 1993.

But the biggest shift is dramatically visible in Figure 2. By 2004 mobile phone subscribers in poor economies had grown in number almost to match that in rich economies (39.7% versus 43.6%, respec-

**Figure 2 World mobile phone subscribers** Percentage located in rich and poor economies

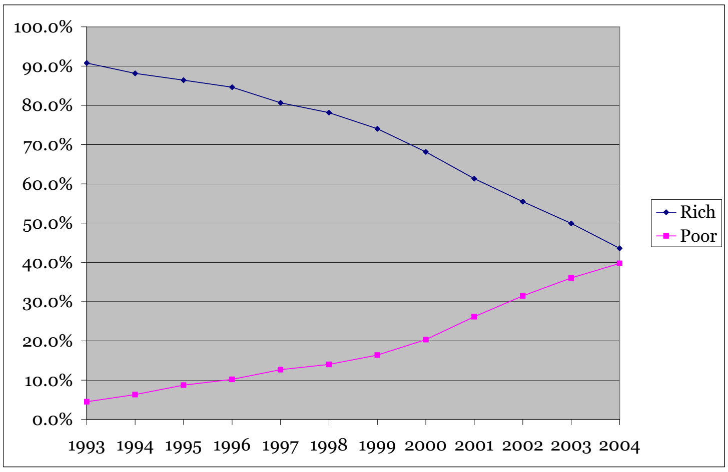


**Figure 3 World PCs** Percentage located in rich and poor economies

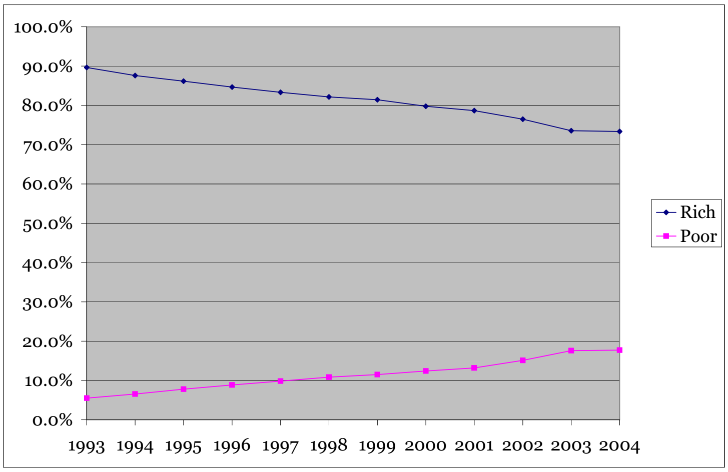
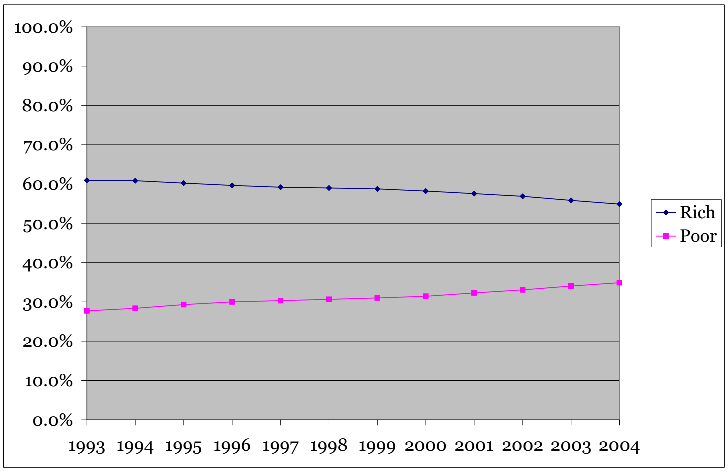


**Figure 4 World Income** Percentage earned in rich and poor economies



tively), even though as late as 1993 the separation had been as large as 86% (90.8% in the rich economies, 4.5% in the poor).

For comparison Figure 4 shows the dynamics of income shares across rich and poor economies over the same time period. Here too convergence is apparent but more gradually than that for Internet users and mobile phone subscribers. In 1993 the rich economies received 60.9% of world income; the poor, 27.7%, so that the separation was 33.2%. By 2004 the shares had changed, falling to 54.9% for the rich, and rising to 34.9% for the poor, so that the separation overall had declined to 20.0%.

To summarize numerically part of the information in Figures 1–4, the annual rate of decline in the gap for income shares across rich and poor is 4.6%, compared to 9.0% for Internet users, 28.2% for mobile phone subscribers, and only 3.8% for PCs.

These aggregate cross-country statistics provide a subtle and varied picture of both differences and similarities across rich and poor economies in the world. They point to how the gap between rich and poor is closing, uniformly in general, but also more rapidly for digital communications technologies like the Internet and mobile telephony, than for purely computational digital ones, like PCs. The more that communications technologies are divorced from computational technologies, the greater the convergence between poor and rich.

In contrast to world shares, per-capita measures provide a relatively more homogeneous description. In per capita income in 2004 the rich economies were 7.5 times as rich as the poor economies. In Internet usage per capita, the rich were 11.1 times better off than the poor; in per capita PCs, 11.7 times. On the other hand, for mobile phone subscribers, that ratio falls to only 5.2, i.e., a ratio lower than that for per capita income.

One potential explanation for this observed distribution is that Internet usage and PCs simply have higher income elasticities than does mobile phone usage. In particular, as income rises, demand for both Internet usage and PCs increase more than proportionally with the change in income, whereas that for mobile phone subscriptions, less. Alternatively, mobile phone technology might provide a better fit with work and consumption patterns in poorer economies. But, regardless, these Digital Divide numbers suggest that different content and delivery methods, varying with the environment, might be more appropriate and effective in different economies: what works in rich countries might not in poor ones.

For every digital technology, however, the gap between rich and poor has been steadily *growing*. Figures 5–8 provide per capita counterparts to the earlier Figures 1–4. In contrast to the convergence displayed in the figures for world shares, all the per capita numbers show *divergence* instead. Over this time period the gap between rich and poor in Internet users per capita grew at an annual growth rate of 35%; in mobile phone subscribers per capita, 27%; in PCs per capita, 12%; and in income per capita, 2%.

These last growth rates and those for world shares in Figures 1–3 need bear no simple, monotone relation with each other. If $Z$ denotes a variable (say mobile phone subscription) and subscripts denote country groupings so that the world total $Z = \sum_j Z_j$, and $N$ denotes population, then the first group of figures in the text, Fig-

**Figure 5 Internet users** (per 100 people), across rich and poor economies

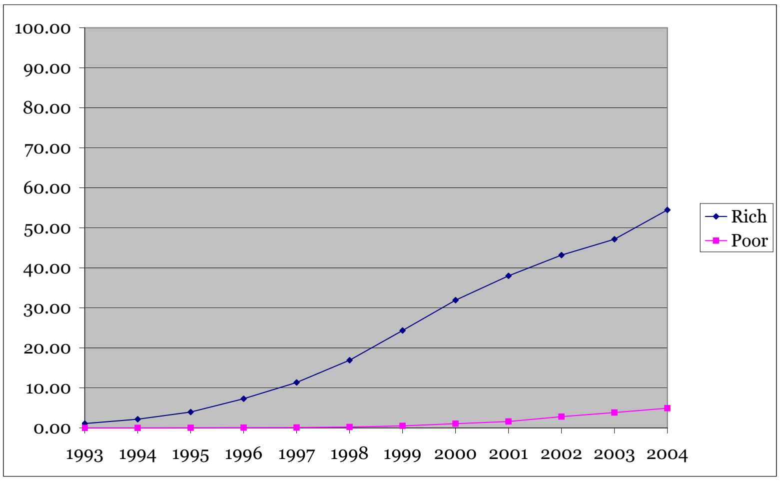


**Figure 6 Mobile Phone subscribers** (per 100 people), across rich and poor economies

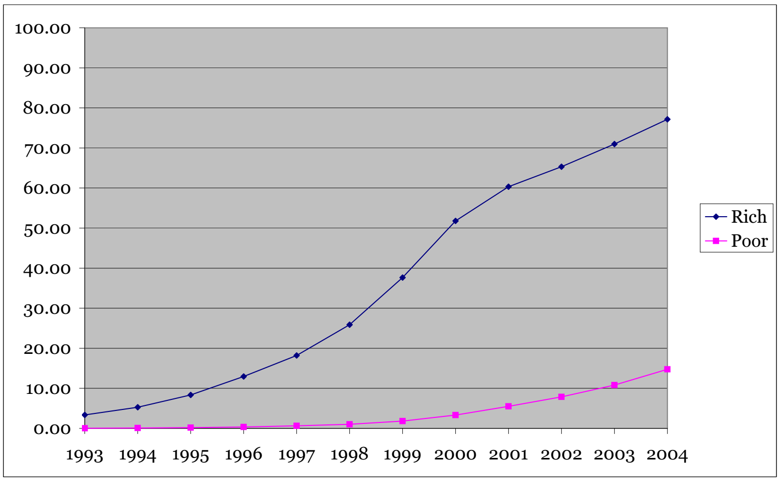


**Figure 7 PCs** (per 100 people), across rich and poor economies

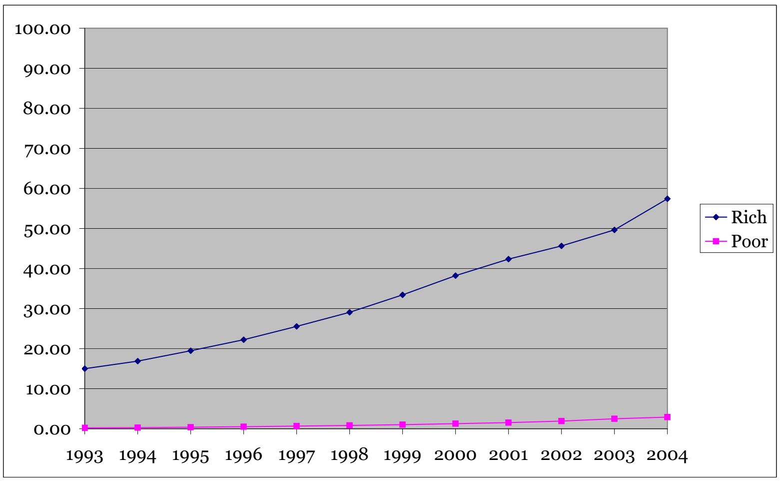


**Figure 8 Per capita Income** $10^3$ International$ (2000), across rich and poor economies

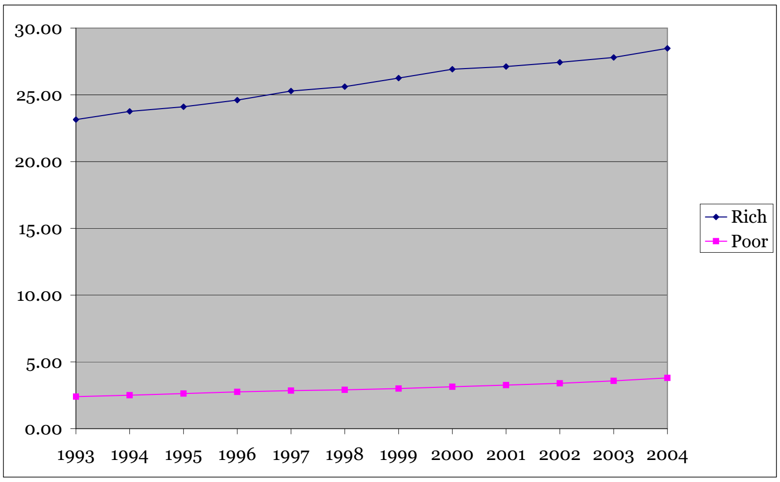


**Table 2** Classification by region and income: See World Bank (2007, p. 287) for the full listing of individual economies.

| Abbreviation | Classification by region and income |
|---|---|
| EAP | East Asia and Pacific |
| ECA | Eastern Europe and Central Asia |
| LAC | Latin America and Caribbean |
| MENA | Middle East and North Africa |
| SA | South Asia |
| SSA | Sub-Saharan Africa |
| OECD | Organization for Economic Cooperation and Development |
| OtherHI | Non-OECD high income economies |

ures 1–3, considers $Z_j/Z$ while the second group, Figures 5–7, looks at $Z_j/N_j$. Thus, for a given variable, say mobile phone subscription, world shares will converge while per capita measures diverge if, among other things, rapid growth in total $Z$ is being driven by the bottom end of the distribution but population growth is even higher there. On the other hand, given the configuration of population growth, per capita mobile phone subscriptiont divergence between rich and poor is faster than per capita PCs divergence while, at the same time seemingly paradoxically, mobile phone subscriber world shares converge faster than PCs world shares. These occur because PCs uptake is faster than mobile phone uptake in those economies intermediate between rich and poor.

To complete this description of a global Digital Divide, turn next to the distribution of digital technologies across regions—to bring a spatial dimension to Figures 1–8—and to their distribution across people *within* economies.

Figures 9–11 show the distribution of Internet users, mobile phone subscribers, and PCs across different world regions, divided according to the standard classification, Table 2. In all cases the OECD's

**Figure 9 World Internet users** Percentage located in different regions. See Table 2 for abbreviations.

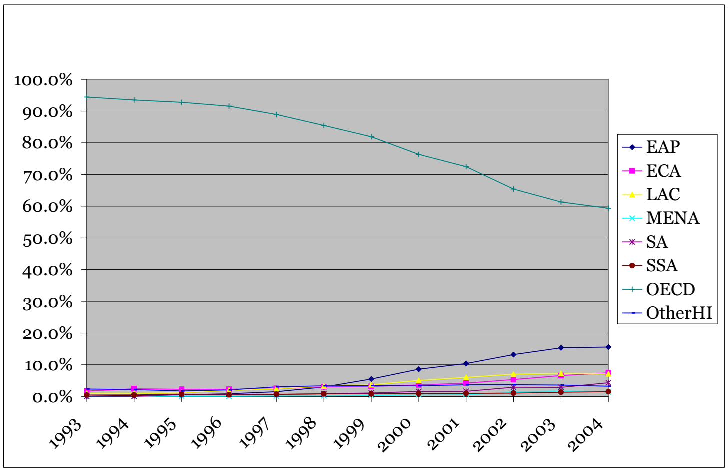


**Figure 10 World mobile phone subscribers** Percentage located in different regions. See Table 2 for abbreviations.

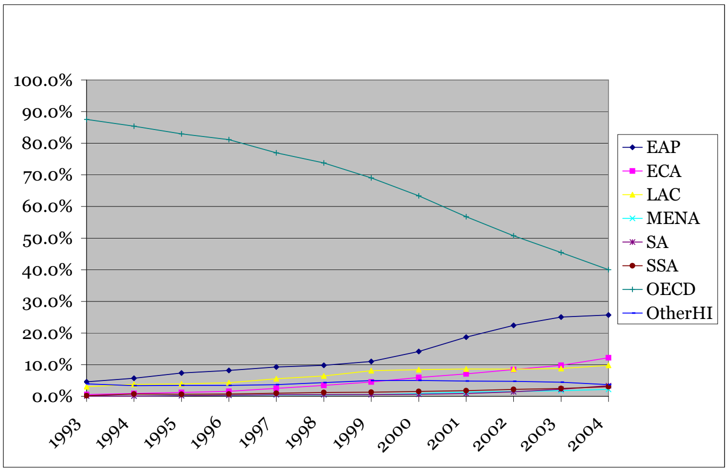
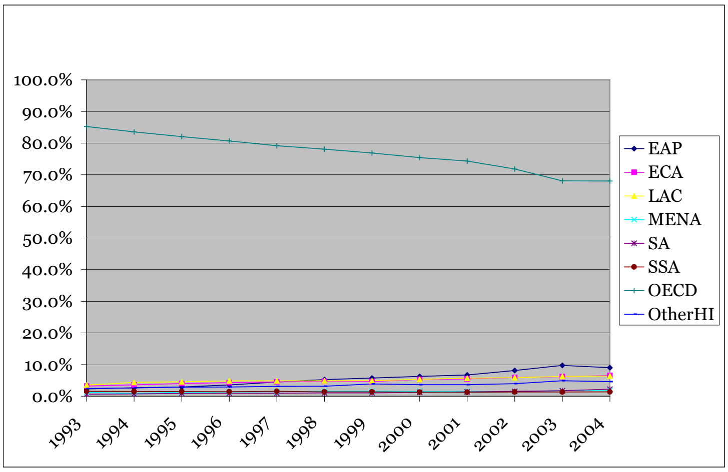


**Figure 11 World PCs** Percentage located in different regions. See Table 2 for abbreviations.



world share began in 1993 highest but then declined, most sharply for Internet users and mobile phone subscribers. Again, in all cases it is the East Asia and Pacific region that has caught up most strongly.[4]

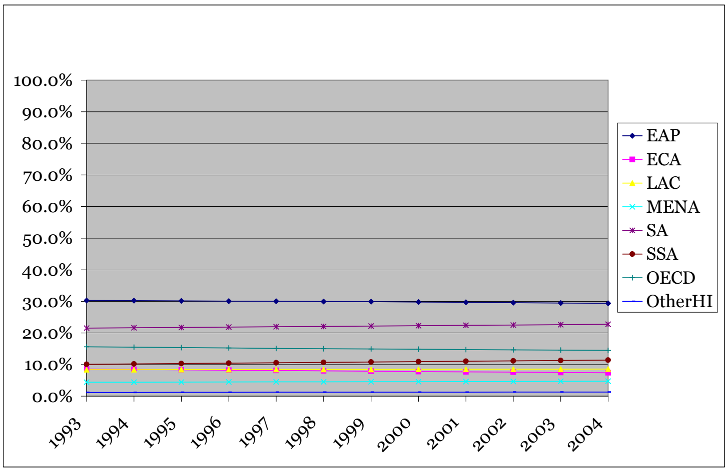
The dynamics in Figures 9–11 are due not to population size dynamics—as expected, world population shares are very stable (Figure 12). Instead, it is variation in per capita quantities that matters for much of these Digital Divide dynamics, as indicated in Figures 13–15.

Mobile Phone subscribers as a fraction of the population have grown strongly everywhere, including notably Sub-Saharan Africa. In contrast, Internet users and PCs have risen most rapidly in the OECD

---

[4] Data on PCs are not available for 1993 MENA and 1993–1996 SSA in World Bank (2006b). Those are instead estimated from fitting the flexible logistic dissemination model, equation (21) in Section 3.4. The resulting estimated counts are so small, however, that they make very little difference to final world shares.

**Figure 12 World population** Percentage located in different regions. See Table 2 for abbreviations.



and other high-income economies, and much less so elsewhere. In Sub-Saharan Africa by 2004 mobile phone subscribers reached 7.4% of the population, nearly double the ratio in South Asia. Even as the OECD and other high-income economies had mobile phone subscribers of almost 80% of the population in 2004, East Asia and the Pacific had 24%; Eastern Europe and Central Asia, 46%; Latin America and the Caribbean, 32%. For Internet users and PCs, however, the analogous percentages of the population in 2004 were OECD, 56% and 58%; East Asia and the Pacific, 7% and 4%; Eastern Europe and Central Asia, 14% and 11%; Latin America and the Caribbean, 12% and 9% only.

For comparison Figures 16 and 17 show world shares and per capita incomes, measured at PPP-adjusted International$. [5]

---

[5] Per capita income in PPP-adjusted International$ are unavailable for *Other high-income* economies for 1993–4 and 2002–04, and so those points are omitted in Figure 17. Total population there is rela-

**Figure 13 Internet users, percent of population** See Table 2 for abbreviations.

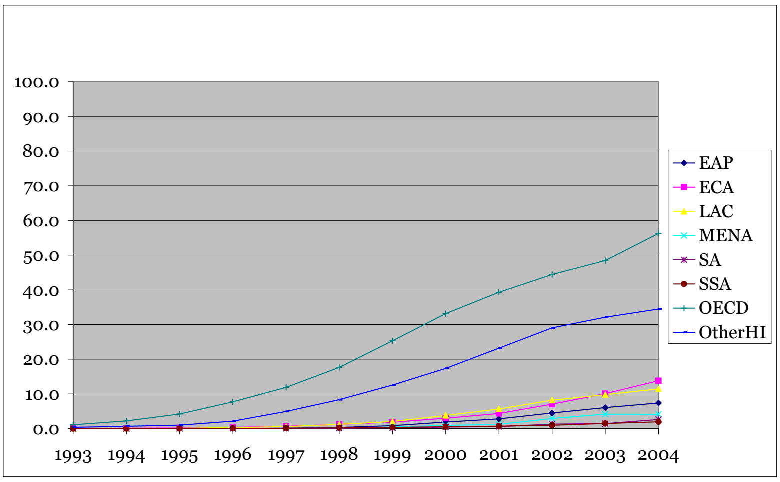


**Figure 14 Mobile phone subscribers, percent of population** See Table 2 for abbreviations.

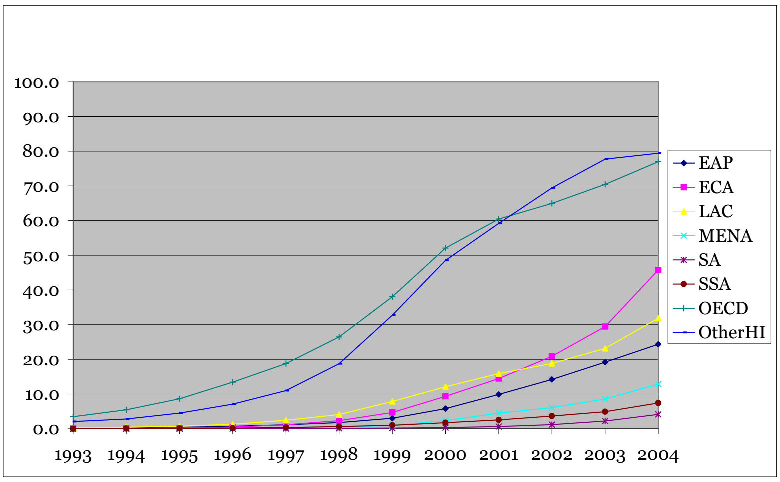


**Figure 15 PCs, percent of population** See Table 2 for abbreviations.

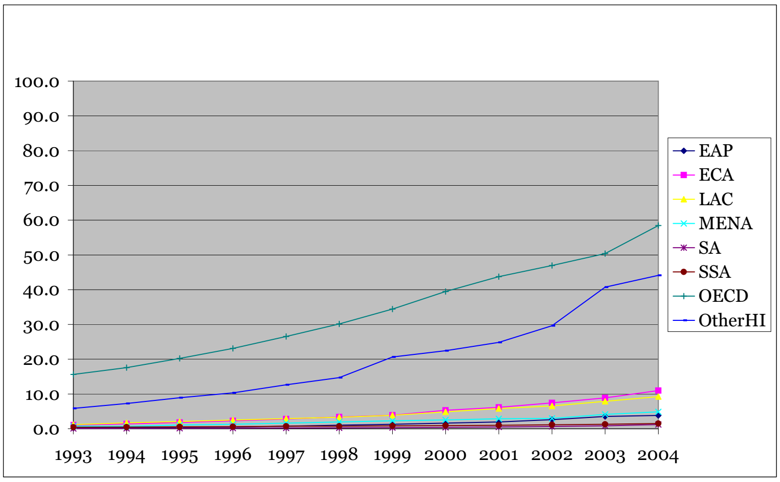


**Figure 16 World income** Percentage located in different regions. See Table 2 for abbreviations.

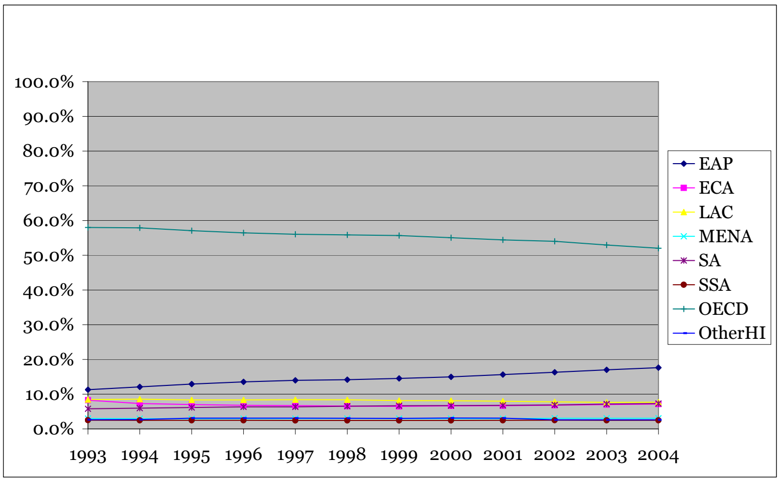
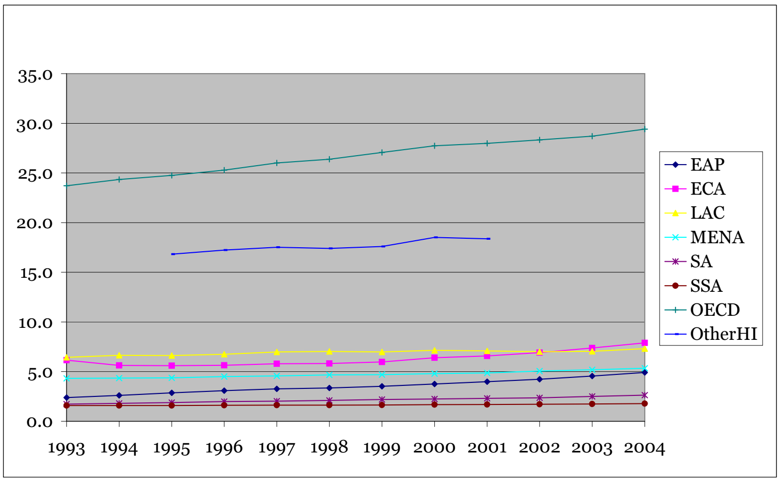


**Figure 17 Per capita income** ($10^3$Intl$) See Table 2 for abbreviations.



The discussion thus far can be summarized as follows. Across countries, the Digital Divide on mobile phones is already closing rapidly; that on Internet usage and PCs, not so. The divide on the latter two is proportionally larger than that on incomes.

Table 3 provides information on the dynamics of the concentration of per capita digital technologies across regions. As most of the underlying data are naturally bounded, I present end-points rather than, say, growth rates. Thus, while the East Asia and Pacific region had had per capita income rise from 10% to 17% of OECD levels between 1993 and 2004, per capita Internet users there had grown by 2004 to 13% of the OECD average from 0.1% in 1993. Even Sub-Saharan Africa had mobile phone subscribers rise from 0.3% to 10%, in contrast to per capita income levels falling from 7% to 6% of OECD

---

tively small, however, so that the income shares plotted in Figure 16 change only imperceptibly whether the per capita income figures are held constant, or extrapolated linearly or exponentially.

**Table 3** Digital technology regional dynamics: Relative per capita concentration over time. See Table 2 for abbreviations.

| | Ratio (%) relative to OECD: (1993, 2004) | | | |
|---|---|---|---|---|
| | Per capita | | | |
| | Income | Internet users | Mobile subscribers | PCs |
| EAP | (10, 17) | (0, 13) | (3, 32) | (1, 6) |
| ECA | (26, 27) | (4, 24) | (1, 59) | (7, 19) |
| LAC | (27, 25) | (3, 20) | (6, 41) | (8, 16) |
| MENA | (18, 18) | (0, 7) | (0, 17) | (5, 8) |
| SA | (7, 9) | (0, 5) | (0, 5) | (0, 2) |
| SSA | (7, 6) | (1, 4) | (0, 10) | (3, 3) |

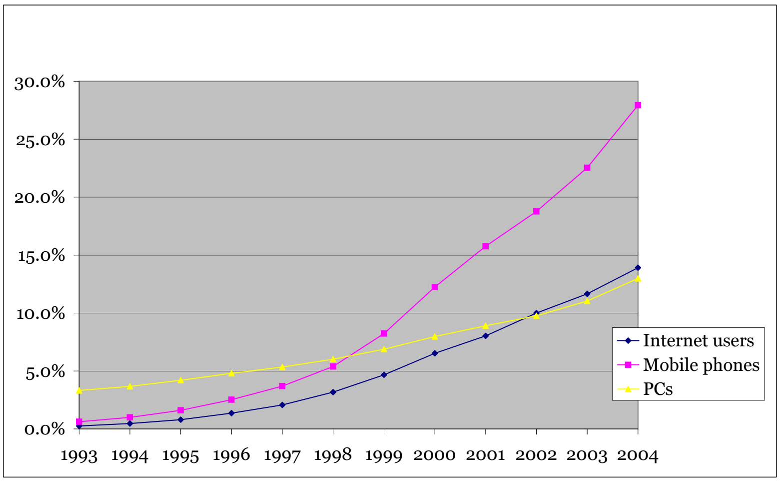
averages over this same time period, and Internet users growing only from 1% to 4% and PCs remaining at 3%. Similarly, the Middle East and North Africa saw mobile phone subscribers increasing sharply from 0.4% to 17%, even though per capita incomes remained flat at 18%, and Internet users and PCs grew much less. Outside of the fast-growing East Asia and the Pacific, per capita income in all regions grew at only the same rate as the OECD. But everywhere saw per capita mobile phone subscriptions growing much faster than in the OECD, and everywhere had mobile phone subscriptions rising much faster than their Internet usage and PCs.

## 2.2 Within economies

Just as there is inequality across economies, obviously so too across people—both looking within a given economy and comparing people across country boundaries.

Figure 18 shows the dissemination over time of digital technologies across the world's population. From Section 2.1 it is no surprise that mobile phone dissemination has been the most rapid, of the

**Figure 18 Dissemination across people worldwide**

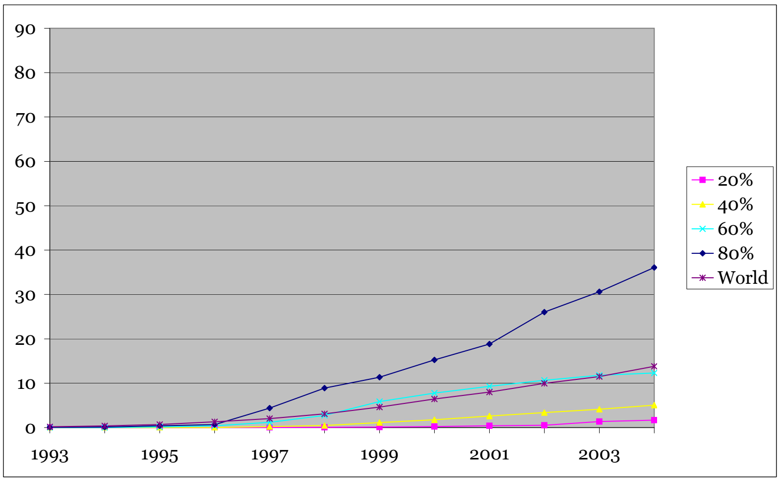


different technologies. In 1993 worldwide, PCs numbered 3% of the population; by contrast, Internet users were 0.3% and mobile phones, 0.6%. By 2004, while PCs worldwide had grown to 13% of the world's population and Internet users to 14%, mobile phones had shot ahead to double that ratio, to 28 of the population%.

Reproducing a figure like Figure 18 one for each of over 200 economies is possible but does not effectively communicate useful information. Instead, the analysis seeks to capture the cross-section dynamics of the within-country Digital Divide by looking at what happens at percentile points in the cross-country distribution. There is no unique and uniformly preferred way to do this so I use the following.

Rank all economies in 2004 by how much a particular digital technology has disseminated in the population. (Choosing the end of the sample to calculate this ranking allows incipient differences across economies to emerge and to manifest more obviously than at the beginning of or on average over the time sample.) We will do this eventully for each digital technology. For a specific technology, how-

**Figure 19 Dissemination within countries: Internet users as percentage of the population** Ranking economies in 2004, the 20th-percentile economy was Sri Lanka; 40th-percentile, Armenia; 60th-percentile, Trinidad and Tobago; and 80th-percentile, Cyprus. The line labelled World treats people as if the world were a single integrated economy.



ever, call the *nth-percentile economy* that economy that in 2004 had achieved dissemination at the $n$th-percentile rank in the cross-country distribution. Fix that economy and look at its dissemination dynamics. Do this for a range of values of $n$.

Figures 19–21 show these dissemination dynamics for the 20th-, 40th-, 60th-, 80th-percentile, and world economies, one figure for each digital technology. For mobile phones Figure 20, the 80th-percentile economy shows mobile penetration 70 percentage points greater than that in the 20th-percentile by 2004, while for Internet users and PCs, the analogous difference is only 34 and 27 percentage points respectively. Mobile phones have spread both significantly and rapidly in poorer economies, but at the same time still unevenly. While poorer economies are catching up with richer ones in this indicator more than

**Figure 20 Dissemination within countries: Mobile phone users as percentage of the population** Ranking economies in 2004, the 20th-percentile economy was the Kyrgyz Republic; 40th-percentile, Guyana; 60th-percentile, South Africa; and 80th-percentile, Cyprus. The line labelled World treats people as if the world were a single integrated economy.

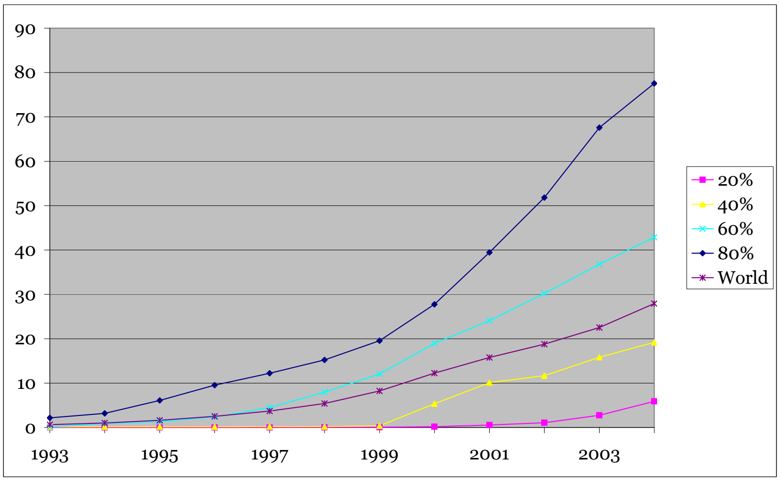
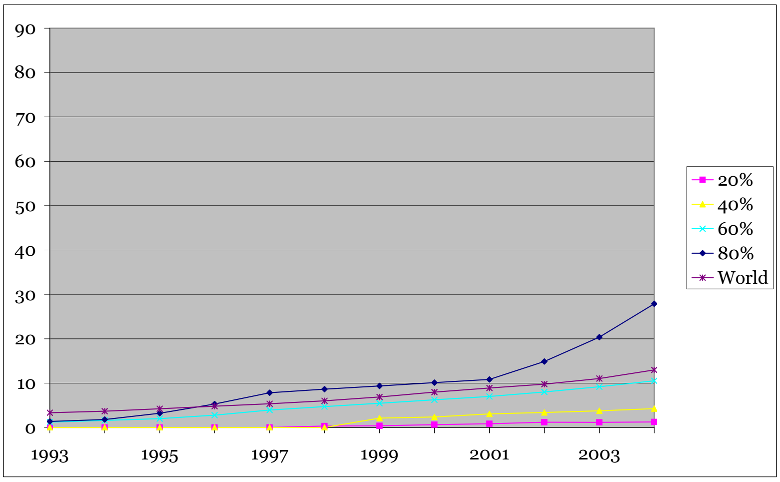


**Figure 21 Dissemination within countries: PCs as percentage of the population** Ranking economies in 2004, the 20th-percentile economy was Bhutan; 40th-percentile, Georgia; 60th-percentile, Trinidad and Tobago; and 80th-percentile, Mauritius. The line labelled World treats people as if the world were a single integrated economy.



any other, across the collection of poor economies inequality, even in mobile phone usage, has continued to grow.

Ono (2005)
DiMaggio, Hargittai, Celeste, and Shafer (2004)
Hargittai (2003)

### 2.3 Potential benefits: First estimates

What are the benefits to closing this Digital Divide? Available estimates are suggestive, if disparate.

The most exhaustive microeconomic evidence is from World Bank (2006a). The surveys carried out over 2000–2003, covering 20,000 firms in 56 low- and middle-income economies, provide some striking findings: In developing countries enterprises that use email to interact with customers and suppliers, compared to enterprises that don't, have higher employment growth, ten times the sales growth, double the profitability, and two-thirds higher labor productivity (World Bank, 2006a, pp. 62, 81).[6] Clarke and Wallsten (2004) estimate that increasing the Internet population by 1% increases exports by 4.3 percentage points and exports from low-income to high-income countries by 3.8 percentage points.

Some examples in the literature, although outside traditional economics, suggest similarly significant welfare gains to closing the Digital Divide.

---

[6] These comparisons condition on enterprise characteristics (such as ownership, size, age, and export status), and unobserved country and sector characteristics. Email is, of course, just one possible indicator of ICT usage. Two others considered in these surveys are the fraction of the enterprise's workforce who use computers in their jobs, and when the enterprise uses to deal with customers and suppliers. The results are similar across alternative indicators.

A widely-cited Harvard Medical Practice Study suggests that in 1997 preventable medical errors caused over 98,000 deaths in the US.[7] Even had this figure been a two-fold over-estimate, preventable medical errors alone would still have accounted for more deaths in the US than auto accidents (43,458), breast cancer(42,297), and HIV/AIDS (16,516).

In the popular misconception, operating-room surgical mistakes are the high-visibility causes for medical errors. However, the reality is that health-care is an information-intensive industry: Much medical provision and care concerns the appropriate flow of information on patients and medications. Estimates reported in Kohn et al. (2000, p. 40) imply that, compared to 1997-vintage medical practice, computer-based drug order entry could have prevented 84% of the missing dose medication errors, 86% of potential adverse drug events, and 60% of the preventable adverse drug events.

To translate such observations into financial terms, recall that 2003 worldwide spending on healthcare amounted to \$3.43 trillion; the US alone accounted for \$1.57 trillion, or 46% of the global total.[8] Walker et al. (2005) shows.

[...]

To understand the Digital Divide outcomes we need at least to balance those potential benefits just described against costs. However, evidence on costs is less easily obtained.

---

[7] See Kohn et al. (2000, p. 30) and references. The study estimated 3.7% of hospitalizations in New York state led to adverse medical events, 13.6% of which led to patient death; 58% of all such events were preventable. A total of 33.6 million hospitalizations occurred in the US in 1997. In a related study Starfield (2000) obtained yet higher numbers for preventable medical deaths, ranging up to 200,000.

[8] By contrast, all of South Asia spent only \$0.03 trillion on healthcare. These data are in constant 2000 US\$, from World Bank (2006b).

[[Logistic curve in dissemination - not universal but certainly relevant here; (Comin, Hobijn, and Rovito, 2006; Norris, 2001) ]]

## 3 Analytics

For analytical convenience it is useful to structure the discussion at three distinct levels, later to be integrated.

The first part of the discussion here involves, mainly, normative issues; the next two, positive concerns. To begin, I provide dynamic welfare calculations. The framework I use is not the only way to calibrate costs and benefits for the exercise here, but it is coherent and can be further extended as needed. The formulation is now standard in macroeconomics (e.g., Lucas, 2003), and has been used to analyze economic growth, business cycles, income inequality, and many other macroeconomic phenomena.

Second, I provide a simple dynamic macroeconomic formalization of cross-country or cross-community technological catchup. This allows discussion of the Digital Divide across entire countries or category groupings. The formalization is little more than a set of mechanical equations but it makes explicit where further calibration and measurement are needed. A narrowing or widening Digital Divide along transition paths to steady states which, in turn, might involve permanent gaps between leading and lagging countries. The model allows identifying what factors matter and what further information is needed to persistence of a Digital Divide across macroeconomic units.

Third, I formalize digital dissemination across individual agents, i.e., businesses or people. The model is one of so-called social or population dynamics (e.g., Montroll, 1978), modified to study the society-wide gradual adoption of technology. The formalization takes into account possible heterogeneity across individuals and feedback from society-wide outcomes to individual actions. Again, just as with that of cross-country dynamics, the model here points to where further information is needed to evaluate the possibilities of a persistent Digital Divide.

These three levels mirror three key questions to formalize in this study of the Digital Divide. First, how does the Digital Divide affect the well-being of different people? Second, what are the dynamics of the Digital Divide across countries, taking as given measurements on average digital attainment in each country? Third, what are the dynamics of the diffusion of digital attainment across individuals—businesses, consumers—within a society? Building our understanding of the latter two questions then allows going back to the first, welfare question and thus gives a calibration of the returns to intervention on the Digital Divide.

### 3.1 Dynamic Welfare

Consider the well-being of individuals in some society (country or community) $A$, compared to those in a different society $B$. Denote consumption by $C$. Let utility at each instant of time be $U$, with lifetime utility then being a present discounted value of the stream of utility over time.

For the time being suppose that consumption $C$ denotes consmption of goods and services *other* than those directly associated with digital technologies. (Assume, again for now, that such a separation can be meaningfully made.) Describe the *digital environment*—availability and cost of Internet access, cellphone telephony, personal computers, digital-mediated entertainment, political information and activism, and so on—by $\mathcal{Z}$. Digital environments in societies $A$ and $B$ cannot of course be directly compared to one another. An environment has multiple attributes: one society might have better Internet access but worse cellphone infrastructure. So it makes no sense to write $\mathcal{Z}_0 > \mathcal{Z}_1$ or $\mathcal{Z}_0 < \mathcal{Z}_1$. But the digital environment does affect an individual's well-being, so that even at the same measured consumption $C$, we might have $U(C \mid \mathcal{Z}_0) > U(C \mid \mathcal{Z}_1)$, when $\mathcal{Z}$ in $A$ is preferred to that in $B$. If this inequality holds and $c$ is the current consumption level in society $B$, suppose that the number $\Psi \geq 0$ gives

$$U(c \mid \mathcal{Z}_0) = U([1 + \Psi]c \mid \mathcal{Z}_1). \tag{1}$$

Then say that $\Psi$ is the [consumption] *welfare gain* of the digital environment $\mathcal{Z}_0$ over $\mathcal{Z}_1$. Thus, $\Psi$ is the value to $B$ of closing the Digital Divide between $\mathcal{Z}_0$ and $\mathcal{Z}_1$, measured in terms of the fraction of current levels of consumption.[9]

Two observations on equation (1) are useful to make right away. First, obviously, (1) provides only a hypothetical calculation. Society $B$ might well be able to raise consumption from $c$ to $[1 + \Psi]c$ *only* if digital environment $\mathcal{Z}_0$ is in place, but not under just $\mathcal{Z}_1$. Proponent of wireless Internet, for instance, might argue that the absence of such infrastructure simply shuts off many consumer possibilities. This, however, is irrelevant to the conceptual welfare calculation described in (1): One can consider the hypothesis that consumers have access to such goods and services, without concerning oneself with the mechanics of how those goods and services are provided.

Second, while equation (1) applies broadly, it omits mention of dynamics and time. But a significant promise of digital technologies is that of boosting economic growth or, more generally, that of rewards spread over time. Making explicit the dynamics should therefore provide essential insight.

To that end, let individual consumption and the digital environment evolve through time. Write their respective timepaths or profiles beginning from time $t = 0$ as $\{\, C(t) : t \geq 0 \,\}$ and $\{\, \mathcal{Z}(t) : t \geq 0 \,\}$, and let $\rho > 0$ denote the discount rate. Then write the well-being of a typical agent living under such a regime as:

$$W = \int_0^\infty e^{-\rho t}\, U(C(t) \mid \mathcal{Z}(t))\, dt. \tag{2}$$

What a welfare gain $\Psi$ measured as in equation (1) means in such a dynamic calculation is not always obvious: Is the entire timepath of

---

[9] Such a calculation with $\mathcal{Z}$ describing not the digital environment but instead income inequality was used in Quah (2006).

consumption changed proportionally by $[1+\Psi]$, or just the immediate, current level of consumption? Or, is some other variation in $C$ more insightful? This choice will need to be determined on an adhoc case-by-case basis.

A leading case of interest arises when the digital environment $\mathcal{Z}$ can be left implicit in $U$ because $\mathcal{Z}$ is hypothesized to affect agents' welfare only through its impact on consumption. For instance, $\mathcal{Z}$ might influence productivity and thus the long-run underlying growth rate for the economy; but it is not itself directly valued for any other reason.[10] Analyze this scenario by considering the following specific class of consumption timepaths:

$$\dot{C}/C = \xi(\mathcal{Z}), \tag{3}$$

so that given an initial level $C(0)$ the consumption timepath is:

$$C(t) = C(0)e^{\xi(\mathcal{Z})t}, \qquad t \geq 0.$$

(The notation $\dot{C} = dC/dt$ indicates taking the time derivative.) The welfare gain calculation (1) can then be naturally made by comparing how variations in $\mathcal{Z}$ affect the growth rate $\xi$ against changes in the level $C(0)$ itself. Conveniently, in this case, $C(0)$ describes both the initial level of consumption and the overall level of the consumption profile.

This example, when numerically calibrated, could be used to show the following. Suppose someone external to the economy under study invests US$ 50bn to upgrade the digital environment $\mathcal{Z}$. The model might show that this produces an improvement in the underlying growth rate $\xi$ so that, using equations (1) and (2), the resulting welfare gain amounts, in absolute terms, to US$ 60bn. The net benefit

---

[10] This highlights a contrast between, on the one hand, many economists' concerns over the productivity paradox—whether 1990s ICT proliferation raised productivity—while, on the other hand, an economically significant fraction of the population enthusiastically threw itself into the political organization and activism, and the social networking on a scale and of a nature impossible without the Internet, mobile telephony, and other digital technologies.

from that investment would therefore be US$ 10bn, and the rate of return 20%.

To carry out such an exercise, we need to specialize functional forms and provide an explicit formula for $\Psi$.

**Lemma 1** *Suppose that in equation* (2) *the digital environment* $\mathcal{Z}$ *affects utility only through the growth rate of* $C$*, as in equation* (3)*. Let utility* $U$ *have the form*

$$U(c) = \frac{c^{1-R} - 1}{1 - R}, \qquad R \geq 1. \tag{4}$$

*The resulting welfare* $W$ *behaves as follows:*

*i. if* $R = 1$ *then*

$$W = \rho^{-1} \log C(0) + \rho^{-2} \xi(\mathcal{Z});$$

*ii. if* $R > 1$ *then*

$$W = (1 - R)^{-1} \times \left\{ \frac{C(0)^{1-R}}{\rho - (1 - R)\xi(\mathcal{Z})} - \rho^{-1} \right\}.$$

The parameter $R$ in equation (4) describes the curvature of the utility function. In a stochastic model, $R$ would be the coefficient of relative risk aversion. As $R$ goes to 1, utility $U$ converges to the logarithmic function.

Under Lemma 1, explicit expressions can be given for the welfare gain $\Psi$ to closing the Digital Divide. This calibration, moreover, turns out to be invariant to the initial level of consumption.

**Proposition 2** *Assume the hypotheses in Lemma 1. Suppose that the current digital environment* $\mathcal{Z}$ *implies a long-run steady state growth rate* $\xi$*, while the environment* $\mathcal{Z}'$ *in some leading economy gives a long-run steady state growth rate* $\xi' > \xi$*. Then, comparing steady states, the welfare gain to closing the Digital Divide when* $R = 1$ *is*

$$\Psi = \exp\left( [\xi' - \xi]\, \rho^{-1} \right) - 1, \tag{5}$$

*and when* $R > 1$ *is*

$$\Psi = \left[ \frac{\rho + (R-1)\xi'}{\rho + (R-1)\xi} \right]^{\frac{1}{R-1}} - 1\ . \tag{6}$$

Equation (6) can be rewritten

$$\begin{aligned} (1+\Psi)^{R-1} &= \frac{\rho + (R-1)\xi'}{\rho + (R-1)\xi} \\ \Longrightarrow\ (R-1)\log(1+\Psi) &= \log\left( \frac{\rho + (R-1)\xi'}{\rho + (R-1)\xi} \right) \\ &= \log\left( 1 + \frac{(R-1)(\xi' - \xi)}{\rho + (R-1)\xi} \right) \end{aligned}$$

to give, for small $\Psi$, the approximation

$$\Psi \approx \frac{\xi' - \xi}{\rho + (R-1)\xi}. \tag{7}$$

[When $R \searrow 1$ approximation (7) also appropriately becomes the analogous approximation derived directly from equation (5).] In words the welfare gain varies proportionally with the improvement in growth rates, with the constant of proportionality decreasing in the discount factor $\rho$ and the curvature of the utility function $R$. When utility is logarithmic that constant of proportionality is $\rho^{-1}$, the reciprocal of the discount rate. In general, however, for the calculation in (5) curvature $R$ has effect similar to the discount rate $\rho$'s. Increases in either, other things equal, lower the potential welfare gain: $R$ downweights further increases in consumption; $\rho$ downweights future increases in consumption.

To bring some numerical intuition into this discussion, consider a representative emerging economy. Suppose that currently its annual per capita growth is 2%, per capita consumption is US$ 4,000 (at purchasing power parity), and population 75 million. (To fix ideas further such numbers make the hypothetical economy similar to Egypt in 2005.)

The discount rate and curvature of the utility function would need to be estimated to make this exercise rigorous, but for illustration

**Table 4** Proposition 2: ("Egypt") Welfare gains for different growth effects $\xi \to \xi'$ and utility curvature $R$, fixing the discount rate $\rho = 5\%$

| | $\Psi$ | | | US$ bn | | |
|---|---|---|---|---|---|---|
| | $R$ | | | $R$ | | |
| $\xi \to \xi'$ | 1 | 2 | 5 | 1 | 2 | 5 |
| $2 \to 4\%$ | 0.49 | 0.29 | 0.13 | 148 | 86 | 38 |
| $1 \to 4\%$ | 0.82 | 0.50 | 0.24 | 247 | 150 | 71 |

assume the discount rate is 5% and utility curvature has $R = 5$. A critical question obviously is the impact on economic growth of closing the Digital Divide. Suppose that a US$ 50bn investment in ICT in this hypothetical economy doubles its growth rate. It is unclear whether such a change is realistic but no modern developed economy has yet sustained a per capita growth rate exceeding 4% annually.

Equation (6) says the resulting welfare gain is 12.7%. Multiplying this fraction by the product of per capita consumption and population size gives a total positive impact of US$ 38bn, i.e., a net *loss* of US$ 12bn relative to the initial investment. If, however, curvature $R = 2$ then the total welfare gain is US$ 86bn, implying a net gain of US$ 36bn. (For interest the breakeven point is $R \approx 3.72$.) When curvature $R = 1$ and utility is therefore logarithmic, the total welfare gain is now US$ 148bn, giving a net gain of US$ 98bn.

Table 4 shows the results from such numerical experiments. Its first row contains the change just discussed. The second row shows what happens if the underlying growth rate is, instead, 1%, so that the increase to 4% is a quadrupling. Then, under logarithmic utility, the net gain can be as much as nearly US$ 200bn; even with $R = 5$ the net gain is now US$ 21bn.

Again, to be clear, these calculations are only illustrative. Nothing has yet been said on what impact closing the Digital Divide will actually have; how much it will take to achieve that; how gradual the economy undergoes in transition before reaching steady-state; what the differential effects are on different groups in the macroeconomy; what impact the Digital Divide has beyond just productivity; and many other issues. But we can now see, from this section, the payoff to addressing these questions quantitatively. The discussion that follows attempts to get at some although necessarily not all of the required calibration.

### 3.2 Macroeconomic catchup

What dynamic mechanism relates Digital Divide outlays to macroeconomic outcomes? Are there feedbacks and spillovers across different economies along the Digital Divide? How does catch-up in economic well-being occur gradually or not at all—will the Digital Divide narrow slowly, or will it persist? This section provides a simple model indicating where explicit quantification is needed to address such questions.

Consider many economies, respectively labelled 0 (leader) and $j = 1, 2, \ldots, J-1$ (followers). Suppose we can measure in each economy a *digital attainment* level $Z \in (0, \infty]$, a scalar variable summarizing the state of the digital environment $\mathcal{Z}$. Economy 0 is said to be the leading economy because $Z_0 \geq Z_j$, for all $j = 1, 2, 3, \ldots, J-1$.

Assume that the leading or frontier digital attainment $Z_0$ can be increased smoothly through time by:

$$\dot{Z}_0/Z_0 = \phi_0(X_0), \qquad \phi_0' > 0 \text{ and } \phi(0) = 0, \tag{8}$$

where $\phi_0'$ denotes the function $\phi$'s first derivative; the scalar $X_0 \geq 0$ is the expenditure in economy 0 intended to raise $Z_0$; and the increasing function $\phi_0$, specific to economy 0, describes how that expenditure is effective in making $Z_0$ grow.

Each economy's setting for $X$ will measure at least R&D expenditure in cutting-edge scientific laboratories. Additionally, it can also take into account broad-based spending on skills, literacy, and education, to raise average human capital in that economy. The point is that raising digital attainment is socially costly, as measured by $X$.

The relevance of this feature becomes more transparent with the following assumed specification for digital attainment dynamics in the follower economies, $j = 1, 2, \ldots :$

$$\dot{Z}_j = \begin{cases} (Z_0 - Z_j)\,\phi_j(X_j) & \text{when } Z_0 > Z_j \text{ and} \\ 0 & \text{otherwise,} \end{cases} \tag{9}$$

where function $\phi_j$ has $\phi_j(0) = 0$ and derivative $\phi'_j \geq 0$. The follower economy adapts the digital attainment in the leader economy for its own use. The greater the size of the gap $Z_0 - Z_j$ the more that economy $j$ has to adapt. Conditional on this gap, an economy can increase the speed of catch-up by spending $X$ to increase $\phi$.

Call *Cross-country Dissemination* the collection of Digital Attainment ratios $S_j = Z_j/Z_0 \in [0, 1]$. The *Cross-country Digital Divide* is the collection of numbers

$$D_j = 1 - S_j = \frac{Z_0 - Z_j}{Z_0} \in [0, 1].$$

Writing $D$ without a subscript to indicate the entire collection $D_j$ for $j = 1, 2, \ldots, J - 1$, the dynamics of the Digital Divide is then traced out by $\{\, D(t) : t \geq 0 \,\}$.

**Proposition 3** *Suppose*

$$X_j,\ j = 0, 1, \ldots, J,$$

*are constants and* $\phi_0(X_0) > 0$. *For each follower economy* $j > 0$ *and from any initial positive* $D_j(0) > 0$, *if* $\phi(X_j) < \infty$ *then the Digital Divide converges to a positive separation in the long run,*

$$D_j(t) \to D_j^* = \frac{\phi_0(X_0}{\phi_j(X_j) + \phi_0(X_0)} > 0, \qquad \text{as } t \to \infty.$$

*Convergence to* $D^*$ *occurs at the exponential rate*

$$[\phi_j(X_j) + \phi_0(X_0)].$$

The greater is the social expenditure $X$ in a given economy, the faster is convergence and the smaller the Digital Divide in steady state. By contrast when the leader economy increases its expenditure

$X$ to improve its digital environment, all follower economies benefit too through faster convergence. However, in that case the Digital Divide is also larger in long run steady state unless the follower economies also increase their expenditures $X$—dissemination is not a free lunch.

### 3.3 Social dynamics

Thus far, the discussion and quantification have been macroeconomic: we have studied what happens only at the aggregate or average level. Within each society, however, individuals experience specific and heterogenous outcomes. This section provides a simple tractable framework to study the resulting distribution dynamics as digital technology disseminates, gradually and differentially, within a society.[11]

Fix an economy and consider in it a continuum of people, indexed on the closed unit interval $[0, 1]$. Call this the *population*. New technologies are available in a (metaphorical) pool surrounding the population, and the individual can choose whether to use a given technology.

Assume the adoption of technology is an absorbing state, i.e., once it occurs, the individual never relinquishes the technology. The case when adopting a digital technology can occur multiple times—e.g., an individual can acquire more than one cellphone or PC—will be considered in Section 3.4.

Here, call those in the population who have adopted the technology *extant adopters* or *digital-savvy*; the others are only *potential adopters* or *digital have-nots*.

Begin by supposing that at the initial time $t = 0$, everyone is only potential. Describe the choice made by a potential adopter in terms of a *hazard rate* or *hazard*,

$$\mathsf{h}(t) \geq 0, \quad t \in [0, \infty).$$

---

[11] Young (2005) discusses this same question using a different but related mathematical framework, with more detailed specification of social spillover.

At time $t$ a potential adopter will over the next infinitesimal unit of time $dt$ adopt the new technology with probability $\mathsf{h}(t) \times dt$. In general the hazard rate $\mathsf{h}$ will vary with time $t$ as well as any other factors relevant to the individual's decision. The individual will weigh costs and benefits in deciding whether to adopt the new technology. Such considerations might be specific to the individual, such as his income or his education or his costs to learn the applications of the new technology (e.g., Quah, 2001). Or, the considerations might be general and society-wide, such as the size of the population in that community who have already adopted the technology.

Beginning from time $t = 0$ denote the time of the first adoption in the population by the *epoch* or timepoint $t_1$; the second adoption by $t_2 \geq t_1$; the third, $t_3 \geq t_2$; and so on. Call $\mathsf{F}(t)$, $t \geq 0$, the fraction of the population who have become extant adopters at time $t$. Since adoption is an absorbing state by assumption, $\mathsf{F}(t)$ only ever increases in time, at random epochs $t_k$. Early adoption might occur mostly because the individual has high income or is computer-literate; later adoption, on the other hand, might occur more through the potential adopter's observing the rewards to that population of already extant adopters.

To understand the effects of different values for $\mathsf{h}$ we can first hypothesize that $\mathsf{h}$ varies only with time and society-wide variables, and that conditional on $\mathsf{h}$ individual adoption decisions are independent. Then probabilistic adoptions are identically distributed and conditionally independent, so that:

$$\frac{d}{dt}\mathsf{F}(t) = \mathsf{h}(t) \times [\,1 - \mathsf{F}(t)\,]. \tag{10}$$

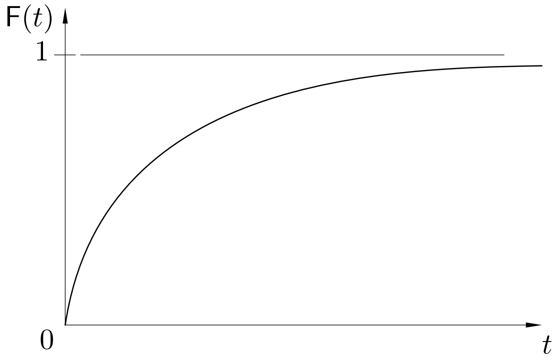
The rate of increase in the extant adopter population equals the hazard rate multiplied by the size of the potential adopter population.

Equation (10) is a differential equation describing the dynamics of $\mathsf{F}$, the digital-savvy fraction of the population, with driving variable $\mathsf{h}$, the adoption hazard rate chosen by individuals in the population. Put differently, equation (10) gives the social or population distribution dynamics implied by actions undertaken at the individual level.[12]

---

[12] What has just been given is not always the standard interpre-

**Figure 22 Exponential dissemination,** $\mathsf{F}(t) = 1 - \exp(-\overline{h}\, t)$**.** The population adopts the new technology rapidly at first but then the adoption rate monotonically falls to zero. Because the digital-savvy fraction rises quickly from 0, and then slows down and converges smoothly towards 1, the Digital Divide is large early on but then vanishes altogether.



By definition $1 - \mathsf{F}(t)$ is the fraction of the population not using the new technology: it forms a natural measure of the Digital Divide in a society. When $1 - \mathsf{F}(t)$ equals 1 everyone is, of course, equally technology-bereft. Thus, while it does not measure inequality, $1 - \mathsf{F}(t)$ measures instead a social distance from new technology.

But beyond providing any specific measure, this model also shows explicitly how the Digital Divide evolves as a collective social outcome. That outcome is one that results from every individual's choice of their own $\mathsf{h}$, selected to reflect costs and benefits appropriately. Call such a collective social outcome, i.e., a timepath for $\mathsf{F}$ consistent with individual $\mathsf{h}$'s and a given initial condition $\mathsf{F}(0)$, an *equilibrium dissemination*.

In the simplest case the hazard is a positive constant, $\mathsf{h}(t) = \overline{h} > 0$. Together with the boundary condition $\mathsf{F}(0) = 0$, the entire society

---

tation for this stochastic specification. Section 6.1 in the Appendix provides that alternative discussion.

begins with no one yet using the new technology, the solution to the differential equation (10) is (Figure 22):

$$\mathsf{F}(t) = 1 - e^{-\overline{h}\,t} \to 1 \text{ as } t \to \infty. \tag{11}$$

More generally, $\mathsf{h}(t)$ will vary with time, so that

$$\begin{aligned} \frac{d\mathsf{F}(t)/dt}{1-\mathsf{F}(t)} &= \mathsf{h}(t) \text{ and } \mathsf{F}(0) = 0 \\ \implies \mathsf{F}(t) &= 1 - e^{-\int_0^t \mathsf{h}(s)\,ds}. \end{aligned} \tag{12}$$

Dissemination is now no longer exponential but depends on the hypothesis for the functional form in $\mathsf{h}$.

If $\mathsf{h}$ is always bounded away from 0 then society eventually reaches complete saturation: the Digital Divide vanishes and there is 100% dissemination of the new technology. Conversely, a Digital Divide can be permanent if $\mathsf{h}$ goes to zero sufficiently quickly, so that the right side of equation (12) remains bounded away from 1 as $t \to \infty$.

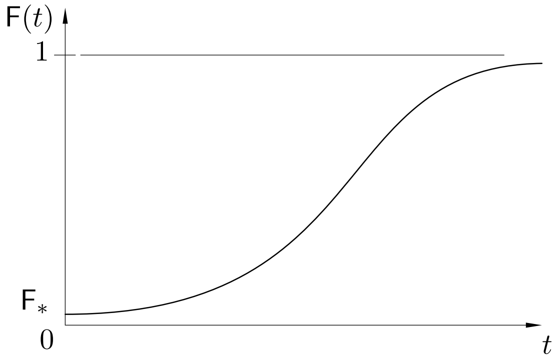
A leading case of interest arises when an individual's decision to adopt depends on aggregate events, such as how much of the population has already adopted:

$$\mathsf{h}(t) = \mathsf{h}(t, \mathsf{F}(t)).$$

Since the social outcome $\mathsf{F}$ affects the individual decision $\mathsf{h}$, feedback occurs from the aggregate to the individual. Individual hazard becomes endogenous relative to the aggregate or social distribution. If $\mathsf{h}$ is rising in $\mathsf{F}$, individual adoption becomes easier from contagion or peer-group effects. If, on the other hand, $\mathsf{h}$ decreases in $\mathsf{F}$, then a natural interpretation is that congestion effects dominate: in response to $\mathsf{F}$ rising the individual becomes progressively loath to adopt the new technology, so that $\mathsf{h}$ declines.

To obtain a model sufficiently flexible for calibration and welfare analysis, the remainder of this section considers two generalizations of the constant hazard model. The first, Proposition 4, provides an explicit analysis of aggregate feedback, and shows how such contagion

**Figure 23 Logistic dissemination,** $\mathsf{F}(t) = [1+(e^{\overline{h}\,t}-1)\mathsf{F}_*]^{-1}\mathsf{F}_*\, e^{\overline{h}\,t}$**.** The digital-savvy fraction rising from its initial low value of $\mathsf{F}_*$ encourages ever more rapid adoption, until reaching some maximum rate. But then dissemination slows as the base of potential adopters shrinks. Because $\mathsf{F}(t)$ converges towards 1 the Digital Divide gradually vanishes altogether.



can imply logistic dissemination, in place of the exponential in Figure 22. The second, Proposition 5, retains the contagion effect but frees up possibilities on whether dissemination must be eventually total; instead, the Digital Divide might persist permanently.

**Proposition 4** *Suppose that for numbers* $\overline{h} > 0$ *and* $\mathsf{F}_* \in (0, 1)$, *we have* $\mathsf{F}(0) = \mathsf{F}_*$ *and for all* $t \geq 0$ *the individual hazard is*

$$\mathsf{h}(t) = \mathsf{h}(t, \mathsf{F}(t)) = \mathsf{F}(t) \times \overline{h}\,. \tag{13}$$

*Then*

$$\mathsf{F}(t) = \frac{e^{\overline{h}\,t}\,\mathsf{F}_*}{1 + (e^{\overline{h}\,t} - 1)\,\mathsf{F}_*}\,, \quad \forall t \geq 0, \tag{14}$$

*is an equilibrium dissemination.*

Proposition 4 sets the initial condition $\mathsf{F}(0) = \mathsf{F}_*$ positive as otherwise, under the feedback hypothesis in equation (13), dissemination never begins. The assumption is that some fraction of the population, exogenously, had previously adopted the new technology. Equation (14) has the proportion $\mathsf{F}(t) \to 1$ as $t \to \infty$, so that this model shows the Digital Divide eventually vanishing. Away from the endpoints in time the dissemination shows obviously logistic behavior (Figure 23). To understand this, notice that equations (10) and (13) imply

$$\frac{d\mathsf{F}}{dt} = (1 - \mathsf{F})\mathsf{F} \times \overline{h}.$$

For times $t$ both small and large, the term $(1 - \mathsf{F})\mathsf{F}$, and thus $d\mathsf{F}/dt$ the rate of dissemination, will be small. At intermediate values of $t$, however, the term $(1 - \mathsf{F})\mathsf{F}$ is large; it is maximized at time $t$ where $\mathsf{F}(t) = \frac{1}{2}$. So too then $d\mathsf{F}/dt$.

While permitting logistic dissemination the model in Proposition 4 is restrictive in imposing eventual 100% saturation always. Instead, the following model might be more appropriate as it allows empirical analysis to reveal whether the Digital Divide eventually vanishes.

**Proposition 5** *Suppose that for* $\overline{h} > 0$, $\mathsf{F}_* \in (0, 1)$, *and* $\mathsf{F}^* \in (\mathsf{F}_*, 1]$, *we have* $\mathsf{F}(0) = \mathsf{F}_*$ *and for all* $t \geq 0$ *the individual hazard is*

$$\mathsf{h}(t) = \mathsf{h}(t, \mathsf{F}(t)) = \left\{ \frac{1 - \mathsf{F}(t)/\mathsf{F}^*}{1 - \mathsf{F}(t)} \right\} \times \mathsf{F}(t)\,\overline{h}. \tag{15}$$

*Then*

$$\mathsf{F}(t) = \frac{e^{\overline{h}\,t} \times \mathsf{F}^*\,\mathsf{F}_*}{\mathsf{F}^* + (e^{\overline{h}\,t} - 1)\mathsf{F}_*} \;\to\; \mathsf{F}^* \text{ as } t \to \infty \tag{16}$$

*is an equilibrium dissemination.*

Equations (13) and (15), of Propositions 4 and 5 respectively, share the feature that society-wide $\mathsf{F}(t)$ spillovers influence individual behavior $\mathsf{h}(t)$. Equation (15) nests (13); they differ when

$$\left\{ \frac{1 - \mathsf{F}(t)/\mathsf{F}^*}{1 - \mathsf{F}(t)} \right\} \neq 1.$$

Under the hypotheses of Proposition 5, this occurs whenever $\mathsf{F}^* < 1$.

With the individual hazard equation (15) then since $\mathsf{h}(t)$ has to be non-negative the implied dissemination grinds to a halt as $\mathsf{F}(t) \nearrow \mathsf{F}^*$, for $\mathsf{h}(t)$ then goes to zero. Thus, complete saturation never obtains; the Digital Divide is permanent. In general, the graph for dissemination (16) is as in Figure 23 except that the upper limit to which $\mathsf{F}(t)$ converges is $\mathsf{F}^* \leq 1$.

Equilibrium dissemination (16) turns out to apply even when the upper limit $\mathsf{F}^*$ exceeds 1. Of course, the expression on the right of equation (15) is no longer a hazard in that case. The needed reformulation is given in Section 3.4. Meanwhile, for reference, Table 5 summarizes the models of dissemination dynamics developed in this section.

### 3.4 Multiple counts

To analyze data such as those for cellphones or PCs from Section 2, the model needs to allow individuals to decide whether to have multiple items of digital technology. The upper limit on digital dissemination, $\sup_t \mathsf{F}(t)$, needs to be reinterpreted as bounding from above the number of items per individual in the population, rather than as the fraction of the population having access to the digital technology. With this, $\mathsf{F}(t)$ can now exceed 1.

The models just developed in equations (10) and (12) and Proposition 4 generalize readily to allow this possibility. That in Proposition 5 does not, however, since the hazard in equation (15) does not remain positive everywhere when the upper limit $\mathsf{F}^*$ is no longer bounded from above by 1.

Since the reasoning is close to that already developed, the discussion needs only highlight the necessary elements. Suppose each individual can have up to $\mathsf{F}^* \geq 1$ units of the digital technology, reflecting the number of cellphones or PCs potentially used. Observed data are $\mathsf{F}(t)$, the number of units of the technology per capita in a given society. The differential equation (10) becomes

$$\frac{d}{dt}\mathsf{F}(t) = \mathsf{h}(t) \times [\,\mathsf{F}^* - \mathsf{F}(t)\,]\,. \tag{17}$$

**Table 5** Dissemination dynamics, $\frac{d}{dt}\mathsf{F}(t) = \mathsf{h}(t) \times [1 - \mathsf{F}(t)]$

| Assumptions | Equilibrium dissemination |
|---|---|
| $\mathsf{F}(0) = 0;\ \mathsf{h}(t) = \overline{h}$ | $\mathsf{F}(t) = 1 - e^{-\overline{h}\,t} \to 1$ |
| $\mathsf{F}(0) = 0;$<br>$\{\,\mathsf{h}(t) : t \geq 0\,\}$ exogenous | $\mathsf{F}(t) = 1 - e^{-\int_0^t \mathsf{h}(s)\,ds}$ |
| $\mathsf{F}(0) = \mathsf{F}_* \in (0,1);$<br>$\mathsf{h}(t, \mathsf{F}(t)) = \mathsf{F}(t) \times \overline{h}$ | $\mathsf{F}(t) = \dfrac{e^{\overline{h}\,t}\,\mathsf{F}_*}{1 + (e^{\overline{h}\,t} - 1)\,\mathsf{F}_*} \to 1$ |
| $0 < \mathsf{F}(0) = \mathsf{F}_* < \mathsf{F}^* \leq 1;$<br>$\mathsf{h}(t) = \left\{ \dfrac{1 - \mathsf{F}(t)/\mathsf{F}^*}{1 - \mathsf{F}(t)} \right\} \times \mathsf{F}(t)\,\overline{h}$ | $\mathsf{F}(t) = \dfrac{e^{\overline{h}\,t} \times \mathsf{F}^*\,\mathsf{F}_*}{\mathsf{F}^* + (e^{\overline{h}\,t} - 1)\mathsf{F}_*} \to \mathsf{F}^*$ |

Consequently, in the simplest case with the hazard constant, $\mathsf{h}(t) = \overline{h} > 0$, and the boundary condition $\mathsf{F}(0) = 0$, equilibrium dissemination is modified from equation (11) to become:

$$\mathsf{F}(t) = \left(1 - e^{-t\overline{h}}\right) \mathsf{F}^* \to \mathsf{F}^* \text{ as } t \to \infty, \tag{18}$$

with Figure 22 unchanged except with the upper limit of the curve set instead to $\mathsf{F}^* \geq 1$.

When the initial condition $\mathsf{F}(0) = 0$ holds and the hazard remains positive but exogenously varies over time then, as in equation (12), dissemination follows:

$$\mathsf{F}(t) = \left(1 - e^{-\int_0^t \mathsf{h}(s)\,ds}\right) \mathsf{F}^* . \tag{19}$$

Finally, suppose the hazard evolves endogenously with the distribution $\mathsf{F}$. Using the right parametrization we will need to modify only minimally the conclusion of Proposition 4. Assume the initial condition $\mathsf{F}(0) = \mathsf{F}_* \times \mathsf{F}^* \in (0, \mathsf{F}^*)$ and the individual hazard

$$\mathsf{h}(t) = \mathsf{h}(t, \mathsf{F}(t)) = \mathsf{F}(t) \times \overline{h}/\mathsf{F}^* . \tag{20}$$

Then equilibrium dissemination is

$$\mathsf{F}(t) = \left[\frac{\mathsf{F}_*\, e^{\overline{h}\,t}}{1 + (e^{\overline{h}\,t} - 1)\,\mathsf{F}_*}\right] \mathsf{F}^* , \quad \forall t \geq 0, \tag{21}$$

with $\mathsf{F}(t) \to \mathsf{F}^* \geq 1$ as $t \to \infty$.

[Equations (18) and (19) follow from (17) upon dividing through the last by $\mathsf{F}^*$, and then executing the calculations as before, using $\mathsf{F}(t)/\mathsf{F}^*$ as the endogenous variable. Similarly, define $\mathsf{F}(t)/\mathsf{F}^*$ to be the dynamic timepath considered in Proposition 4 to obtain equation (21).]

Collecting equations (17) and (20) give

$$\frac{d}{dt}\mathsf{F}(t) = \mathsf{F}(t)\overline{h}\,[\,\mathsf{F}^* - \mathsf{F}(t)\,]\,/\mathsf{F}^*,$$

the same as obtains from combining equations (10) and (15) of Proposition 5. The model in Proposition 5 is therefore the same as that

**Table 6** Dissemination dynamics, $\frac{d}{dt}\mathsf{F}(t) = \mathsf{h}(t) \times [\mathsf{F}^* - \mathsf{F}(t)],\ \mathsf{F}^* \geq 1$

| Assumptions | Equilibrium dissemination |
|---|---|
| $\mathsf{F}(0) = 0;\ \mathsf{h}(t) = \overline{h}$ | $\mathsf{F}(t) = \left(1 - e^{-\overline{h}\,t}\right)\mathsf{F}^* \to \mathsf{F}^*$ |
| $\mathsf{F}(0) = 0;$<br>$\{\,\mathsf{h}(t) : t \geq 0\,\}$ exogenous | $\mathsf{F}(t) = \left(1 - e^{-\int_0^t \mathsf{h}(s)\,ds}\right)\mathsf{F}^*$ |
| $\mathsf{F}(0) = \mathsf{F}^*\mathsf{F}_* \in (0, \mathsf{F}^*);$<br>$\mathsf{h}(t, \mathsf{F}(t)) = \mathsf{F}(t) \times \overline{h}/\mathsf{F}^*$ | $\mathsf{F}(t) = \left[\frac{e^{\overline{h}\,t}\,\mathsf{F}_*}{1 + (e^{\overline{h}\,t} - 1)\,\mathsf{F}_*}\right]\mathsf{F}^*$<br>$\to\ \mathsf{F}^*$ |

just given in equations (17) and (20), only with final endpoint $\mathsf{F}^* \leq 1$. Equilibrium dissemination (21) thus applies generally, for all positive values of $\mathsf{F}^* \lesseqgtr 1$.

Table 6 summarizes the models developed here, in parallel with the earlier Table 5.

## 4 Empirical calibration

This section calibrates the models studied in the previous Section 3

Comin, Hobijn, and Rovito (2006), Draca, Sadun, and van Reenen (2007), Greenstein and Prince (2006), Hargittai (2003),

Pohjola (2003), Jorgenson (2001).

Norris (2001)

On the earlier point, it is not always immediately obvious that measured productivity is increased from raising ICT investment

The first point is an appealing one for researchers, obviously, but perhaps less so for others, especially as early studies seeking to quantify the impact of digital technology in particular (or R&D in general) often concluded there was no clearcut positive impact on aggregate productivity and economic growth (e.g., Gordon, 2000; Jones, 1995).

Studies of microeconomic settings, however, had early on

More recent developments, however, have reversed that conclusion, with one critical difference in microeconomic settings being organizational restructuring (e.g., Brynjolfsson and Yang, 1996; Draca et al., 2007) but even macroeconomic evidence now shows...

A significant complicating factor in such discussion is that a considerable fraction of time and spending devoted to digital attainment contributes to welfare directly, not through increasing an economy's supply-side productivity. Examples include the digital infrastructure devoted to activities such as social networking, digital entertainment, advertising, and information filtering and aggregation.

[[**Document numbers and use in calibration below.**]]

This complication arises partly because digital technologies and digital goods and services have peculiar economic properties in how they are nonrival, expansible, and aspatial (e.g., Quah, 2003). While thus resembling pure knowledge, digital goods and services do not always have as their primary purpose raising economic productivity.

## 5 Conclusion

This paper has.

# 6 Technical Appendix

This appendix collects the more technical discussion and proofs to all the key results in the body of the paper.

## 6.1 Alternative interpretation to equation (10)

Equation (10) in the text allowed deriving the dynamics of digital dissemination from the behaviours and actions of individuals within a population. Those individual actions altered the state of an individual, and thus shifted the cross-section distribution of characteristics.

However, equation (10)'s alternative and perhaps more typical interpretation omits mention of population dynamics or cross-section distributions. To see that more typical interpretation (e.g., Cox and Isham, 1980) consider random epochs:

$$\{\, t_k : \ k = 1, 2, \ldots \} \subset [0, \infty) \quad \text{with } t_1 \geq 0, \ \ldots, \ t_{k+1} \geq t_k, \ldots .$$

Each epoch is a point in time when some significant event occurs. Suppose that at epoch $t_k$ the random timespan $t_{k+1} - t_k$ until the next epoch is, for all $k \geq 0$, independent and identically distributed $\mathsf{P}$. Then $1 - \mathsf{P}(t)$ is the probability of no events occurring by timespan $t$. The arrival rate of events is the rate at which this probability declines. Define the hazard to be the proportional arrival rate of events:

$$\mathsf{h}(t) = -\frac{d}{dt}\log(1 - \mathsf{P}(t)) = \frac{d\mathsf{P}(t)/dt}{1 - \mathsf{P}(t)}. \tag{22}$$

Equation (22) bears a superficial resemblance to equation (10) in Section 3.3. But equation (22) here describes arrival times for isolated, possibly recurrent events while, by contrast, equation (10) describes social dynamics, or gradual dissemination across a given population. Nonetheless, because to some degree the formal analysis is identical, the manipulation, intuition, and results for one can provide useful insight for the other.

If hazard $\mathsf{h}$ is a positive constant then the inter-epoch times $t_{k+1} - t_k$ are distributed exponentially, i.e., for $\mathsf{h}(t) = \overline{h} > 0$,

$$\frac{d}{dt}\mathsf{P} = (1 - \mathsf{P}) \times \overline{h} \quad \text{and} \quad \mathsf{P}(0) = 0 \implies \mathsf{P}(t) = 1 - e^{-\overline{h}\,t}, \quad t \geq 0.$$

Such a process is memoryless. To see this, suppose without loss of generality that the current time is 0 and consider a fixed point in time $\overline{t} > 0$. Suppose that in the runup to $\overline{t}$ no event has yet taken place. Only two cases are possible: Either $\overline{t}$ is an epoch when an event has just occurred, or $\overline{t}$ is not such an epoch. In the first case, since inter-epoch times are exponential, the probability of no event occurring within time $t$ after $\overline{t}$ is

$$1 - \mathsf{P}(t) = e^{-t\,\overline{h}}.$$

In the other case, that same probability conditional on no event having taken place by $\overline{t}$ is

$$\frac{1 - \mathsf{P}(t + \overline{t})}{1 - \mathsf{P}(\overline{t})} = \frac{e^{-(t+\overline{t})\,\overline{h}}}{e^{-\overline{t}\,\overline{h}}} = e^{-t\overline{h}},$$

equal to the probability in the first case. Thus, the stochastic process shows no memory on whether events have occurred.

In general, however, the hazard rate will vary in its time argument. If the hazard is increasing then an event is more likely the longer that one has not yet occurred. Conversely, if the hazard is decreasing then an event becomes progressively less likely the longer one has not yet taken place.

## 6.2 Proofs

### Proof of Lemma 1

*i. Write* $\xi = \xi(\mathcal{Z})$*. As* $R \to 1$*, the function* $U$ *converges to the* log *function. Then*

$$U(C(t)) = \log C(0) + \xi\, t,$$

*so that*

$$W = \int_0^\infty e^{-\delta t}\, U(C(t))\, dt = \delta^{-1} \log C(0) + \xi \times \int_0^\infty t\, e^{-\delta t}\, dt.$$

*But that last integral evaluates to:*

$$\int_0^\infty t\, e^{-\delta t}\, dt = -\delta^{-2} \times \left[\ (1+\delta t)e^{-\delta t}\Big|_0^\infty\ \right] = -\delta^{-2} \times [0-1] = \delta^{-2}.$$

*Thus, as required,*

$$W = \delta^{-1} \times \log C(0) + \delta^{-2}\xi.$$

*ii. For $R > 1$, again writing $\xi = \xi(\mathcal{Z})$, the definition*

$$U(C(t)) = \frac{C(0)e^{(1-R)\xi\, t} - 1}{1-R}$$

*gives*

$$\begin{aligned} W &= \int_0^\infty e^{-\delta t} U(C(t))\, dt \\ &= (1-R)^{-1} \\ &\qquad \times \left\{ C(0)^{1-R} \int_0^\infty e^{-[\delta-(1-R)\xi]t}\, dt - \int_0^\infty e^{-\delta t}\, dt \right\} \\ &= (1-R)^{-1} \times \left\{ \frac{C(0)^{1-R}}{\delta - (1-R)\xi(\mathcal{Z})} - \delta^{-1} \right\}. \end{aligned}$$

*Q.E.D.*

**Proof of Proposition 2** *Denote by $c$ the initial consumption level in the economy. Using part i. in Lemma 1, when $R = 1$ the welfare gain $R$ satisfies*

$$\delta \log c + \xi' = \delta \log([1+\Psi]c) + \xi.$$

*The term $\log c$ appears symmetrically on both sides of the equation and thus can be removed altogether. Rearranging then gives:*

$$\delta \log(1+\Psi) = \xi' - \xi \implies \Psi = \exp\left( [\xi' - \xi]\delta^{-1} \right) - 1.$$

*On the other hand, when $R > 1$, part ii. in Lemma 1 implies*

$$\frac{[\,(1+\Psi)c\,]^{1-R}}{\delta-(1-R)\xi} = \frac{c^{1-R}}{\delta-(1-R)\xi'}$$
$$\Longrightarrow\ (1+\Psi)^{1-R} = \frac{\delta-(1-R)\xi}{\delta-(1-R)\xi'}\,,$$

*again $c$ vanishing symmetrically on both sides of the equation, so that*

$$\Psi = \left[\,\frac{\delta+(R-1)\xi'}{\delta+(R-1)\xi}\,\right]^{\frac{1}{R-1}} - 1.$$

*Q.E.D.*

**Proof of Proposition 3** *For convenience consider Digital Divide dynamics for economy $j = 1$; the calculations for all other $j > 1$ are exactly the same. Relation $D_1 = 1 - S_1$ implies $\dot{D}_1 = -\dot{S}_1$. Since*

$$S_1 = Z_1/Z_0 \implies \dot{S}_1/S_1 = \dot{Z}_1/Z_1 - \dot{Z}_0/Z_0,$$

*we can write*

$$\begin{aligned}
\dot{D}_1 &= -(\dot{S}_1/S_1)S_1 = -\left[\,\dot{S}_1/S_1 - \dot{S}_0/S_0\,\right](1-D_1)\\
&= -\left[\left(\frac{Z_0}{Z_1}-1\right)\phi_1(X_1) - \phi_0(X_0)\right]\times(1-D_1)\\
&= [\,\phi_1(X_1)+\phi_0(X_0)\,]\times(1-D_1) - \phi_1(X_1)\frac{Z_0}{Z_1}\times(1-D_1)\\
&= -\,[\,\phi_1(X_1)+\phi_0(X_0)\,]\,D_1 + \phi_0(X_0).
\end{aligned}$$

*Defining for convenience*

$$\begin{aligned}
d_1 &= D_1 - \frac{\phi_0(X_0)}{\phi_1(X_1)+\phi_0(X_0)},\\
\beta &= \phi_1(X_1)+\phi_0(X_0) > 0,
\end{aligned}$$

*the equation becomes*

$$\dot{d}_1 = -\beta\, d_1.$$

*With initial condition* $d_1(0) = D_1(0) - \beta^{-1}\,\phi_0(X_0)$ *the timepath for* $d_1$ *is then*

$$d_1(t) = d_1(0)e^{-\beta\, t} \to 0,$$

*or*

$$D_1(t) \to \frac{\phi_0(X_0}{\phi_j(X_j) + \phi_0(X_0)} > 0, \qquad \text{as } t \to \infty,$$

*exponentially at rate* $\beta = \phi_j(X_j) + \phi_0(X_0)$. *Q.E.D.*

**Proof of Proposition 4** *When* $\mathsf{F}$ *is given by equation* (14) *then*

$$\begin{aligned}\frac{d\mathsf{F}}{dt} &= \frac{\overline{h}\,\mathsf{F}_* e^{\overline{h}\,t}}{1 + (e^{\overline{h}\,t} - 1)\mathsf{F}_*} - \frac{\mathsf{F}_* e^{\overline{h}\,t}}{[1 + (e^{\overline{h}\,t} - 1)\mathsf{F}_*]^2} \times \overline{h}\,\mathsf{F}_* e^{\overline{h}\,t} \\ &= \mathsf{F}(t)\,\overline{h} - \mathsf{F}(t)^2\,\overline{h} = [\,1 - \mathsf{F}(t)\,]\mathsf{F}(t)\,\overline{h} \\ \Longrightarrow\ \mathsf{h}(t) &= \frac{d\mathsf{F}/dt}{1 - \mathsf{F}(t)} = \mathsf{F}(t) \times \overline{h}\,,\end{aligned}$$

*as in equation* (13). *Moreover, at* $t = 0$,

$$\mathsf{F}(t) = \frac{\mathsf{F}_*}{1 + 0 \cdot \mathsf{F}_*} = \mathsf{F}_*\,.$$

*Thus* $\mathsf{F}$ *in equation* (14) *is an equilibrium dissemination.* *Q.E.D.*

**Proof of Proposition 5** *When* $\mathsf{F}$ *is given by equation* (16) *then*

$$\begin{aligned}\frac{d\mathsf{F}}{dt} &= \frac{\overline{h}\,e^{\overline{h}\,t}\,\mathsf{F}_*\mathsf{F}^*}{\mathsf{F}^* + (e^{\overline{h}\,t} - 1)\mathsf{F}_*} - \frac{e^{\overline{h}\,t}\,\mathsf{F}_*\mathsf{F}^*}{[\mathsf{F}^* + (e^{\overline{h}\,t} - 1)\mathsf{F}_*]^2} \times \overline{h}\,e^{\overline{h}\,t}\,\mathsf{F}_* \\ &= \mathsf{F}(t)\,\overline{h} - \mathsf{F}(t)^2\,\overline{h}/\mathsf{F}^* = [1 - \mathsf{F}(t)/\mathsf{F}^*]\mathsf{F}(t)\overline{h} \\ \Longrightarrow\ \mathsf{h}(t) &= \frac{d\mathsf{F}/dt}{1 - \mathsf{F}(t)} = \left\{\frac{1 - \mathsf{F}(t)/\mathsf{F}^*}{1 - \mathsf{F}(t)}\right\} \times \mathsf{F}(t)\,\overline{h},\end{aligned}$$

*as in equation* (15). *Moreover, at* $t = 0$,

$$\mathsf{F}(t) = \frac{\mathsf{F}_*\mathsf{F}^*}{\mathsf{F}^* + 0 \cdot \mathsf{F}_*} = \mathsf{F}_*,$$

*and finally*

$$\mathsf{F}(t) \to \mathsf{F}^* \leq 1 \quad \text{as } t \to \infty.$$

*Thus* $\mathsf{F}$ *in equation* (16) *is an equilibrium dissemination, where complete saturation need not obtain.* *Q.E.D.*

The equation

$$\frac{d\mathsf{F}}{dt} = [1 - \mathsf{F}(t)/\mathsf{F}^*]\mathsf{F}(t)\overline{h}$$

appearing in the Proof of Proposition 5 is a special case of the Verhulst equation (e.g., Montroll, 1978).

## 7 Supplement

This section contains qualitative discussion of the costs and benefits of digital technologies that don't fit naturally into the more quantitative analysis in the body of the paper.

i. Indonesian health workers can use text-messaging technology on digital cellphones to file reports on bird flu outbreaks, speeding up a process that might otherwise take days or weeks (Wall Street Journal, 17 August 2006). The wireless network covers more than 90% of the Indonesia's 220m people, whereas land lines do not even exist in many parts of the country: 47m cellphones are in use, and only 13m landline phones (CIA, 2006).

ii. In Somalia—without a functioning central government since 1991, without a banking and financial system, and without a public power infrastructure (CIA, 2006)—a system of doing business using cellphones has successfully emerged (Financial Times, 04 October 2006). In 2006 Somalian infant mortality is 11%; life expectancy at birth, 48 years; adult literacy, 38%; per capita GDP, $600. Nonetheless, in the population of 9m people, half a million cellphones are in use, whereas landline phones number only 100,000.

iii. Willinsky (2006) describes how, from 1979 through 2001, diminishing funds, rising prices, and a fluctuating Kenyan currency forced the Kenya Medical Research Institute (KEMRI) library in Nairobi to slash its journal subscriptions to just five medical titles. Moreover, none of these remaining five, which KEMRI could barely afford, focused on tropical diseases, the Institute's primary concern. Consequently, one of East Africa's leading medical research institutes was attempting to conduct research without ready access to the most relevant, recent publications in its field.

In July 2001 the situation changed. The World Health Organization convinced a number of publishers to allow institutions in poorer countries open access to electronic versions of their medical journals. This initiative quickly grew to cover 2,000 journal titles and 1,000 institutions from over 100 developing countries.

Willinsky (2006) used this example to show the importance for knowledge dissemination of recent institutional movement towards greater openness and availability. The growth of this Open Access movement became one of 2003's top science stories, touching on both professional ethos in scientific research dissemination and the economics of the publishing industry. Many observers readily agree that a place like KEMRI should have greater access to research journals and should have more computer hardware, as the research that KEMRI undertakes is potentially socially valuable and insufficiently prioritized. Public health is a quintessential public good, and absent explicit intervention it will typically be under-supplied.

Also mentioned in the account, although with a different message, is that by June 2003 KEMRI had only one computer with a high-speed Internet connection able to access conveniently the increase in supply of published research. A clipboard sign-up sheet became the rationing mechanism to mediate demand and supply. Open Access alone was insufficient for raising digital attainment; computer hardware instead was the bottleneck that

> mattered.
>
> This second message expands, both in the KEMRI account and more generally. Closing the Digital Divide will entail simultaneous progress on several different fronts. Internet access matters, clearly, but so do useable computer hardware, appropriate user skills, organizational structure, sufficiently high demand for digital content, and so on. Any one or more of these can turn out to be the binding constraint. Under circumstances different from KEMRI's, providing computer hardware to close the Digital Divide might remain ineffective because it might then be yet something else that holds back digital attainment.
>
> That such absorption capabilities figure critically is widely acknowledged, and is a familiar notion from development economics more generally. Most relevant for the current discussion on digital attainment, Benjamin (2001) documents the relative failure of telecentres in South Africa when an infusion of telecommunications hardware was not matched by sufficient training and transparent incentives locally. Joris Komen in `tatejoris.blogspot.com` (accessed October 2006) provides similar first-hand accounts of digital attainment failure in specific Namibian educational projects, despite significant donor provision of ICT hardware and software.

The Digital Divide entails not just the hypothesis and the policy proposal that a better environment—however that comes about—might raise digital attainment in a given country or particular groups of people. Instead, just as intricate a Digital Divide question is whether the dynamics inherent in how digital attainment spreads—be it across countries or across people—will lead to lowered or heightened inequality (Hargittai, 2003). Will digital attainment through Internet availability, say, improve access equally for all—lowering information barriers, enhance health service provision, making markets more transparent—and thus reduce inequality? Or, instead, will differential speeds of dissemination improve opportunities most for those already better off, so that even though everyone benefits, those who are worse off benefit least, thus raising inequality?

## References

Peter Benjamin. *Telecentres and Universal Capability.* PhD thesis, Aalborg University, August 2001.

Erik Brynjolfsson and Shinkyu Yang. Information technology and productivity: A review of the literature. *Advances in Computers*, 43:179–214, February 1996.

CIA. *The CIA World Factbook.* Central Intelligence Agency: Office of Public Affairs, 2006.

George Clarke and Scott Wallsten. Has the Internet increased trade? evidence from industrial and developing countries. Policy Research Working Paper 3215, World Bank, Washington DC, 2004.

Diego Comin, Bart Hobijn, and Emilie Rovito. Five facts you need to know about technology diffusion. Working Paper 11928, NBER, Cambridge, January 2006.

David R. Cox and Valerie Isham. *Point Processes.* Chapman and Hall, London, 1980.

Paul DiMaggio, Eszter Hargittai, Coral Celeste, and Steven Shafer. Digital inequality: From unequal access to differentiated use. In Kathryn Neckerman, editor, *Social Inequality*, chapter 9, pages 355–400. Russel Sage Foundation, New York, 2004.

Mirko Draca, Rafaella Sadun, and John van Reenen. Productivity and ICTs: A review of the evidence. In Robin Mansell, Christine Avgerou, Danny Quah, and Roger Silverstone, editors, *Oxford Handbook of ICTs*, chapter 5. Oxford University Press, Oxford, 2007.

Robert J. Gordon. Does the 'New Economy' measure up to the great inventions of the past? *Journal of Economic Perspectives*, 14(4): 49–74, Fall 2000.

Shane Greenstein and Jeff Prince. The diffusion of the Internet and the geography of the digital divide in the United States. In Robin Mansell, Christine Avgerou, Danny Quah, and Roger Silverstone, editors, *Oxford Handbook of ICTs*, chapter 7. Oxford University Press, Oxford, 2006.

Eszter Hargittai. The digital divide and what to do about it. In Derek C. Jones, editor, *New Economy Handbook*, chapter 35, pages 821–839. Academic Press Elsevier Science, London, 2003.

Charles I. Jones. R&D-based models of economic growth. *Journal of Political Economy*, 103(3):759–784, August 1995.

Dale W. Jorgenson. Information technology and the U.S. economy. *American Economic Review*, 91(1):1–32, March 2001.

Linda T. Kohn, Janet M. Corrigan, and Molla S. Donaldson, editors. *To Err is Human*, Washington DC, January 2000. Institute of Medicine, The National Academies Press.

Robert E. Lucas. Macroeconomic priorities. *American Economic Review*, 93(1):1–14, March 2003.

Elliott W. Montroll. Social dynamics and the quantifying of social forces. *Proceedings of the National Academy of Sciences*, 75(10): 4633–4637, October 1978.

Pippa Norris. *Digital Divide: Civic Engagement, Information Poverty, and the Internet Worldwide.* Cambridge University Press, Cambridge, 2001.

Hiroshi Ono. Digital inequality in East Asia: Evidence from Japan, South Korea, and Singapore. *Asian Economic Papers*, 4(3):116–139, October 2005.

Matti Pohjola. The adoption and diffusion of information and communication technology across countries: Patterns and determinants. In Derek C. Jones, editor, *New Economy Handbook*, chapter 4, pages 77–100. Academic Press Elsevier Science, London, 2003.

Danny Quah. The weightless economy in economic development. In Matti Pohjola, editor, *Information Technology, Productivity, and Economic Growth*, UNU/WIDER and Sitra, chapter 4, pages 72–96. Oxford University Press, Oxford, 2001.

Danny Quah. Digital goods and the New Economy. In Derek C. Jones, editor, *New Economy Handbook*, chapter 13, pages 289–321. Academic Press Elsevier Science, London, 2003.

Danny Quah. Life in unequal growing economies. Working paper, Economics Dept., LSE, September 2006.

Barbara Starfield. Is US health really the best in the world? *Journal of American Medical Association*, 284(4):483–485, July 2000.

Jan Walker, Eric Pan, Douglas Johnston, Julia Adler-Milstein, David W. Bates, and Blackford Middleton. The value of health care information exchange and interoperability. *Health Affairs*, 19 January 2005.

John Willinsky. *The Access Principle.* The MIT Press, Cambridge MA, 2006.

World Bank. *Information and Communications for Development: Global Trends and Policies.* The World Bank, Washington DC, 2006a.

World Bank. *World Development Indicators Online.* The World Bank, Washington DC, April 2006b.

World Bank. *World Development Report: Development and The Next Generation.* The World Bank, Washington DC, 2007.

H. Peyton Young. The spread of innovations by social learning. Working paper, Johns Hopkins University, November 2005.