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Supporting Online Material for

**The World's Technological Capacity to Store, Communicate, and Compute Information**

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**This PDF file includes:**

Materials and Methods

Figs. A1 to E12

Tables SA1 to SE24

References and Notes

# The world's technological capacity to store, communicate and compute information

## Supporting online material:

### Material and Methods

- A. General concepts
- B. Compression
- C. Storage
- D. Communication
- E. Computation

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# Contents

<b>A</b>	<b>General concepts</b> .....	<b>6</b>
A.1	Datasheets .....	6
A.2	Differences and grey zones between storage, communication and computation .....	9
A.3	References .....	11
<b>B</b>	<b>Compression</b> .....	<b>12</b>
B.1	The “optimal level” of compression .....	12
B.2	Text .....	13
B.2.1	RAR .....	13
B.2.2	ZIP .....	14
B.2.3	Text Compression Rates over time .....	15
B.3	Still Images .....	17
B.3.1	JPEG .....	19
B.3.2	GIF .....	20
B.3.3	Image compression rates over time .....	21
B.4	Sound .....	25
B.4.1	Voice .....	26
B.4.2	Audio: MPEG .....	31
B.4.3	Audio compression rates over time .....	33
B.5	Video .....	36
B.5.1	MPEG-2 .....	37
B.5.2	MPEG-4 .....	40
B.5.3	Video compression rates over time .....	40
B.6	References .....	42
<b>C</b>	<b>Storage</b> .....	<b>50</b>
C.1	Paper .....	50
C.1.1	Newspapers: quantity .....	51
C.1.2	Newspapers: performance .....	52
C.1.3	Books and other paper for printing/writing/reprographics: quantity .....	55
C.1.4	Books and other paper for printing/writing/reprographics: performance .....	56
C.1.5	Content compression .....	57
C.2	Films for cinema and TV .....	58
C.2.1	Motion Pictures: quantity .....	58
C.2.2	Cinematographic Films: performance .....	60
C.2.3	TV Films and TV episodes: performance .....	62
C.2.4	Content compression .....	64
C.3	Analog Photography .....	64
C.3.1	Negatives: performance .....	64
C.3.2	Printed photos: performance .....	65
C.3.3	Negatives and printed photographs: quantity .....	66
C.3.4	Content compression .....	67
C.4	Radiography .....	68
C.4.1	Radiographs: quantity .....	69
C.4.2	Radiographs: performance .....	70
C.4.3	Content compression .....	71
C.5	Vinyl .....	71
C.5.1	Vinyl LP: quantity .....	72
C.5.2	Vinyl: performance .....	72
C.5.3	Content compression .....	72
C.6	Audio Cassettes .....	73
C.6.1	Audio Cassettes: quantity .....	73

C.6.2	Audio cassettes: performance .....	75
C.6.3	Content compression .....	75
C.7	Analog video tapes.....	75
C.7.1	VHS tapes: performance .....	76
C.7.2	VHS tapes: quantity .....	77
C.7.3	VHS-C and 8mm: performance .....	78
C.7.4	VHS-C and 8mm tapes: quantity .....	78
C.7.5	BetaMax tapes: performance.....	79
C.7.6	BetaMax tapes: quantity .....	80
C.7.7	Content compression .....	80
C.8	Hard Disk Drives (HDD) .....	81
C.8.1	Hard Disks: quantity .....	81
C.8.2	Hard disks: performance .....	82
C.8.3	Content Compression .....	85
C.9	Magnetic Data Tapes .....	87
C.9.1	Data Tapes: quantity .....	87
C.9.2	Data Tapes: performance.....	88
C.9.3	Content Compression .....	89
C.10	Flexible Disks (FD, Floppy Disks) .....	90
C.10.1	Floppy Disks: quantity.....	90
C.10.2	Floppy Disks: performance .....	91
C.10.3	Content compression .....	92
C.11	CD (Compact Disc) y MiniDisc .....	92
C.11.1	CD and MiniDisc: quantity .....	93
C.11.2	CD and MiniDisc: performance .....	93
C.11.3	Content compression .....	94
C.12	DVD, HD-DVD, DVD 8cm and Blu-Ray .....	94
C.12.1	DVD, D-DVD, DVD 8cm y Blu-Ray: performance .....	95
C.12.2	DVD, HD-DVD, DVD 8cm y Blu-Ray: quantity .....	95
C.12.3	Content compression .....	96
C.13	Video-Game Consoles .....	96
C.13.1	Videogame software: performance.....	97
C.13.2	Consoles: performance.....	98
C.13.3	Videogame software: quantity .....	99
C.13.4	Consoles: quantity .....	99
C.13.5	Content compression .....	100
C.14	Chip Card .....	100
C.14.1	Chip cards: performance.....	101
C.14.2	Chip cards: quantity.....	101
C.14.3	Content compression .....	102
C.15	Memory Cards.....	102
C.15.1	Memory Cards: quantity .....	103
C.15.2	Memory Cards: performance .....	103
C.15.3	Content compression .....	104
C.16	Portable Media Player and USB Flash.....	105
C.16.1	iPod, MP3, MP4, USB flash: quantity .....	105
C.16.2	iPod, MP3, MP4, USB flash: performance.....	106
C.16.3	Content compression .....	107
C.17	Mobile Telephones and PDA .....	107
C.17.1	Mobile telephones: quantity .....	108
C.17.2	2G Mobile phones: performance .....	108
C.17.3	Smartphones (2.5G y 3G) and PDA: performance .....	109
C.17.4	Content compression .....	110
C.18	Digital cameras and camcorders .....	110
C.18.1	Digital cameras and camcorders: quantity .....	111
C.18.2	Digital cameras: performance .....	111
C.18.3	Content compression .....	111
C.19	References .....	112

<b>D</b>	<b>Communication .....</b>	<b>135</b>
D.1	General concepts .....	135
D.2	Postal Service .....	135
D.2.1	Postal Service: Quantity .....	136
D.2.2	Postal Letters: Performance .....	137
D.2.3	Newspapers: Performance .....	138
D.2.4	Advertising: Performance .....	139
D.2.5	Compression of Content .....	139
D.3	Radio .....	140
D.3.1	Radio: Quantities .....	140
D.3.2	Radio: Performance .....	141
D.3.3	Compression of content .....	141
D.3.4	Effective use .....	142
D.4	Television .....	142
D.4.1	Television: Quantity .....	143
D.4.2	Television: Performance .....	147
D.4.3	Content compression .....	152
D.4.4	Effective use .....	153
D.5	Fixed-line Telephone .....	153
D.5.1	Fixed-line telephone: Quantity .....	154
D.5.2	Fixed-line telephone: Performance .....	154
D.5.3	Content Compression .....	155
D.5.4	Effective Use .....	156
D.6	Mobile Telephones .....	156
D.6.1	Mobile telephony: Quantity .....	157
D.6.2	Mobile voice: Performance .....	160
D.6.3	Mobile Voice: Compression of Content .....	161
D.6.4	Mobile Voice: Effective use .....	163
D.6.5	Mobile data: Performance .....	163
D.6.6	Mobile data: Actual use .....	164
D.6.7	Mobile data: Content compression .....	165
D.7	Internet .....	166
D.7.1	Internet: Quantity of dial-up, ISDN, xDSL, FTTH/B cable modem and others .....	167
D.7.2	Internet Dial-up: Performance .....	169
D.7.3	Internet ISDN: Performance .....	169
D.7.4	Internet xDSL, Cable Modem and others (wireless WiFi, satellite, power line, electric, unidentified, etc): Performance .....	169
D.7.5	FTTH/B: Performance .....	172
D.7.6	Compression of Content .....	173
D.7.7	Actual use .....	181
D.8	Personal Navigation Device (GPS) .....	182
D.8.1	Personal Navigation Device: Quantity .....	182
D.8.2	Personal Navigation Device: Performance .....	183
D.8.3	Personal Navigation Device: Compression of content .....	183
D.8.4	Actual use .....	183
D.9	References .....	183
<b>E</b>	<b>Computation .....</b>	<b>209</b>
E.1	General concepts .....	209
E.1.1	MIPS as an indicator of hardware performance .....	209
E.1.2	Speculations on the contributions of faster algorithms .....	211
E.1.3	General-purpose and application-specific computer .....	213
E.2	Personal computers (PC) .....	213
E.2.1	Personal computers: capacity .....	214
E.2.2	Personal computers: performance .....	215
E.2.3	Personal computers: effective use .....	216
E.3	Professional computers .....	216
E.3.1	Professional computers: quantity .....	217

E.3.2	Professional computers: performance .....	219
E.3.3	Professional computers: effective use .....	220
E.4	Supercomputers .....	221
E.4.1	Supercomputers: performance .....	221
E.4.2	Supercomputers: quantity .....	222
E.4.3	Supercomputers: effective use .....	223
E.5	Game consoles.....	223
E.5.1	Game consoles: performance .....	224
E.5.2	Game consoles: quantity.....	224
E.5.3	Game consoles: effective use .....	225
E.6	Electronic calculators .....	225
E.6.1	Calculators: Quantity.....	226
E.6.2	Calculators: performance.....	227
E.6.3	Calculators: effective use .....	227
E.7	Mobile phones and PDAs .....	228
E.7.1	Mobile phones, PDAs, and handheld PCs: performance .....	228
E.7.2	Mobile phones, PDAs, and handheld PCs: quantity.....	229
E.7.3	Mobile phones, PDAs, and handheld PCs: effective use .....	229
E.8	Digital Signal Processors (DSP).....	230
E.8.1	DSP: performance.....	230
E.8.2	DSP: quantity.....	230
E.9	Microcontroller (MCU).....	233
E.9.1	MCU: performance .....	234
E.9.2	MCU: quantity .....	234
E.10	Graphic Processing Units (GPU) .....	234
E.10.1	GPU: quantity .....	235
E.10.2	GPU: performance .....	235
E.11	References .....	236

## A General concepts

We emphasize transparency in outlining the methodological assumptions and sources on the basis of which we elaborated the presented estimates. Much more than arguing in favor of one specific number or the other, we present the estimates as a first approximation, which could certainly be refined in the future (depending on the available resources). In order to facilitate future generations of research on this topic, the next 250 pages outline the details of the applied methodology, enlisting including all 1120 sources that inform our estimates.

### A.1 Datasheets

The following tables are the statistical basis for the figures and tables presented in the main article.

**Table S A-1: World's technological installed capacity to store information, in optimally compressed Megabytes (MB) per year, for 1986, 1993, 2000 and 2007.**

		1986	1993	2000	2007
Analog	Books	5.14E+08	7.40E+08	9.67E+08	1.19E+09
	Other paper & print	2.04E+09	3.53E+09	5.54E+09	6.37E+09
	Newsprint	6.17E+09	8.83E+09	1.21E+10	1.18E+10
	TV movie film	4.83E+09	7.73E+09	1.31E+10	2.71E+10
	X-Rays	1.98E+10	2.25E+10	2.56E+10	2.91E+10
	TV episodes film	1.24E+10	1.58E+10	2.29E+10	3.57E+10
	Vinyl LP	3.76E+11	3.19E+11	1.49E+11	3.81E+10
	Cine movie film	1.43E+10	1.87E+10	2.74E+10	3.95E+10
	Photo negative	1.22E+11	1.67E+11	2.71E+11	1.04E+11
	Audio cassette	3.09E+11	6.64E+11	7.22E+11	2.66E+11
	Photo print	2.20E+11	3.71E+11	5.66E+11	6.04E+11
	Video analog	1.53E+12	1.36E+13	3.89E+13	1.77E+13
	Digital	Chip Card	2.50E+03	1.02E+08	3.84E+08
Floppy disks		6.04E+08	4.88E+09	1.23E+11	3.80E+10
Camera & camcorder internal		-	9.16E+07	2.73E+08	8.09E+10
Videogames others		5.26E+06	3.23E+08	4.10E+09	1.07E+11
Mobile phones & PDA		-	1.38E+05	1.85E+08	2.06E+11
Memory Cards		-	-	1.01E+09	1.86E+12
Portable Media Player		-	-	3.26E+08	5.54E+12
Other hard-disks (portable)		6.79E+06	1.46E+07	2.07E+09	6.49E+12
CDs and MiniDiscs		1.63E+10	3.80E+11	5.50E+12	1.88E+13
Server & Mainframe hard-disk		3.87E+08	6.13E+09	3.27E+11	2.45E+13
Digital tape		3.35E+09	1.33E+11	4.56E+12	3.25E+13
DVD & Blu-Ray		-	-	2.17E+11	6.30E+13
PC hard-disk		1.24E+08	8.44E+09	2.99E+12	1.23E+14

	<b>SUM</b>	<b>2.64E+12</b>	<b>1.58E+13</b>	<b>5.45E+13</b>	<b>2.95E+14</b>
	Analog	2.62E+12	1.52E+13	4.08E+13	1.89E+13
	Digital	2.08E+10	5.33E+11	1.37E+13	2.76E+14

Source: authors' own elaboration, based on Supporting Online Material: Material and Methods, Sections C. Storage and B. Compression.

**Table S A-2: World's technological effective capacity to broadcast and telecommunicate information, in optimally compressed Megabytes (MB) per year, for 1986, 1993, 2000 and 2007.**

		1986	1993	2000	2007
Broadcasting analog	TV-Terrestrial analog	3.42E+14	5.20E+14	7.03E+14	9.44E+14
	TV-Cable analog	5.54E+13	1.33E+14	2.80E+14	3.91E+14
	TV-Satellite analog	2.63E+12	2.57E+13	4.68E+13	5.45E+13
	Radio analog	3.10E+13	3.54E+13	3.70E+13	3.21E+13
	Paper Newspapers	3.08E+11	2.47E+11	2.24E+11	1.75E+11
	Paper advertisement	5.11E+09	7.85E+09	9.96E+09	1.40E+10
Broadcasting digital	TV-Satellite digital	-	-	6.03E+13	2.27E+14
	TV-Cable digital	-	-	2.11E+13	1.62E+14
	TV-Terrestrial digital	-	-	1.03E+12	7.05E+13
	Radio digital	-	-	1.19E+12	8.60E+12
	GPS	-	-	1.63E+08	1.55E+10
Telecom analog	Fixed (voice) phone analog	2.24E+11	1.45E+11	3.88E+10	1.81E+10
	Postal letters	9.48E+08	1.14E+09	1.39E+09	1.02E+09
	Mobile (voice) phone analog	4.89E+07	2.68E+09	1.13E+10	1.71E+10
Telecom digital	Internet fixed	2.35E+06	6.19E+09	1.15E+12	6.31E+13
	Fixed (voice) phone digital	5.57E+10	3.17E+11	9.42E+11	9.59E+11
	Mobile (data) phone digital	-	-	1.01E+07	7.18E+11
	Mobile (voice) phone digital	-	1.18E+08	9.52E+10	5.44E+11
	<b>SUM</b>	<b>4.32E+14</b>	<b>7.16E+14</b>	<b>1.15E+15</b>	<b>1.96E+15</b>
	Analog broadcast	4.32E+14	7.15E+14	1.07E+15	1.42E+15
	Digital broadcast	-	-	8.37E+13	4.68E+14
	<b>Broadcast</b>	<b>4.32E+14</b>	<b>7.15E+14</b>	<b>1.15E+15</b>	<b>1.89E+15</b>
	Analog telecom	2.25E+11	1.48E+11	5.15E+10	3.63E+10
	Digital telecom	5.57E+10	3.23E+11	2.19E+12	6.53E+13
	<b>Telecom</b>	<b>2.81E+11</b>	<b>4.71E+11</b>	<b>2.24E+12</b>	<b>6.54E+13</b>

Source: authors' own elaboration, based on Supporting Online Material: Material and Methods, Sections D. Communication and B. Compression.



Table S A-3: World's technological installed capacity to compute information, in MIPS, for 1986, 1993, 2000 and 2007.

		1986	1993	2000	2007
General-Purpose	Personal computers	9.85E+07	2.85E+09	2.48E+11	4.20E+12
	Videogame consoles	2.69E+07	2.77E+08	1.32E+10	1.61E+12
	Mobile phones/ PDA	0.00E+00	2.01E+07	9.25E+09	3.73E+11
	Servers and mainframe	5.12E+07	1.00E+09	1.72E+10	1.73E+11
	Supercomputers	1.03E+05	6.95E+06	2.12E+08	2.13E+10
	Pocket calculators	1.23E+08	2.68E+08	6.87E+08	1.92E+09
	<b>SUM</b>	<b>3.00E+08</b>	<b>4.43E+09</b>	<b>2.89E+11</b>	<b>6.38E+12</b>
Application-specific	Digital Signal Processors (DSP)	1.72E+07	1.03E+09	1.25E+11	2.01E+12
	Microcontroller Units (MCU)	3.89E+08	1.02E+10	3.69E+11	3.21E+12
	Graphic Processing Units (GPU)	2.70E+07	6.77E+09	9.54E+11	1.84E+14
	<b>SUM</b>	<b>4.33E+08</b>	<b>1.80E+10</b>	<b>1.45E+12</b>	<b>1.89E+14</b>

Source: authors' own elaboration, based on Supporting Online Material: Material and Methods, Section E. Computation.

Table S A-4: World's technological effective capacity to compute information on general-purpose computers (gross usage), in MIPS, for 1986, 1993, 2000 and 2007.

	1986	1993	2000	2007
Personal computers	5.86E+05	8.56E+07	9.72E+09	2.79E+11
Videogame consoles	5.85E+04	4.31E+06	4.78E+08	1.11E+11
Mobile phones/ PDA	0.00E+00	0.00E+00	9.90E+08	6.87E+10
Servers and mainframe	1.54E+07	3.02E+08	5.18E+09	5.77E+10
Supercomputers	1.03E+05	6.95E+06	2.12E+08	2.13E+10
Pocket calculators	1.21E+06	3.22E+06	1.01E+07	3.05E+07
<b>SUM</b>	<b>1.73E+07</b>	<b>4.02E+08</b>	<b>1.66E+10</b>	<b>5.38E+11</b>

Source: authors' own elaboration, based on Supporting Online Material: Material and Methods, Section E. Computation.

Table S A-5: World population for 1986, 1993, 2000 and 2007, with compound annual growth rates.

1986	1993	2000	2007	CAGR 86-07
4,902,499,030	5,505,145,979	6,062,726,734	6,596,812,714	1.42%
CAGR since previous measurement	1.7%	1.4%	1.2%	

Source: (1).

## A.2 Differences and grey zones between storage, communication and computation

Technologies can be defined as standardized solutions to prototypical problems, which are derived from knowledge about the world<sup>1</sup> and are embedded in physical structure (2-4). Information and Communication Technologies (ICT) provide standardized solutions to three kinds of related prototypical problems: how to communicate information between points A and B (the transmission of information through space); how to transmit information from time 1 to 2 (the transmission of information through time, or storage in some memory) and how to transform information (computation), either from X to x (translation of symbols), or from X into Y (transformation of meaning) (5). These are the most fundamental information processes, and everything that can be done with information has to do with one of those three or a combination of them. Given the relatedness of all three information operations through space and time, it is not surprising that there are significant grey zones between them.

For example, it is not always clear when an informational process belongs to the world's technological capacity to compute or to store information. In our account of storage, we include those technologies whose main priority is to store information for "later" retrieval. Remembering that a computer, in the sense of a Turing machine, is nothing else than a machine that stores and retrieves information from some kind of storage (in some particular order), it would of course be justified to also include supporting memory, such as RAM (random-access memory), in the global stock of information storage. However, the information in this volatile storage is lost upon disconnection with the power supply and its primary purpose consists in supporting the computational processes, not in storage of information through "longer" periods of time (in sensu stricto, this of course depends on the time-scale applied to define "longer"). We therefore do not include RAM in our account of storage devices. We count only storage technologies that have the final end of storing information, while the capacity of RAM is indirectly included in the account of the world's computational power.

A similar grey zone exists between the classification of storage and communication. We include some technologies in both groups. For example, we classify newspapers both as part of the world's communication capacity and as part of the stock of storage (assuming that each newspaper is stored for one week and then destroyed). We also consider the amount of information communicated through the fixed or mobile Internet, and the amount of information that can be stored in fixed or mobile hard disks. In other cases we only account for one category. For example, we do not account for the amount of information transmitted when a friend lends a book to another friend or when you carry a book from your desk to the bedroom (even though one might as well argue that this "communicates" information from place A to place B). We account for this book in our storage inventory. Similarly, in our estimate of the communication capacity we include the amount of information that is delivered to the home through broadcasting channels and displayed at a TV receiver, but not

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<sup>1</sup> Knowledge about the world is a more casual expression for meaningful algorithms (i.e. algorithms that represent mutual information between the code and the real world).

the amount that is carried to the home on a videogame console or DVD and displayed at the same TV receiver. In both cases, we consider that the primary function of a book or a DVD is storage (through time), not the transmission of information over a geographic distance (through space).

This being said, we have decided to define communication as the amount of information that is effectively delivered to the consumer after it has been transmitted over a considerable distance, which we delineate as being *outside the local area*. Of course, this definition is not absolutely precise and depends on how “local area” is defined. We consider that the 50 cm between the TV screen and the user is not to be considered as transmission, while kilometers between the broadcast station and the TV set are to be included. There are cases that fall between the cracks. One example concerns information that is transmitted in closed local networks that do not make part of the Internet (such as closed company LANs or surveillance camera networks). The nature of the information transmission in them is conceptually similar to the example of carrying a book from one room into the other. Their main purpose is a local sharing of information, not the overcoming of distance. One could account for this kind of information within the global capacity to store information, or one might as well argue that this information is transmitted over a certain distance and count it as a contribution to the world’s communication capacity. We chose to account for it as storage, last but not least because of the lack of trustworthy and representative statistics on closed, private and local networks.

In the case of storage, we estimate the total installed capacity, which means that we suppose that the entire storage space is used completely. For the case of computation, we elaborate two estimates. On the one hand we estimate the amount of instructions per second that can be processed by a computer. This can be represented in MIPS (million instructions per second) or multiplied by 365.2422 days \* 24 hours \* 60 minutes \* 60 seconds, to obtain the instructions that are possible per year. On the other hand, we also made estimations based on the effective gross usage of the computers, which implies counting differential usage rates for each technology (see specification in E Computation). We call it “gross usage” because these statistics simply tell us how long a user has been interacting with a computer, not how many seconds the computer was running at full capacity.

The case of communication is tricky in this regard. Some communication technologies could be running all day long at full capacity (i.e. broadcasting TV and radio), while others share their common backbone infrastructure and would collapse if every subscriber would demand total bandwidth at the same moment (i.e. Internet, mobile telephony or the postal system). Therefore we opt for the effective communication in this case and count only those bits that are effectively sent. We only account for the number of minutes that are received by a TV set from a broadcasting station, and do not account for the bandwidth reported by the access provider in Mbps, but the installed backbone traffic, which reflects the effective usage of a shared network.

## A.3 References

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## B Compression

In order to be able to meaningfully estimate the amount of information that is stored and communicated in technological devices, we require statistics on (i) the quantity of devices, (ii) the hardware capacity of each device, and (iii) the compression rate with which information is compressed. The normalization on compression tells us how much information (bits) are stored on each hardware binary digit (1-2). The normalization compression rate depends on (iii.a) the type of content that is compressed (the probabilistic structure of the source). The largest distinction consists between sources of different content types: text, still images in black and white, still images in color, audio, music, voice, and moving images (video). Therefore, we will require an estimation of the type of content. And, (iii.b) we have to know the dominating compression algorithm used for this kind of content. Since these last two statistics are very rare and quite unreliable, we decided to focus only on four representative years over the past two decades: 1986 (which is basically before the digital age); 1993 (which is at the starting era of the Internet and mobile telephony); 2000 (which is at the height of ICT investments at the stock market); and 2007 (the last year for which we obtained reliable global statistics). This choice of four equally distant points in time allows us to measure three periods of growth (86-93; 93-00; 00-07), which is the minimum requirement to obtain a basic understanding of the overall shape of the growth process.

### B.1 The “optimal level” of compression

The majority of information sources are redundant, which is to say, they contain a lot of information that is predictable, and therefore does not represent “information”, in the sense that they reduce uncertainty (1,2). Information Theory (1-5) permits the calculation of the theoretically possible compression level when the probable distribution of the source (which could be text, image, sound, etc.) is known. Unfortunately in many cases this distribution is not known (e.g. what is the probability of a blue pixel appearing in a video?). Coding theory aims to reach this theoretical level in practice. Lamentably, there exists no systematic method. In general, progress consists of engineering processes of “trial and error”, and in some cases it is not even understood why some specific algorithms have reached a performance as close to the theoretical limit. It is a continual process and significant advances have been achieved over the last 20 years in getting closer to the optimal level of compression (which is to say, in removing the largest amount of redundancy). Here we assume that the most efficient level of compression achieved in 2007 represents the “entropic” level and refer to it as “optimal level of compression”. We normalize on this level of compression. It might well be that future algorithms discover ways to compress certain kinds of content even further. Only the future will tell if this will be the case. If this is the case, it might be useful to renormalize on the newly found “entropic level” of compression.

In practice one often uses “lossy” compression, which means that some of the true information is deleted. While this decreases the quality of the information in question, we only chose those algorithms which result in a loss that can usually not be noted by the human observer. All of this being said, for our practical purposes, we define the “entropic” level of compression as *the optimally achievable level of compression with very good and excellent quality results in 2007*. We normalize our estimates on what in 2007 was seen as “optimal available compression”. In the future, this might of course change as coding theorists discover how to exploit yet unknown structures in the most diverse streams of data. In general, we can observe that with every new technological progress in compression algorithms (consisting of exploiting the underlying structure of information from a certain kind of source, focusing on detecting the redundancy in a message), we are able store more information (bits) with less symbols (binary digits, or “data”).

The following explains the operating principles of the most efficient algorithms, which occasionally are also the most popular ones, and presents the achieved compression rates. We also report the most commonly used algorithms (“dominant design”) in 1986, 1993, 2000 and 2007, which are necessary to estimate at which level of compression a certain type of content can be found at which point in time.

## B.2 Text

Although many specific algorithms exist for the compression of text (6, 7, 8), the most popular compression programs used in computers are the RAR and ZIP formats. Both are widely used principally in the compression of text, but can also be used for the storage/transmission of several coded files of diverse contents (for example, all the songs contained on a disk or a photo album from some special occasion can both be compressed into one ZIP file). We also use the compression levels of RAR and ZIP algorithms as an approximation for the compression algorithms used by Microsoft in its Word processor program (in “.doc” and “.docx” files, both of which achieve rates very similar to those of RAR and ZIP).

### B.2.1 RAR

RAR is a proprietary format, an acronym for *Roshal Archive (or RoshalARchiver)*, with its names owing to its creator Eugene Roshal, who developed this method as his doctoral thesis. Its implementations in software have the particular characteristic of permitting the user to specify the amount of redundancy (as a percentage of the original size of the data to be processed), in this way allowing the data to be more or less robust against file corruption depending on the amount of redundancy left (6).

RAR has two compression modes: general and special. The first of the two utilizes an algorithm based on LZSS, very similar to ZIP’s *deflate*. Starting with version 3.0, RAR also uses a

special compression mode to improve the compression of like-text data. This mode is based on the PPMD mode (also known as PPMII).

In Table S B-1 we present the results of the compression of text in this format (other types of content besides text are not considered, because it known that RAR is not as efficient as other methods when it comes to other types of content).

**Table S B-1: Results of the benchmark for optimal compression algorithms.**

Algorithm	Data to be compressed [bytes]	Compressed data [bytes]	Compression factor <sup>2</sup>
PPMD (WinRAR 3.6)	1,000,000,000	198,454,545	5.04
	100,000,000	22,713,569	4.40
LZSS (WinRAR 2.01)*	3,393,000	782,050	4.34

Source: (9, 10)

## B.2.2 ZIP

The compressed file format ZIP is very simple. It permits a reduction in size of a group of files (each in an independent manner), and is widely used. Applications such as WinZip, Gzip, etc. utilize a method called *deflate*<sup>3</sup>. This is a very popular method and is used by other applications such as HTTP protocol, the protocol of compression control PPP, PDF (*Portable Document File*) and the graphic file formats PNG and MNG (*Multi-Image Network Graphics*), among others (6).

Developed by Philip Katz in 1989, the *deflate* method and the ZIP file format are part of the public domain, which is why there exists a grand number of applications which utilize them in different computing platforms. In order to identify an average compression factor for ZIP (regardless of the application being used), we consider a simple average of the compression factors reported in Table S B-2, which results in 4.61.

**Table S B-2: Results of the benchmark for optimal compression algorithms.**

Algorithm	Data to be compressed [bytes]	Compressed data [bytes]	Compression factor
7-Zip	3,393,000	650,610	5.22
Bzip2	3,393,000	678,030	5.00
advZip	3,393,000	808,720	4.20
Gzip	3,393,000	841,490	4.03

Source: (10)

<sup>2</sup> The presented figure corresponds to the quotient between the original size of the file and its compressed size.

<sup>3</sup> The ZIP format utilizes several methods for compression (all based on the dictionary, such as LZW, LZ77, based on sliding window, etc.); however, *deflate* is the one most commonly used.

### B.2.3 Text Compression Rates over time

#### 1986

Around 1986, the LZW algorithm (an improvement on LZ77), developed by Abraham Lempel, Jacob Ziv, and Terry Welch in 1984, was implemented in the program *compress*, and was the standard utility in the UNIX system (113). This algorithm is referred to as the standard. The compression rate achieved by LZW is variable and depends on the type of data (text) that is being compressed. Based on what is reported in (11), we have formed a simple average of each of the rates, obtaining a result of 2.2:1.

#### 1993

The assumptions for this year are that in comparison with the period before 1993, the distribution of compressed data formats did not vary in 1993; and that there is a direct proportional relation between what is transferred and what is stored (it is known that this is not always the case, but given the lack of information, it is considered valid).

Table S B-3 presents the percentages, which represent each of the formats and their respective compression rates. With respect to the percentages, that is to say, the distribution of use of LZW, ZIP, and others, they were calculated starting with the number of archives most commonly transferred by FTP (*File Transfer Protocol*) (12), and not the number of bits that such file transfers involve, this being because said number would better indicate the preferences of the users regarding the use of the different formats. We may suppose that the assigned compression rate with other formats (different than LZW and ZIP, among which include the files .arj, .uu, .dms, .lzh, etc.) is the same achieved by LZW (on this subject, no other statistic is known).

Table S B-3: Distribution of formats of file compression and their respective compression rates.

Algorithm	Percentage [%]	Compression factor
LZW	45%	2.2
Zip (deflate)	31%	4.6
Others	24%	2.2
Sum and weighted averaged		
Total text	100%	2.9

Source: Authors' own elaboration, based on various sources (see text).

#### 2000

It is supposed that the ZIP format is the most used in compression of text files in this period. While it is so that the RAR format had already been introduced in 1996, for the fact of being proprietary software, it still was not able to get a significant percentage of use (apart from that, both formats present a very similar performance: 4.6:1 versus 4.7:1). On the other hand, LZW fell out of use owing to technical problems and difficulties with the patent in 1987 (113), so it is assumed that its percentage of use is negligible.



## 2007

For this year we suppose the most common use of RAR in combination with ZIP for the compression of text. The difference is marginal, given that both formats present a very similar performance (4.6: 1 versus 4.7: 1). It is important to note that new algorithms have been developed for the compression of text (PPM, CM, etc) that achieve a higher performance; however, their use still is not very wide, mostly owing to problems with the applications which implement them (for example, they require certain hardware characteristics to be able to function correctly) or to a lack of market interest or publicity.

## Optimal

There exists a large amount of literature on the different types of text compression algorithms, which has generated a series of contradictory results. For our studies, we have decided to use the Mahoney report (13), which is used in the selection of the winner of the Hutter Prize<sup>4</sup>. It evaluates the performance of 120 different programs, each of them implementing one or a combination of the following text compression algorithms: based on dictionary, LZ77 (Lempel-Ziv-1977), LZW (Lempel-Ziv-Welch), ROLZ (Reduced Offset Lempel-Ziv), LZP (Lempel-ZivPredictive), PPM (PredictionbyPartial Match), SR (Symbol Ranking), BWT (Burrows-WheelerTransform), DMC (DynamicMarkovCoding) and CM (ContextMixing). The programs are utilized to compress the first 10<sup>8</sup> (considered for the Hutter prize) and 10<sup>9</sup> bytes of the English version of Wikipedia on March 3, 2006.

The program with the best performance was DURILCA, a compressor based on the PPMD algorithm with compression filters for different types of files (text, executable .exe and data with fixed length registers), developed by the Russian Dmitry Shkarin in 2006. Eight versions of the program were evaluated (with 27 distinct configurations in all), each of them serving different sizes in byte of compressed archives. The next table shows the average performance of this program calculated as a simple average of the sizes of compressed files (for results with more detail, see (14)).

Table S B-4: Results of the benchmark for the optimal compression algorithm.

Algorithm	Data to be compressed [bytes]	Compressed data [bytes]	Compression Factors
PPM (durilca)	1,000,000,000	136,578,536	7.32
	100,000,000	17,023,623	5.87

Source: (14)

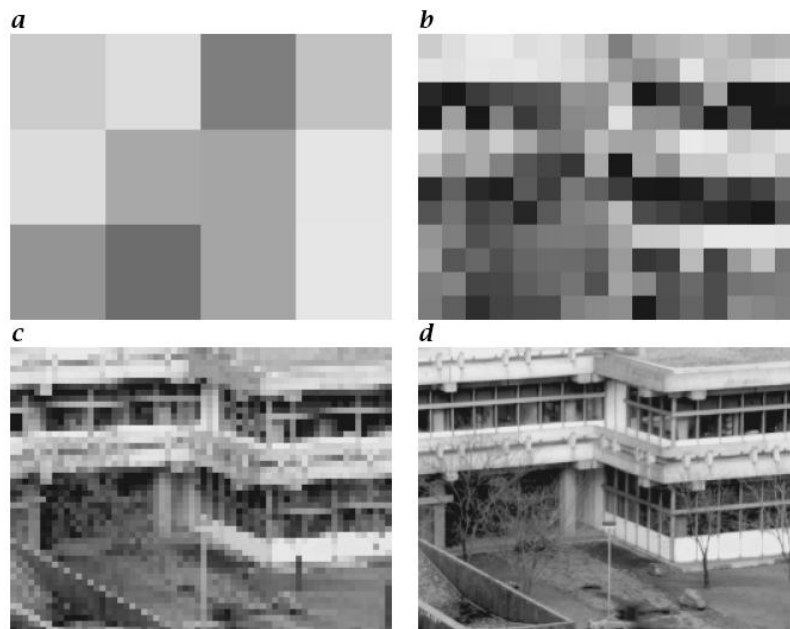
Given the difference in the observed compression rates caused by the difference between the texts to be compressed, we have opted to utilize an average compression ratio of both –equal to 6.6:1 (original: compressed). This way it is taken into consideration that the

<sup>4</sup> The aim of the Hutter Prize is to promote research in the field of artificial intelligence, specifically in the area of text compression; <http://prize.hutter1.net/>.

algorithm in effect presents a performance, which is not always constant. This would imply that on average, every character, which at first is coded with 8 bits (UTF-8), would need only 1.21 bits to be represented, which is within the proposed limits by Claude E. Shannon (5) in his publication “*Prediction and Entropy of Printed English*”: between 0.6 – 1.3 bits per character.

### B.3 Still Images

A continuous image (non-digital or “analog”) is the spatial distribution of irradiance<sup>5</sup> on a plane. In laymen terms, what the scanning process does is divide that image into small areas and then calculate the average irradiance for each one to create a two dimensional array (of  $m$  rows and  $n$  columns), in which the value of each of its components –called pixels or pel (*picture element*)- corresponds to the average irradiance. Pixels are fundamental in the digitization and the resolutions<sup>6</sup> already equal to  $m \times n$  of the image depending on their size. In Figure S B-2, the same image with different numbers of pixels (different resolutions) is shown (15).



**Figure S B-2: Dependence of resolution on the number of pixels. Image with different resolution (pixel count): (a) 3x4, (b) 12x16, (c) 48x64 y (d) 192x256 (15).**

The first step in the digitization of a continuous image corresponds to sampling, a process in which a continuous space is converted into a discrete one. Following the sampling of an image, it becomes necessary to quantify the sample values: to measure the irradiance of each pixel in a two-dimensional image, they should be mapped out on a limited number of discrete values (quantization levels) in gray or in color. Figure S B-3 shows monochromatic images quantified with 2 to 256 levels of grey. It can be easily observed that with fewer levels, it becomes more difficult to recognize objects that show a slow spatial variation of grey values.

<sup>5</sup> The irradiance is the quantity used to describe the power per unit area for all kinds of electronic radiation, corresponding to the visible spectrum.

<sup>6</sup> The term resolution is sometimes used to indicate the number of pixels per unit length in the image. Examples of this are the units ppi or pdi.

With two levels (1 [bit/pixel]), the image produced is in black and white. Generally, the image data of these types are quantized in 256 levels of gray. So, each pixel is represented by 8 bits ( $2^8$ ) (15). Also, each component of a color image is quantized with 24 bits, yielding a total of more than 16 million different colors. This is known as “true color” (16).

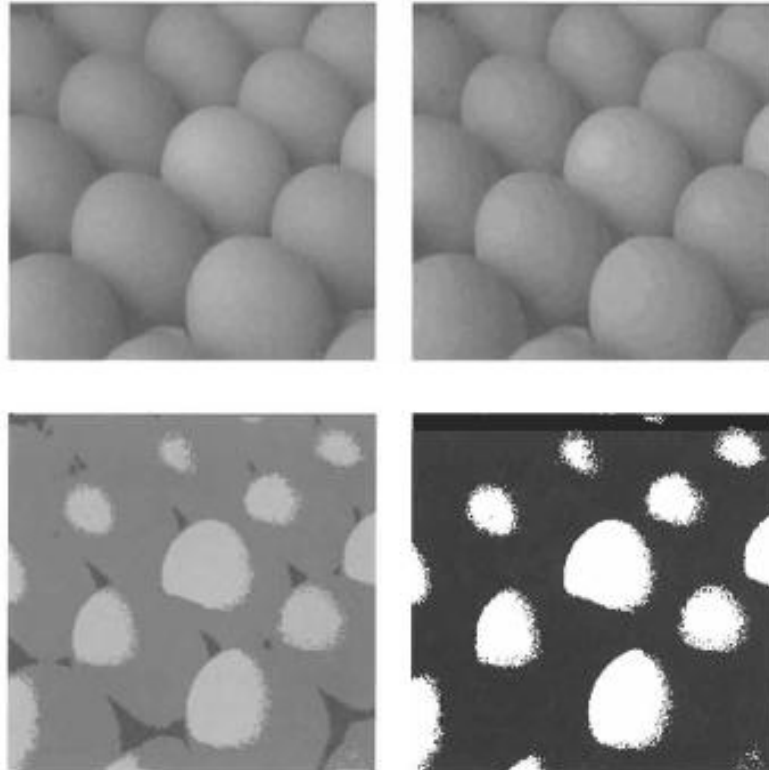


Figure S B-3: Effect of quantization levels on the quality of the image: (a) 8 [bit/pixel], (b) 4 [bit/pixel], (c) 2 [bit/pixel] y (d) 1 [bit/pixel] (17).

Digital images tend to use a lot of space on the storage hardware. For example, a 512x512 pixel resolution in true color (24 [bit/pixel]) uses 786 432 bytes, while one of 1024x1024 requires 3 145 728 bytes for its storage purposes. With this in mind, image compression algorithms have become essential. Lossy compression aims at discarding some of the features that are not visible to the naked eye, without losing the quality of the compressed image. The idea is the corner stone of lossy compression algorithms, which in addition to classic reduction or elimination of redundant content used in lossless algorithms, also uses the additional concept of removing irrelevant content (information that is not noticeable to the human senses).

When coming up against the challenge of cutting out the redundancy of an image, the art of image compression consists in exploiting the correlation between pixels. If two pixels are perfectly correlated, then all that needs to be done is store the first ones: the second is predictable in relation to the first, and therefore it does not transmit any additional information. One of the problems with images is that there exists no clearly established alphabet and dictionary of shapes and colors, as there does for letters and words. This makes it somewhat difficult to calculate the probabilities of each pixel in the image. For example, if a

pixel has the color blue, what are the chances that the pixel to the left is green? This depends on a lot of things and varies for different types of images.

That said, there are many algorithms to compress images, each with its own advantages and disadvantages. For this study, we look at the three most-used which as well show good performance at the time of compression. The selected techniques are JPEG, PNG and GIF. According to (18), more than 90% of users utilize JPEG and following several sources, among them (19, 20, 8), GIF and PNG are the most-used format on the Web.

### B.3.1 JPEG

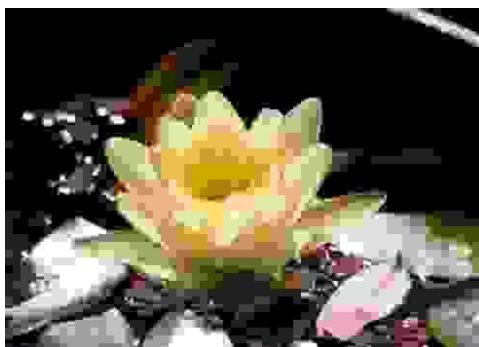
JPEG (Joint Photographic Expert Group) is a compression technique with and without losses for images in color or in gray scale, standardized by the joint group CCITT/ISO in 1991. In 2000, the successor to the lossy JPEG was standardized: JPEG2000, which gives better results in terms of trade-off quality/compression than did its predecessor (21, 22). The better performance of JPEG2000 in highly compressed images is due to the fact that it does not present pixelization (notable pixels in the image), but something more like a “blur” (see Figure S B-4). However, it is clear that these high rates (greater than 100:1) greatly affect the image quality.



JPEG (21:1 – high quality)



1.1.1.1.1 JPEG2000 (21:1 – high quality)



1.1.1.1.2 JPEG (217:1 – Poor quality)



1.1.1.1.3 JPEG2000 (217:1 – Poor quality)

Figure S B-4: Comparison JPEG vs JPEG2000 (22).

One key feature that has allowed the all-around success of JPEG is that it lets the user configure many parameters, including the amount of losses permitted and the compression ratio, which in the end enables the user to determine the quality and the desired compression.

The sequential lossless mode is based upon predictive coding principles, a simple method which predicts the value of a pixel by the value of previously encoded pixels, given the correlation between them. The typical ratio achieved is 2:1 for moderately complicated color images (23, 24, 6). This can be understood as follows: each pixel in the image is represented by 16 binary digits, so after compression, on average, it would then be represented by only 8 binary digits. This compression level is not very effective and still ends up being a fairly large image. The DCT based sequential mode (Baseline JPEG) is a lossy image compression and is the most-used (following 18). JPEG *Baseline* meets the standards of *criteria of fidelity* defined by Shannon, which say that an accurate representation of the original message is not necessarily needed because of the limitations of the human perceptual system (i.e. vision) (25). In this case, it takes advantage of the fact that the human eye is less sensitive to color changes than changes in the brightness of an image. In color images, the majority of spatial information is found in their “brightness”, while the color components remain largely redundant (6, 17, 20, 23, 24).

(24) proposes a guideline on the quality and quantity of bits (binary digits) per pixel for a color image with moderately complex scenes. These can vary significantly depending on the characteristics of the image source and on the content of the scene, but they do give a good base for making estimations on the amount of information (Table S B-5).

**Table S B-5: Relationship between the number of bits per pixel and the quality of the resulting image.**

[bits/pixel]	Characteristics
0.25 – 0.5	Moderate to good quality, sufficient for some applications
0.5 – 0.75	Good to very good quality, sufficient for most applications
0.75 – 1.5	Excellent quality, sufficient for almost all applications
1.5 – 2.0	Usually indistinguishable from the original, sufficient for most demanding applications

Source: (24).

### B.3.2 GIF

The GIF format (Graphic Interchange Format) was developed in 1987 by Compuserve Information Services as a format for efficiently compressed graphic files (19). Due to its superior compression ratio and greater color depth, JPEG has replaced GIF in the storage of photographic images during the last years, even though GIF is still used for other applications, mainly in Web browsers (because it compresses at a smaller size). The main features of a GIF image are that they can have up to 256 colors (using from 1 up to 8 bits per pixel) (6). GIF scans images row by row and finds out the correlation between the pixels in them but not the correlation between the different rows. This shows that GIFs inefficiency lays in the singular dimensional work of the GIF encoder, where the images are two dimensional. It could be that

a certain image has a large region of constant values which can be taken advantage of when considering two dimensional areas. Recently, a new standard called PNG has arrived which utilizes the fact that the surroundings of a pixel present a variation of its values, generally in a small sub-area of a coded image. PNG (Portable Network Graphics) utilizes the differences in neighboring pixels, and therefore can achieve between 10% - 40% more storage than GIF (19). Another factor to be considered is the fact that GIF does not introduce losses of information because it does not eliminate what is irrelevant and preserves each original pixel.

### B.3.3 Image compression rates over time

The following summarizes the compression ratios achieved by different compression methods for still images. Regarding JPEG, we arrived at our estimation based on the data presented in Table S B-5 and considered that a pixel has 24 bits in the case of a color image or 8 bits in gray scale. For the rest, we verified the information by other sources taken from (20). It should be mentioned that the column on the ratio of black and white compression is only an estimation (there is no specific information on the respect) based on the number of bits per pixel in the case of JPEG, which is achieved once the compression is the same as for colors. This assumption is justifiable since much of the information is contained in the brightness (reflecting exactly a grayscale image) while the information provided by the color components are practically redundancies. From this we may conclude that the amount of byte/pixel must be very similar in both cases.

Table S B-6: Compression rates for the algorithms considered<sup>7</sup>.

Format	Typical compression rate (color)	Typical compression rate (B&W)	Description
GIF	4:1 – 10:1 [7:1]	4:1 – 10:1 [7:1]	Lossless compression for images with a palette of 256 colors
JPEG (high quality)	12:1 – 16:1 [14:1]	4:1 – 5.3:1 [4.7:1]	High quality. Little or no loss in image quality with continuous original tones
JPEG (moderate to high quality)	16:1 – 32:1 [24:1]	5.3:1 – 10.7:1 [8:1]	
JPEG (moderate quality)	32:1 – 48:1 [40:1]	10.7:1 – 16:1[13.4:1]	Moderate quality. Usually the best choice for use on the Web
JPEG (poor quality)	48:1 – 96:1 [72:1]	16:1 – 32:1 [24:1]	Poor quality. Ok for simple images (thumbnails). The pixelation is obvious
PNG	10 – 30% smaller than GIF	10 – 30% smaller than GIFs	It behaves in a similar way to GIF but with higher quality

Source: (20, 24)

Since there is no information available on the percentages of color or black and white images, we will follow the same distribution of photographic negatives (for more in depth details see Table S C-19, Appendix C). Different from text compression, the factors are not the

<sup>7</sup> In (20) the conjoining of JPEG is slightly different. It reports that for high quality, they vary between 10:1 – 20:1, for medium quality –without separation between upper-middle and lower-middle– between 30:1 – 50:1 and for low quality, between 60:1 – 100:1, which is consistent with reports by (24).

same for each type of storage device and for transmission technologies for certain years because it is considered that they store or transmit images with different qualities.

### 1986

Although the history of the digital image dates back to 1957 (26), in 1986 the commercial compression methods were still in the experimental stage. That is why we may assume that the compression factor is equal to 1: 1 (that is to say, no image is compressed) for all storage devices and all transmission technologies.

### 1993

Since JPEG was established in 1992 (12), it may be assumed that in 1993 its use was still minimal, so we will assume that all digital images were compressed in GIF format with a compression ratio of 7:1 (average compression is chosen with the aim ensuring that the image has good quality). As support for this assumption we have (27), which indicates that 99.8% of server image requests were in GIF format in 1994 (for black and white and color images).

### 2000

(28) reports that 77.5% of image files in 1999 were stored in GIF format, while 22.5% corresponds to JPEG. This ratio is considered for 2000, furthermore assuming that the distribution is valid for any storage device or transmission. Since it is assumed that the images are stored/transmitted with different qualities, the compression factor will vary in accordance with the technology. Below we look over the details.

#### *JPEG moderate-low quality*

Compressed images of moderate to low quality are mainly used on the Web, producing slight but noticeable distortions. They do not support extensions (whether done by the zoom of some photo editor or in print) without affecting the quality negatively. It is assumed that technologies that store JPEG with low-medium quality are for WWW, FTP and e-mail traffic. On the other hand, with the exception of newspapers, we can suppose that the distribution between color and black and white images is the same as those of photographic films for this year (97.5% and 2.5%, respectively), so that if we calculate a weighted average it would yield a compression factor equal to 14.28.

**Table S B-7: Compression Factors.**

Compression factors	Percentage [%]
---------------------	----------------

	Color	B&N	
GIF	7.0	7.0	77.5
JPEG	40.0	13.4	22.5
Average factors	14.43	8.44	-
Percentage	97.5	2.5	
Weighted average		14.28	

Source: Authors' own elaboration, based on various sources (see text).

#### *JPEG medium-high quality*

Within this category, we have considered images stored on mobile phones (which only store color JPEG color, not the GIF combination), floppy disks, digital data magnetic tapes and video-game console data storage devices. Compression factors are shown in the next table. Considering the combination of JPEG and GIF, the resulting weighted average of the image in color and in black and white is equal to 10.74.

**Table S B-8: Compression Factors.**

	Compression factors		Percentage [%]
	Color	B&N	
GIF	7.0	7.0	77.5
JPEG	24.0	8.0	22.5
Average factors	10.83	7.23	-
Percentage	97.5	2.5	
Weighted average		10.74	

Source: Authors' own elaboration, based on various sources (see text).

#### *JPEG High quality*

In this case, we will suppose that USB, PDA and hard disks store high quality JPEG, and that furthermore, only digital cameras and CD/DVD use JPEG exclusively. For images stored in "analog" (paper and film photographs; radiographies, etc.), only JPEG is used at this quality; this is because this level of compression does not produce additional losses in quality. It is important to keep in mind that the low level of quality of printed images has already been considered during the process of digitization, and therefore, any further reduction through compression would result in an impoverishment that would not fit with reality.

**Table S B-9: Compression factors.**



	Compression Factors		Percentage [%]
	Color	B&N	
GIF	7.0	7.0	77.5
JPEG	14.0	4.7	22.5
Average factors	8.58	6.48	-
Percentage	97.5	2.5	
Weighted average	8.53		

Source: Authors' own elaboration, based on various sources (see text).

## 2007

(29) reports that in 2005, 63.7% of the compressed images on servers that contained all Danish web pages were stored were in JPEG format and the remaining 36.3% in GIF. Supposing that the portions were kept constant with the passage of time and are valid for the entire world, we consider the resulting weighted compression rates.

### *JPEG medium-low quality*

Table S B-10: Compression factors.

	Compression factors		Percentage [%]
	Color	B&N	
GIF	7.0	7.0	36.3
JPEG	40.0	13.4	63.7
Average factors	28.02	11.08	-
Percentage	97.5	2.5	
Weighted average	27.60		

Source: Authors' own elaboration, based on various sources (see text).

### *JPEG medium-high quality*

Table S B-11: Compression factors

	Compression factors		Percentage [%]
	Color	B&N	
GIF	7.0	7.0	36.3
JPEG	24.0	8.0	63.7
Average factors	17.83	7.64	-
Percentage	97.5	2.5	
Weighted average	17.57		

Source: Authors' own elaboration, based on various sources (see text).

### *JPEG High quality*

The corresponding compression ratios are shown in the following table. We must mention that the PNG image format, since its standardization in 2003, has grown in popularity and according to (30) has started to replace the dominating GIF standard on the Internet and in the storage of digital images, because it achieves between 10% - 40% better compression. Nevertheless, due to the lack of information about percentage of use, this format is not included in the estimate.

Table S B-12: Compression factors.

	Compression Factors		Percentage [%]
	Color	B&N	
GIF	7.0	7.0	36.3
JPEG	14.0	4.7	63.7
Average factors	11.46	5.53	-
Percentage	97.5	2.5	
Weighted average	11.31		

Source: Authors' own elaboration, based on various sources (see text).

## Optimal

For this case, we will assume the maximum level of JPEG compression rates for each of the categories seen.

Table S B-13: Optimum compression factors for still images.

Quality	High	Medium-High	Medium-Low
Color compression factors	16	32	48
Black and white	6.0	10	16

Source: Authors' own elaboration, based on various sources (see text).

## B.4 Sound

The compression of sound information is grouped into two categories: voice and audio. In each case, the algorithms take advantage of the very characteristics of each type of information, and furthermore of the functioning of the human auditory system, to eliminate the greatest amount of redundancy and, in the case of lossy compression, any irrelevant information. The logic of digitization is common to both. In the first stage –sampling– the continuous wave that represents sound is transformed into a sequence of simple values which are taken in certain regular intervals of time. In practice, these take a rate 10% - 12% greater than that obtained with the application of the Sampling Theorem (6, 31). When sound is digitized at high fidelity, a sample rate of 44.1 [kHz] is utilized, which is only slightly greater than twice the maximum audible frequency. Any lesser rate would lead to distortions (which become more noticeable the lesser they are), while higher sample rates do not produce notable improvements in the reconstruction (reproduction) of sound. Many low fidelity applications sample sound at a rate of 11 [kHz] and the telephone system, originally designed for conversations and not for digital communication, samples at 8 [kHz]. In this last case, any frequency larger than 4 [kHz] is distorted and it is because of this that, during a call, it is difficult to distinguish between the sounds of an “f” and an “s”, or of a “p” and a “b” or “d”, reason why it is customary to use reference words when spelling over the phone (“a as in apple”, etc).

In the second stage of the process –quantization- the number of predefined discrete values is determined by the quantity of binary digits with which each sample is codified. In general, 8 to 16 bits are assigned by sample: if the first is utilized, a higher compression of the file is achieved; but a poorer reconstruction of the audio would be the result than when using 16 binary digits, since the sound would only present 256 distinct amplitudes ( $2^8$ ), instead of 65,536 ( $2^{16}$ ). In Figure S B-5, we present a comparison between an original sound wave (sampled at 8 [kHz] and coded with 8 bits per sample) and a reconstruction. Using a little imagination, it is possible to see that if quantization considers a smaller number of bits per sample, which implies that the range between maximum and minimum signal amplitudes is divided in less intervals (for example, if 4 bits per sample are used, this range would be divided in only 16 ( $2^4$ ) intervals versus the 256 intervals achieved with 8 bits per sample), the reconstructed signal would present longer vertical “steps” and the wave would present even greater distortions than what is presented in the figure. The contrary situation would occur if more bits per sample were used.

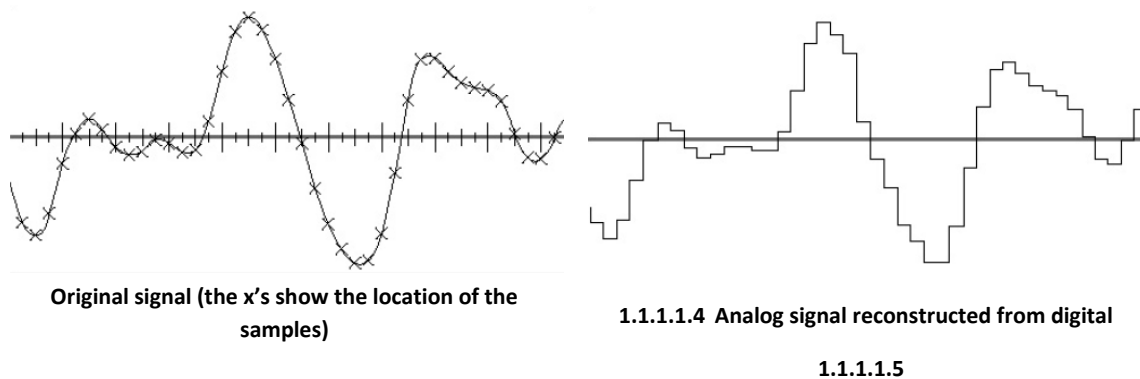


Figure S B-5: Comparison between an original audio signal and an analog reconstruction from digital<sup>8</sup> (32).

### B.4.1 Voice

Among audio encoders, there exist a few that are designed specifically for the compression of voice signals, owing to the nature of the human voice, which has certain properties that allow for the achievement of more efficient signals (33). The basis of voice compression techniques is the strong correlation that exists between adjacent samples in a digitized audio signal, including in samples that are separated by 20 [ms] (6). Rarely some kind of perceptual modeling is utilized (such as the kind used in MPEG-4 for other types of audio), since the perception of the voice is quite different from other non-voice sounds (experiments

<sup>8</sup> While at first sight it would seem that the two are radically different (the “soft” form of the original wave is replaced with another with well-defined “steps”); mathematically, the abrupt jumps that occur when moving from one sample to another represent the high frequency components of the signal. These are usually eliminated with a filter (high-pass), which is located at the exit of the digital/analog converter and amplifier before its reproduction. This causes the wave to regain, to a certain point, its softness (32).

have indicated a specialization in the brain, where one part is in charge only of processing voice information (34)).

The basic techniques of voice compression come from the time of the invention of the telephone by A. Graham Bell and the possibility to represent the form of a voice wave as an electric analog signal by Homer Dudley (35). There are three principle types of voice encoders:

- Waveform: attempts to reproduce the original waveform signal, producing good to excellent quality voice after compression and decompression, but generate high bit rates (10 - 64 [kbps]). They do not predict the form in which the sound is generated, but base it on a simple digitization of the sound (improving results with the application of companding, ex. G.711). In voiced sound samples, they are correlated (ex. ADPCM) or transform the audio samples to frequency domain, taking advantage of the difference in sensitivity of the ear to different frequencies (ex. SBC y ATC);
- Vocoders: use a predictive mathematical model for the calculation of certain parameters that describe the production of voice, generating voice with low to acceptable quality and compressing at very low rates (up to 2 [kbps]);
- Hybrids: combine the previous two to produce voice with quality ranging from acceptable to good, with bit rates of between 2 and 16 [kbps].

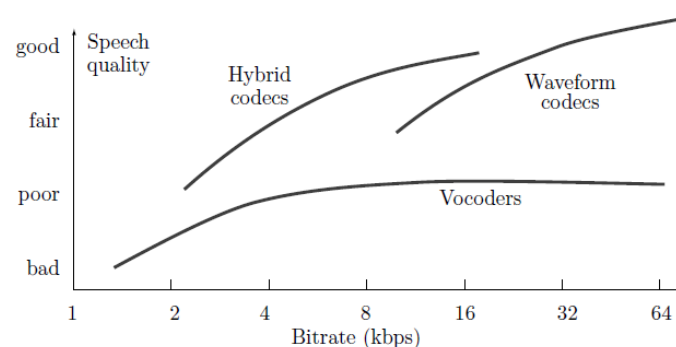


Figure S B-6: Comparison of different kinds of voice encoders in terms of quality achieved (6).

For example, a telephone voice signal requires 64 [kbps] to be transmitted without a great loss in quality, but modern compression techniques permit the bit rate to be reduced from 13 to 8 [kbps] with algorithms based on a paradigm called “analysis-by-synthesis”<sup>9</sup> (RTP-LPE o CELP, for example) –the base of hybrid encoders and the principle responsible for those achievements-, with very little additional degradation (35). On the other hand, the appearance of new applications, like video-conference services and the third generation of mobile phones

<sup>9</sup> The term “analysis-by-synthesis” refers to the active analytic process that can be applied to signals that are produced by a generator whose properties are known. The nucleus of a system that implements this technique is a generator of signals able to synthesis all the analyzed signals. The signals analyzed by the generator are compared with the signals to be analyzed, and a measure of error is calculated. Different signals are generated until it finds one that causes an error to reach some small value, the moment in which the analyzer indicates the properties of the internally generated signal (35).

(3G), has let to the development of new encoders to provide higher fidelity voice than that of classic telephony which limits the signal frequencies up to 4 [kHz], extending the aforementioned range up to 8 o 16 [kHz] (36). From this we may infer that by increasing the bandwidth, the quantity of contained redundancy in the digitized signal is raised to improve the robustness of the message.

Within the Speech Profile of MPEG-4, specialized tools are integrated for the codification of voice, which operate in the range of 2 to 24 [kbps]. They are CELP (CodeExcited Linear Prediction) and HVXC (Harmonic Vector eXcitationCoding), which was selected to cover the range from 2 to 4 [kbps] (34, 37, 38). Both are part of the hybrid encoder family. It is important to note that the value of optimal compression is approximated using predictive analysis, which eliminates the greatest amount of redundancy possible in the signal.

#### **B.4.1.1 Voice compression rates over time**

Regarding digital fixed-line phones, from 1972 up to today the standard is G.711, with compression factors equal to 1.63 and 1.75 for the United States, Japan, and Australia, and for Europe and the rest of the world, respectively; has remained constant (39). The case of mobile telephones and VoIP is different and is presented in the following.

##### **1986**

Only the analog mobile phone existed by this time, for which no compression scheme is used.

##### **1993**

The only digital mobile technology commercially available was GSM (since 1992), which utilized the GSM.FR algorithm, based on RPE-LPC, achieving a compression factor equal to 8.

##### **2000**

In the year 2000, there already existed GSM and 2.5G GPRS, PDC, TDMA, iDEN and cdmaOne technologies. To calculate the average compression factor, we consider the percentages that each of them represents of the total subscribers of digital technologies and their respective compression factors. In this way obtaining a weighted average of 13 (Table S B-14).

**Table S B-14: Compression factors for technologies in use in 2000.**

	GSM	cdmaOne	PDC	TDMA	iDEN
% subscribers	68.1	12.4	7.8	10.4	1.3
Compression factor	15.1	4.9	15.5	8.0	8.0
Average factor	13.0				

Source: Authors' own elaboration, based on various sources (see text).

VoIP had already been functioning for five years in 2000 (in 1995, a small company called VocalTech released the first software with support for VoIP (40), right after the appearance of the Intelx486 which could manage the coding/decoding of voice in real time). VoIP supports a large amount of compression algorithms, and the one that is eventually utilized is “negotiated” between the participants in agreement with those used by each party and with the nature of the web traffic at this moment. Table S B-15 shows the most common encoders, together with their compression rates. Given that there is no *a priori* knowledge on which percentages represent each one or which is the most popular, we have opted to utilize a simple average of the representative compression factor, equal to 7.9: 1.

**Table S B-15: Most-used compression algorithms by VoIP before 2000 and their respective compression rates.**

Codec	Year	[kbps]	Sample Rate[kHz]	Bits/Sample	Compression Factor
G.711	1988	64	8	13 or 14	1.7
G.729	1996	8	8	13	13.0
G.723.1	1996	6.3	8	13	16.5
G.723.1	1996	5.3	8	13	19.6
G.726	1990	32	8	13	3.3
G.726	1990	24	8	13	4.3
G.722	1988	48	16	14	4.7
G.722	1988	56	16	14	4.0
G.722	1988	64	16	16	4.0
GSM	1986	13	8	13	8.0
Average compression factor					7.91

Source: (41-43)

## 2007

To the previous technologies, we add those of the third generation: (UMTS), cdma2000 1x y cdma2000 1xEV-DO. The procedure for obtaining the average compression factor is the same as described above.

**Table S B-16: Compression factors for technologies in use in 2007.**

	GSM	cdmaOne	PDC	TDMA	iDEN	CDMA2000 1x	WCDMA	CDMA2000 1xEV-DO
% subscribers	81.0	0.4	0.5	0.2	0.9	9.0	5.6	2.5
Compression factor	15.1	4.9	15.5	8.0	26.0	15.0	16.8	20.2
Average factor	15.4							

Source: Authors’ own elaboration, based on various sources (see text).

Given that there is no further information regarding VoIP, we have opted to use a simple average of the compression factors reported in Table S B-15 and Table S B-17, which is equal to 8.28.

**Table S B-17: Most-used compression algorithms by VoIP and their respective compression rates.**

Codec	Year	[kbps]	Sample rate	Bits/Sample	Compression Factor
-------	------	--------	-------------	-------------	--------------------

		[kHz]			
iLBC	2002	15.2	8	16	8.4
Speex	2003	2.15 – 24.6	8	16	9.6
Speex	2003	4.0 – 44.2	16	16	10.6
Average compression factor (considering Table S B-15)					8.28

Source: (41-43)

### Optimal

We have considered the subjective results of the quality evaluations of encoded narrowband voice (37, 39). These are expressed in MOS (*Mean Opinion Score*) values, which provide a numerical index of the perceived quality of sound received after compression and/or transmission. Just as the name indicates, this index is subjective, and is based on the perceived quality by the persons that participate in the sample. The relevant question follows a scale of 1-5, with 5 points being excellent quality, and 1 point poor quality. Table S B-18 shows the equivalence between the value of this measure and the quality.

Table S B-18: Description of MOS rating system

MOS	5	4	3	2	1
Quality	Excellent	Good	Acceptable	Poor	Very Poor
Distortion	Imperceptible	Perceptible, but not annoying	Slightly annoying	Annoying	Very annoying

Source: (118)

Measurements have been made on how many bits are needed to encode different telephone calls with CELP-MPE/HVXC. It has been found that for acceptable quality (close to 3 on the MOS scale, see Table S B-19) some 4 kbps are required to digitize all of the information contained in a call with CELP-MPE/HVXC, while for good quality (close to 4 MOS points), 12 kbps would be required. It has been discovered that MOS for digital land line telephony (G.711 codification) is in the MOS range of [3.6 - 4.1] (44, 46). For our purposes we have therefore considered the highest average MOS rate from the tests, that of 12 [kbps] with CELP-MPE, for the calculation of the compression rate. Similarly, in the case of analog transmission, where an acceptable quality has been supposed, a rate of 8.3 [kbps] will be used, which is also achieved with CELP-MPE (see Table S B-19).

Table S B-19: Results of subjective quality tests on coding of narrowband voice in SpeechProfile MPEG-4.

	HVXC	HVXC	CELP-MPE	CELP-MPE	AMR-WB	EVR-C
Bit rate [kbps]	2	4	8.3	12	12.65	8.55
MOS	2.53	2.92	3.25	3.69	3.78	3.82

Source: (39, 47, 48).

Regarding mobile telephony, as a compression technique, RPE-LPC utilized for GSM has an MOS that varies from between 2.91 and 3.16 (47). Following the logic of selecting the transmission rate achieved with the codification in accordance with quality, it can be said that a rate of 4 [kbps] is appropriate, given that the perception of quality is comparable. On the

other hand, in agreement with (49), the typical MOS for a call in AMPS is 2.3, a rate of 2 [kbps] is considered the most suitable for analog telephony.

The following table presents the compression factors for consideration. They were calculated in the following fashion: in digital telephony it is supposed that, in accordance with the MOS, its compression rate can be optimally compressed at 12 [kbps]. This implies that it achieves a compression rate of 9.0, which is equal to the ratio between the simple average of the digitized rates (112 y 104 [kbps]) and the compressed rates (12 [kbps]). As for analog telephony, we may follow the same logic, supposing however that the optimally compressed rate is 8.33 [kbps] and the average rate of digitized voice is 100 [kbps], which would indicate a compression factor of 12.

**Table S B-20: Compression rates for the transmission of voice via telephone**

	Fixed-line analog	Fixed-line Digital	Analog Mobile	Digital Mobile	
				2G/2.5G	3G
Compression factor	12.0	9.0	32.0	16.0	22.9

Source: Authors' own elaboration based on (39, 47).

For 2G/2.5G mobile telephony, compression factors achieved with HVXC are used for bit rates of 2 to 4 [kbps], which is to say, 32 and 16 respectively. For 3G, we consider a weighted average –in accordance with the percentage of users- of the compression factors with Wideband AMR-WB and CELP WB algorithms. It is important to mention that in spite of these algorithms achieving higher compression (lower rates than those considered for the calculation on capacity), a potential compromise forces us to chose the rates that assure to maintain the same level of quality. In the case of VoIP, there is no typical measurement, as the MOS varies depending on the encoder used, the conditions of the web, etc. The maximum is obtained with the use of G.711 (MOS = 4.4) (50), and various sources report that a fall below 3.5 would serve as an indication of problems (51). It is for this reason that we consider the compression of 2007 and not that which would be obtained in Table S B-19, since this one is less than the achieved compression of 2007.

### B.4.2 Audio: MPEG

Audio compression methods, like image compression, may or may not allow losses of irrelevant information. Any loss does normally not result in a large damage of the quality of the reconstructed archive. Lossless algorithms take advantage of the fact that adjacent signal samples are highly correlated (it is not difficult to imagine if you consider that generally, in the digitization of an audio signal, more than 40 thousand samples are taken in a single second) (52). Audio signals may be generated using a great number of different mechanisms. For this reason, the compression algorithms for lossy audio are focused on a model of sound perception, in other words, they utilize a psychoacoustic (ear+brain) model of human hearing, unlike voice compressors which are based on a model of the information source (in the output of the voice) to be able to identify the structures in the voice signal that can be used for their



compression (6, 8, 31). With the identification of what can and can not be heard, the schemes achieve a high level of compression by removing what can not be perceived.

There exist a large quantity of file formats and compression algorithms, both with losses and without, but the method of lossy compression most widely used is MPEG (*Moving Pictures Experts Group*) (54, 111, 112). The original objective of MPEG was to create a standard for the codification of both audio and video in digital media storage. However, the part associated with the codification of audio began to be developed separately thanks to diverse studies and experiments. These trials proved that it was possible to compress a lossy audio signal without damaging its quality (6). With this, MPEG audio began to be utilized for several applications; such as the transmission of digital audio (with Eureka-147 DAB, WorldSpace, ARIB, DRM), the storage of archives in broadcasting, the sound in digital television (DVB, Video CD, ARIB), streaming Internet, portable audio devices and for the storage and interchange of music files in computers.

The standard codification of MPEG-1 audio (1992) contains three different layers known as I, II, and III. MPEG-2 (1994) inherits and incorporates a new characteristic for improving the efficiency of codification, which in 1997 became the MPEG-2 AAC (*Advanced Audio Coding*) standard, a second generation audio compression scheme for the generic codification of stereo and multichannel signals (6, 8, 31, 53-55). One famous standard is the MPEG Audio Layer-3, better known as MP3. The difference between the different layers is that their complexity and performance increase progressively.

For its part, MPEG-4 is different than the two standards that came before. It puts more emphasis on the development of new features than on the efficiency of the codification. This standard aims to facilitate the growing interaction and overlap between the worlds of telecommunications, computation and massive electronic devices (TV and radio). As far as audio is concerned, MPEG-4 has a family of compression algorithms that range from voice compressors (at rates as low as 2 [kbps]) to high quality audio encoders for low bit rates (64 [kbps] per channel). It must be noted that for medium and high bit rates, MPEG-4 does not implement any improvement over MPEG-2 AAC.

MPEG does not work at a fixed compression rate. The resulting bit rate depends on the desired quality of the person who is using the encoder. For example, MP3s may have rates that vary from 8 to 320 [kbps], with which the compression ratio shifts between 4:1 and 176:1. What matters here is that the larger the bit rate or the less the compression rate, the better the quality, as the audio compression meets the general rule that says that the higher the bit rate, the better the quality of the audio played, since more original information is included in the compressed file. In addition to this, the audio quality depends as much on the quality of the encoder as on the nature of the signal to be encoded.

Based on various studies that have tested diverse encoders and digital audio formats in a subjective manner (i.e., a group of listeners listen to different sound archives and then grade them), we present the bit rates and their respective qualities (see Table S B-21). It is certain that there exist qualities lower than this, but given the consequences of the use of

lower rates (noticeable noise, unnatural sound, poorly defined bass/treble, “elimination” of instruments, etc.), such types have not been included in this study. In other words, this is equivalent to saying that at the time of compressing audio files, users prefer to have a backup of acceptable quality, although it would use more space in their storage devices.

**Table S B-21: Bit rates vs. Quality for different audio compression methods.**

Quality	MPEG-1/2 Layer 1	MPEG-1/2 Layer 2	MPEG-1/2 Layer 3	MPEG-2 AAC <sup>10</sup>
Excellent (indistinguishable from CD)	384 – 448 [kbps]	256 – 384 [kbps]	224 – 320 [kbps]	160 – 256 [kbps]
Very good (very similar to CD, small loss of quality)		224 – 256 [kbps]	192 – 224 [kbps]	128 – 160 [kbps]
Good (sound different than CD, noise perceptible, but not annoying)		192 – 224 [kbps]	128 – 192 [kbps]	96 – 128 [kbps]

Sources: (56-63)

Because, perhaps, the main use of audio encoders is by common people who “rip” their CDs so that they may store them digitally on computers or other digital devices, we consider that MPEG-1/-2 signals are digitized in accordance with the audio CD format. In other words: 44 100 samples per second, per channel (i.e., 88 200 samples per second if it is seen immediately that two stored stereo sound channels are sampled), each coded with 16 bits (64), which results in a rate of 1 411.2 [kbps]. In the case of MPEG-4, the digitization of the signal is generally sampled with 48 [kHz] per channel (96 thousand samples per second if it is stereo sound), coded with 16 bits per samples, showing a rate of 1 536 [kbps]. In Table S B-22, we present the percentages of compression, derived from the quotient between the resulting bit rates after compression and the digitized rates.

**Table S B-22: Compression Factors**

Quality	MPEG-1/2 Layer 1	MPEG-1/2 Layer 2	MPEG-1/2 Layer 3	MPEG-2 AAC
Excellent (indistinguishable from CD)	3.15 – 3.68	3.68 – 5.51	4.41 – 6.30	6.00 – 9.60
Very good (very similar to CD, small loss of quality)		5.51 – 6.30	6.30 – 7.35	9.60 – 12.00
Good (sound different than CD, noise perceptible, but not disturbing)		6.30 – 7.35	7.35 – 11.03	12.00 – 16.00

Source: Authors’ own elaboration, based on various sources (see text).

### B.4.3 Audio compression rates over time

<sup>10</sup> The equivalences between bit rates and quality between the MPEG-2 AAC and MP3 formats are like those of the following (respectively): 96 is like 128 [kbps], 128 is like 192 [kbps], 160 is like 256 [kbps], 192 is like 256 [kbps], and 256 is like 320 [kbps].

Audio compression is applied in three main fields: storage, broadcasting, and streaming.

### **1986**

The compression of digital audio was still being developed, and had not yet been standardized.

### **1993**

An algorithm existed that was used only for Digital compact Cassettes, PASC (*Precision Adaptive Sub-Band Coding*) and was based on MPEG-1, achieving a compression ratio of 3.68:1 (110). However, given the sporadic use of this method, we do not consider compression for this year. Sound stored on film (movies) is a special case. Since 1991, Dolby Digital codification has remained the most utilized format (65). We assume that the typical sample rate is 44.1 [kHz], each sample coded with 16 bits and the sound with 6 channels (66). This results in a rate of 705.6 [kbps] per channel and a total of 4 233.6 [kbps]. Given that the compressed bit rate is commonly found at 384 [kbps], a compression factor equal to 11.025 is obtained.

### **2000**

#### *Storage*

MPEG Audio Layer-3 or MP3 (from 1996) rapidly became the most popular format for the compression of digital audio (67), which can be assumed to be used starting from the appearance of the first completely functional MP3 reproduction software in 1997-1998 –the well-known Winamp (68)–. Storage devices are divided into two categories: those that utilize MP3 with excellent quality, and those with good quality, with average compression factors equal to 5.36 and 6.83, respectively (calculated with the simple average or the corresponding range in Table S B-22). A compression of very good quality compares to the quality of digital audio without compression (CD). This sacrifice of storage capacity is due to the lower compression that is achieved at higher quality.

In the case of film used for shooting movies, the audio is encoded with Dolby Digital, a format which achieves an average compression rate of 12:1, this being the factor used to make comparable the analog sound stored in the film.

#### *Radio Broadcasting*

It must be considered that the transmission of digital radio and the sale of devices able to reproduce this information began only recently in 1999, with the standardization of DAB, also known as Eureka 147. In those times, MPEG-2 Layer II (MUSICAM) was used as the compression algorithm, with a stereo transmission rate of 128 [Kbps] (109), the quality with which the signal was reproduced was quite poor), which would imply a compression ratio of 11.025 : 1.

#### *TV Audio Broadcasting*

The transmission of digital TV began in 1998 in the United Kingdom, the same algorithm (implementing DVB, ATSC and ISDB) was used, except in this case with a rate of 128

[Kbps] and a total transmission rate equal to 256 [Kbps] (69). Considering this, the compression ratio for television is 5.51 : 1.

#### *Streaming audio*

For the streaming of audio, at least three systems existed in 2000: IceCast, Darwin Streaming Server and SHOUTcast, which were used as MP3 compression algorithms. *Internet Radio* was used to encode music (mono) with rates that vary between 28 and 56 [Kbps], so it could be transmitted over dial-up connections in which we saw the predominant numbers (117). Given what has been stated before, the corresponding average compression rate is 16.8: 1. This quality is not very good, but corresponds to the quality of streamed music.

### **2007**

#### *Storage*

At the start of 2002, with the introduction of other compressed audio formats such as *Windows Media Audio* and *Ogg Vorbis* which have a better quality/bit rate than MP3, it was expected that the latter would become obsolete. Notwithstanding MP3 today continues to be the most used standard. We therefore consider the same compression rate in storage systems as in 2000. It is important to mention however, that the “new generation” of MPEG coding (AAC, HE-AAC, etc.) is winning ground. While this technology was designed mainly for streaming, iTunes 9 and many mobile telephones convert MP3 files to one of the aforementioned formats to be stored. For films we also keep the previous compression rate.

#### *Radio Broadcasting*

For audio broadcasting, MPEG-4 HE-AAC is the new standard in digital radio systems DAB+ (69). It allows for more redundancy and is less extreme in its lossy compression, which brings it up to a compression factor of 7.35.

#### *TV audio Broadcasting*

For digital TV, MPEG-4 has also been adopted by the new standard DVB (DVB-T2/-S2/-C2); however in 2007 this was not yet used. Since there is no evidence in the change of audio encoding, the same compression rate is considered (6: 1).

#### *Streaming audio*

It is known that the mobile environment MPEG-4 AAC and AACv2 have been widely adopted (note that streaming came with the introduction of 3G technologies in 2001). With rates that vary between 48 and 64 [kbps] were able to play music with very good quality (70). This results in a compression rate of 27.42 : 1.

In the field of wired audio streaming, although MPEG-4 counts with advantages, the majority of content providers do not yet support it (114). While many streaming systems already support at least AAC encoding, according to (63), MP3 continues to dominate the scene. However, not anymore with the bit rates used in 2000. Following (71) currently the rates vary from between 96 and 192 [Kbps] (in most cases the user can choose the rate which

works best with the bandwidth which is available) with stereo sound. Considering the average bit rate between the two, we end up with a compression rate equal to 10: 1.

It could seem strange that the compression rate in broadcasting and streaming does not decrease when compared with the performance in 2000 and 2007. This is due to increasing the bit rate available to users allowed to transmit higher quality audio (monaural sound versus stereo 60 [kbps] versus one which varies between 128 and 192 [kbps]). In the case of broadcasting, the use of spectrum has been optimized. In short, this tendency does not say that the performance of the encoders has worsened (as far as the compression rate is concerned), but that content providers have preferred to increase the quality of signals transmitted given the evolution in the transmission of files.

## **Optimal**

### *Storage*

MPEG-4 is currently the optimal way to encode audio and from the ranges shown in Table S B-22, we select one that represents the maximum compression for each one of the grades shown. Following the assumption made above and considering MPEG-4 AAC (designed for storage), for analog devices (excellent quality) corresponds with a factor of 9.6 and for the rest (very good quality), one of 12.

### *Broadcasting (Radio and TV)*

MPEG-4 HE-AAC (v1 and v2) is the encoding profile of MPEG-4. It has been developed for applications which need good quality at a lower bit rate, like streaming and broadcasting (70). In the case of radio transmission, DAB+ is the technology that implements this encoder and in accordance with (72) has the following characteristics: for quality better than FM: 56 – 96 [kbps]; for quality similar to FM: 40 – 64 [kbps]; for quality poorer than FM: 24 – 48 [kbps]. According to tests reported by (73 -75), at 64 [kbps] an excellent quality is achieved for radio broadcasting, which is why we choose the average rate “superior quality FM” (76 [kbps]) as the best rate for use. This implies a compression factors equal to 20. In the case of audio transmission by TV, we assume that the same rate is applicable.

### *Streaming audio*

In the mobile field, (76) indicates that a rate of 48 [kbps] is the minimum for very good quality, which is supported by sources like (77, 78). With this the compression rate is equal to 32: 1. For the wiring stage, we have selected a rate of 64 [kbps], backed up by (79), which provides recommendations so the service may work properly. Thus the compression factor is 24.

## **B.5 Video**

The compression of video enabled this type of content to go beyond the world of broadcast and enter the world of telecommunication (videoconferences, the streaming of video on Internet, etc.) and the storage of the same with high quality in magnetic or optical

devices (80). We review the principles of the encoding codec used, which is also MPEG, i.e. MPEG-2 to MPEG-4. Both are the leading standards.

### B.5.1 MPEG-2

At the beginning of the 90s, the Motion Picture Experts Group (MPEG) had already begun their investigation into the development of coding techniques for video storage, for example CD-ROMs. With this, the first MPEG generation was born, called MPEG-1, which was capable of exceeding the previous rate of no more than 1.2 – 1.5 [Mbps]. However, this standard was not very well received on the part of the broadcasters (the image obtained with analog cameras had a higher quality than that achieved after compression with MPEG-1, besides that fact that it was designed to encode video “progressive” and not “interlaced” like the one used on TV). Years later, the situation took a turn with the appearance of the MPEG-2, standard which allowed the embedded video coding with a rate which varied between 2 and 9 [Mbps]. Currently MPEG-2 is the most popular of the video codecs that exist, being used in a wide range of application, among which are noteworthy formats like digital terrestrial TV, satellite and cable, the HDV format of the video recorders and storage in DVDs (81).

The standard MPEG-2 introduces the concept of profiles and levels. Of all existing profiles the one considered for this study is the one called Main (MP), being the one which is most general consumer oriented (53, 82, 83). We continue with reviewing the bit rate used to store video and audio in a device. MP@ML (Main profile at the Main level) has a maximum rate of 15 [Mbps] and is relevant to the distribution of SDTV (*Standard-Definition Television*) and the storage in DVD at a rate between 2 and 6 [Mbps], having a maximum rate of 9.8 [Mbps]. For PAL systems (720 x 576 con 25 [fps]), the rates vary between 4 and 6 [Mbps]; for NTSC (720 x 480 con 30 [fps]), the rates vary between 2 and 3 [Mbps]. For its part, MP@HL (at high level) is relevant for the distribution of HDTV (High-Definition Television), with a rate that varies from 12 to los 20 [Mbps] (84, 85). MP@LL (at low-level) is employed in the storage of video in CD (SVCD) with a maximum rate of 2756 [kbps].

**Table S B-23: Bit rates resulting from digitization with different sub-sampling of color components (SDTV).**

Sampling structure		4:4:4	4:2:2	4:2:0
Number of pixels per line (Y)		720	720	720
Number of pixels per line (C <sub>R</sub> )		720	360	360
Number of pixels per line (C <sub>B</sub> )		720	360	360
Number of lines per frame	NTSC	480	480	240
	PAL	576	576	288
Number of frames per second	NTSC	30	30	30
	PAL	25	25	25
Transmission rate [bps]	TNTSC	248 832 000	165 888 000	124 416 000
	PAL	248 832 000	165 888 000	124 416 000

Source: Authors' own elaboration, based on various sources (see text).

For quality video, MPEG-2 uses the recommendation 601 of the CCIR (now called ITU Rec. B.601) which defines that each line in a frame must be sampled with 720 pixels (both NTSC and PAL/SECAM), besides supporting the sub-sampling of color 4:2:0 for the transmission of TV and the storage in DVDs, and 4:2:2 for the storage of videos mainly in magnetic tapes (see Table S B-23 bit rate results) (86, 87) (Table S B-24). We consider the average of the rates mentioned in the previous paragraph for each category and then calculate the compression rates with the ratio between the previous value and the bit rate of the signal, considering in the sub-sampling scheme 4:2:0 y 4:2:2 where appropriate.

**Table S B-24: Compression factors for MPEG-2 typical rate.**

Application		Compression factor	Application		Compression factor
Television	NTSC	49.78	DVD		41.47
SD	PAL	24.88	Video Tape		27.03

Source: Authors' own elaboration, based on various sources (see text).

#### Box B-1: Video coding MPEG-2

The encoding process consists of three main stages: data preparation, spatial and temporal compression and quantization. The purpose of the first is to ensure that the frame samples are organized in a way which is appropriate for compression. The video information enters the codifier in form of coded samples of lamination components  $Y$  and chrominance ( $C_R$  y  $C_B$ ). These samples are regrouped into blocks of 8 x 8 pixels, which become utilized in the removal of spatial redundancy (like in the encoding of JPEG still images). This process aims at removing those parts of the image that are the same, for example parts of a blue sky. Instead of coding "pixel1 is blue", "pixel 2 is blue", "pixel 3 is blue", etc., one uses a pattern and codes "pixel 1 is blue", "equally pixels 2, 3, 4, etc". These blocks are regrouped in micro blocks of 16 x 16 pixels and they are then used in the removal of temporal redundancy. Finally, the micro blocks are grouped into slices corresponding to these basic units for data compression.

MPEG data streaming consists of three types of compressed frames: I- frames (Intra-frames), P-frames (predicted) and B-frames (bireactional). The removal of spatial redundancy, also known as intra-frame, as the information collected can be restored at the receiving end. The compression is lossless. It takes advantage of the fact that the difference between two consecutive frames is very small, which is why it is not necessary to transmit the entire of each frame as it is the repetition of the previous one. To describe the difference between a frame and the frame before it, two components are put to use: the motion vector and the frame difference. To explain how each reference is made we will use the following example: let us suppose that you have two frames (consecutive) shown in Figure S B-6. The elements which are repeated in the second frame, those that are redundant, are: horse, frog, globe, light bulb, leaves, tree and traffic light. Next, to avoid redundancy, change only the image content of those described: the movement of the lion from cell A1 to cell B2 and the introduction of the airplane into cell A1. The movement vector describes the movement of the lion between the cell and combines with the first frame to produce a predicted frame (see Figure S B-8).

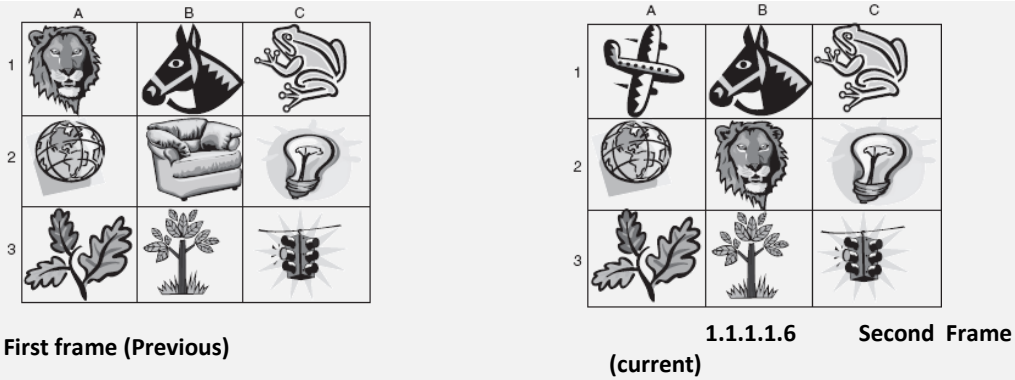


Figure S B-7: Example, two successive frames (31).

The frame difference (which describes the introduction of the airplane A1) is obtained with the subtraction between the predicted frame and the second frame (see Figure S B-9). Both components (the motion vector and frame difference) are combined to form what is known as a P-frame.



Figure S B-8: Frame predicted from the sum of the previous frame and the motion vector.

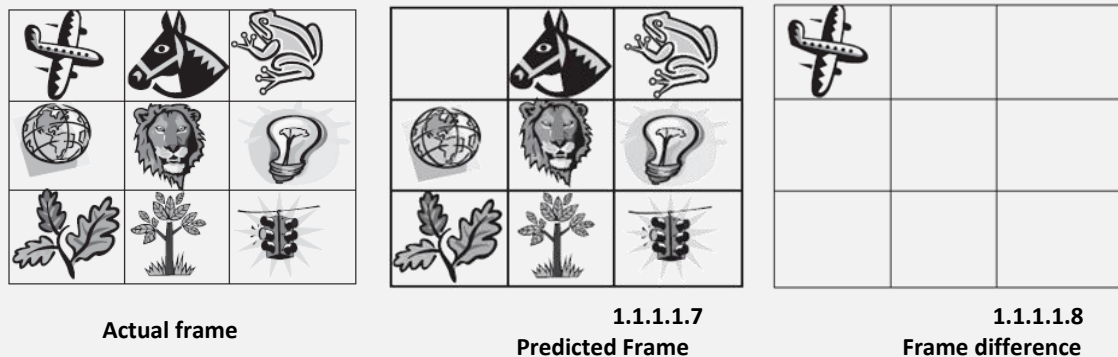


Figure S B-9: Frame difference obtained from the subtraction between the current frame and the predicted frame.

The vector motion compensation alone is just not enough to define video content for the frame in an image. The movement of a block fails to define the appearance of new elements, like the background that could be revealed after the blocks movement. This implies that more information is needed. This is obtained by the prediction on what the P-frame would be like if it were reconstructed using only the motion compensation vector and then comparing it with the real frame. The difference between the two is where the additional information is found, which in conjunctions with the motion compensation vector defines the entire content of a frame. The P-frame is constructed with the addition of a motion vector at the same frame that was used to obtain the vector. Later, it is subtracted from the current frame to create a difference frame, which is also known as residual or prediction error. The difference frame contains a series of pixel values with its format appropriated for the next compression of spatial data compression. The bit rate of the output stream is highly dependent on the accuracy of the motion vector (88). Bidirectional prediction tries to improve the accuracy of the motion vector. This technique is based on the future position of a moving



block as well as in the previous position.

## B.5.2 MPEG-4

With the help of MPEG-4, video compression can be dramatically increased, enabling the distribution of content and services, which vary from those with low bandwidth requirement up to high definition quality, though broadcast systems, broadband web or wireless networks, etc. MPEG-4 is formed by 21 individual parts interrelated although distinct, which can be implemented in an individual manner or combined with others. The two important aspects for video are parts 2 (MPEG-4 Visual) and part 10 (MPEG-4 AVC – *Advanced Video Coding*). MPEG-4 Visual (1999) was defined for applications in the area of multimedia communications with low bit rates, but was later extended to broadcasting application. The impact it had on the last industry was not significant when compared with MPEG-2. It only achieves compression gains between 15% and 20%, which was not enough to change the current standard. The case of AVC/H.264 is different. It is an integrated part of MPEG-4 and in 2004 the DVB consortium amended its standard to also include AVC/H.264 as a high definition television codec. Other applications have already adopted this streaming standard of multimedia content on the Internet (with low bit rates), such as 3G mobile phones, digital cinema, the storage in HD-DVD and BD-ROM, etc. Comparing AVC/H.264 with MPEG-2, the first is at least twice as efficient at reducing the bit rate to obtain the same quality, at the expense of greater complexity in the software encoder/decoder (89-92).

This method includes different profiles of which the most notable are the *main profile* and the *high profile*, used for *broadcasting applications with* (SDTV) standard definition and with high definition (HDTV), respectively; while the other two profiles (*baseline* and *extended*) are used for real time, mobile and *e-streaming applications* (89, 93).

## B.5.3 Video compression rates over time

Unfortunately, for video compression factors, there is not a good index of quality (like MOS for voice), so it is not possible to differentiate between the different storage devices and transmission technologies in accordance with the perceivable quality.

### 1986

Like other types of multimedia content, the compression of digital video was in full development and testing at the end of the 80s. That is why no compression is assumed at for this year.

### 1993

#### *Storage*

In this year, only in storage –mainly in CD-ROMs-, two compression algorithms were already in use: Cinepak and Indeo Intel Video (encoder owner). For lack of more information, it

is assumed that Cinepak was the predominant. This is supported by the fact that the year following their commercialization (1992) they were already forming their part in the Apple Quicktime suite and in 1993 started to be supported by Microsoft Windows, also being used in the games of some SEGA consoles, the Atari Jaguar CD and Panasonic 3DO (94).

Cinepak was designed to encode video with resolution 320 x 240 or 180 x 240 pixels, with frame rates between 12 and 15 frames per second, sub-sampling 4:2:0 to 150 [Kbps], achieving a theoretical compression rate ranging from 20:1 up to 200:1 (116) and proving good video quality for action movies of moderate action. Even though (95) indicates that the average compression rate is 60:1, the resulting image quality is quite poor at this level (96). Therefore, 20:1 is chosen to ensure an acceptable video quality.

## 2000

### *Storage*

By this year, the revolution of digital video had already begun. Starting with storage, DVDs and video-CDs, were already available which codified videos with MPEG-2 and MPEG-1 with an average compression rate of 41: 1 y 27: 1, respectively (see Table S B-24, the first factor, backed up by (97). For its part, videos downloaded off the Internet and stored in hard disks were generally coded in the same format (and with the same quality) as video-CDs, for which the same compression rate should be considered. For all storage devices, except for DVD-video, we consider a compression factor of 27.

### *Broadcasting video*

For standard quality television with MPEG-2 Video, with a rates that vary between 2 and 3 [Mbps] for NTSC y 4 to 6 [Mbps] for PAL/SECAM, we obtain the compression factors presented in Table S B-25 (supposing the higher end of the mentioned range).

**Table S B-25: Factors of compression for TV transmission.**

	Terrestrial		Cable		Satalite
	NTSC	PAL/SECAM	NTSC	PAL/SECAM	
Compression Factor	49.8	24.9	41.5	20.7	20.7

Source: Authors' own elaboration, based on various sources (see text).

### *Streaming video*

Before 1998, the limited bandwidth of the Internet prohibited the streaming of videos in formats like MPEG, QuickTime or AVI (4). For the case of videoconferences, compression algorithms were already used, such as H.263 (see Box B-1), which has a resolution of 176 x 144 pixels at a rate of 100 [Kbps] for the 10 [fps], achieving a compression factor of 27:1 (98). While MPEG for video was already standardized and widely used in storage, the low bit rate coding did not present a comparatively higher quality than H.263, this being the main reason for its preference. Moreover, in the streaming of video (non-video conference), RealVideo encoder was one of the most widely used (99). It is based on H.263 and shows only mild

improvements (115). Given that (99) indicates that most videos are 10 [fps] (without stating the resolution), we assume that the compression rate achieved in this area is the same as that of H.263 (27: 1).

## 2007

### *Storage*

Compared with compression storage methods, the big difference is found in the encoding of videos downloaded from the Internet (mainly through P2P). In 2007, XviD –one of the standard MPEG-4 parts for videos– was already considered to be the standard due to its good quality/bit rate and because it is not a proprietary algorithm, which allowed the provision of a large amount of free codecs in many devices (unlike DivX, which requires its users to pay for permission even though it should not be overlooked that it is still a very popular program). While this encoder can achieve compression rates of up to 200:1 (100), the need to ensure excellent or near to excellent picture quality forces a lower rate to be chosen. The average coding rate achieved by said algorithm with the prior conditions is around 60:1 (101).

### *Broadcasting*

In 2007 the use of MPEG-4 AVC/H.264 was standardized as a DVB system encoder. It allows for larger number of programs over the same bandwidth with standard definition, or fewer with high definition. However its use in 2007 was marginal and was only being tested at that time, reason why we assume the same compression rate as in 2000.

### *Streaming video*

MPEG-4 AVC/H.264 is the most used algorithm, being the standard on YouTube. It allows for a saving of up to 60% of the bandwidth requirements compared with other compression methods (102). The typical video resolution is 320 x 244 pixels at a bit rate of 192 [Kbps] and the compression ratio achieved is around 50:1. In the case of streaming video in mobile phones and in teleconferences, the typical resolution is 176 x 144 pixels, with rates ranging from 64 to 192 [Kbps], achieving average compression of 60:1.

## **Optimal**

Since we do not have much information on the compression achieved by MPEG-4 for the different applications we are looking at, we will extrapolate from the case of digital TV. (103-108) all indicate that for SDTV and HDTV reductions of about 50% are achieved. Therefore, for all technologies that use MPEG-2, we assume that MPEG-4 doubles the compression ratio of MPEG-2, that means to about 60:1. We use this as the optimal compression benchmark for video. For other technologies which are already using MPEG-4, the compression factors are kept the same.

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## C Storage

In this Chapter, we present the methodologies employed for estimating the amount of bits contained in the following storage technologies: paper (periodicals, books, etc.), film (movies, photographs, and radiographs), electromechanical (vinyl), analog magnetic (cassette tapes, video tapes), and digital (hard disks, floppy disks, and magnetic tape data storage), optical (CDs, Minidiscs, DVD, Blu-ray), and solid state (console cartridges and memory cards, memory cards, portable media players, USB pendrives and internal memory present in digital cameras and cellphones/PDAs ). Each chapter is divided into three sections, one regarding how the number of installed equipment in the world is estimated, another regarding the performance of each equipment, and lastly, on the applicable compression algorithms.

In this study we do not consider volatile storage, which is why RAM<sup>11</sup> is excluded. This is justified in that the ultimate end of volatile memory consists in computational processes, not in storage per se. Volatile memory acts like a notepad during computation and what is stored is automatically lost upon disconnection with the power supply. The capacities that we are measuring here contribute to information storage with the end of being stored, while RAM is utilized primarily to support computational power (which is measured in the section on computation).

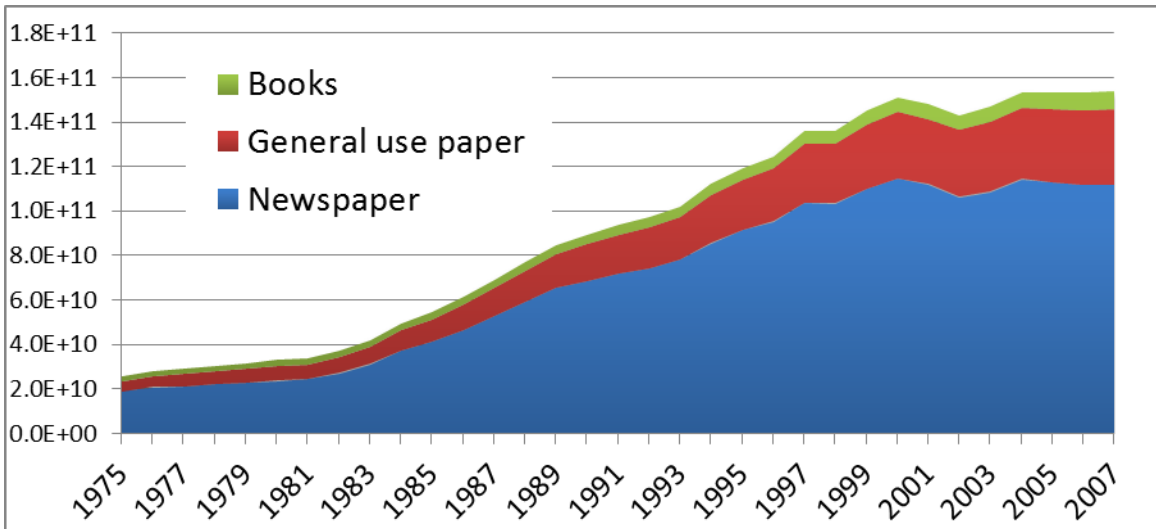
### C.1 Paper

We include three types of paper products: paper for book printing, paper for general use (for writing, printing, and photocopying), and paper for the printing of newspapers (Fig. S C-1).

**Fig. S C-1: Storage capacity provided by books, newspapers, and general use paper (MB), without normalizing for compression (Hardware capacity).**

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<sup>11</sup> RAM (*Random Access Memory*) is utilized to temporarily store data that the central processing unit requires for in functionality (Operating system, executed applications, instructions, as well as information that these applications process and the results they obtain). These are manufactured with semiconductive material that enables writing and reading information randomly (it is not necessary to arrange bytes in sequential order to obtain required data). All of the information that is stored during the functioning of the device is erased on restart or powering off.

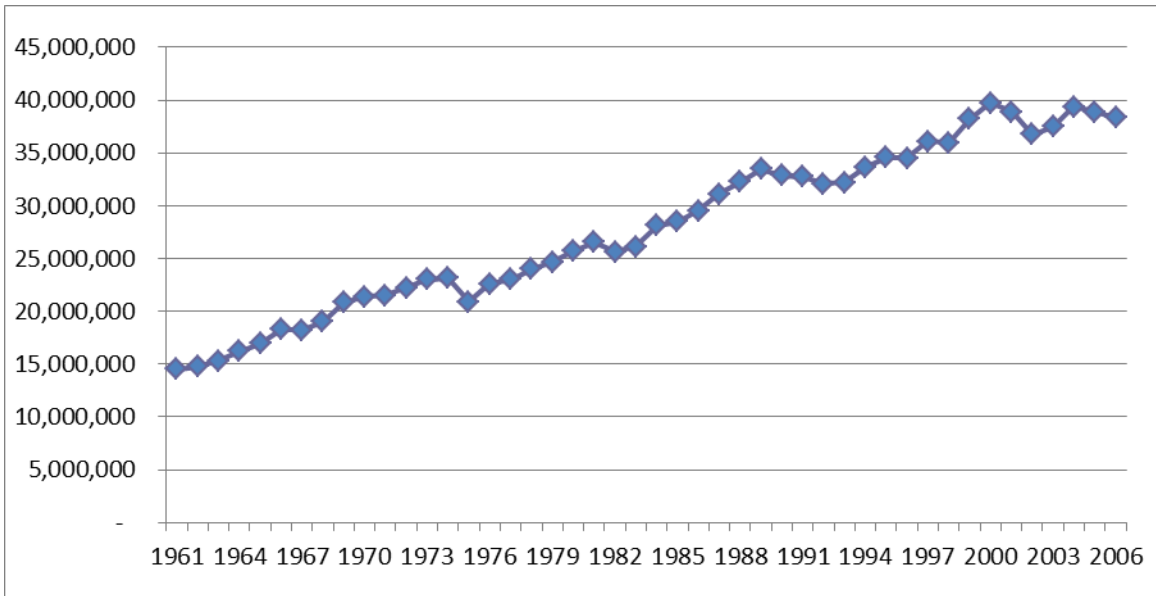


Source: Author's own elaboration, based on various sources (see text).

### C.1.1 Newspapers: quantity

The ForesSTAT database (Food and Agriculture Organization of the United Nations [FAO] (1) provides the consumption of sheets of “newsprint” (in tons) in different countries in the world<sup>12</sup>. The FAO maintains the following definition for this category: “NEWSPRINT: Uncoated paper, unsized (or only slightly sized), containing at least 60% (percentage of fibrous content) mechanical wood pulp, usually weighing not less than 40 g/square m and generally not more than 60 g/square m of the type used mainly for the printing of newspapers.”

Fig. S C-2: World consumption of paper for newspapers (in metric tons).



Source: Previous explanation, based on (1)

<sup>12</sup> In 1980, for 108 countries, representing 89.94% of 1980's world population; in 2007 for 192 countries, representing 99.18 of the world population.

The grammage per m<sup>2</sup> is reported by (Government Printing Office [GPO], 1999). We opt for the simple average among the four most common alternatives (Table S C-1).

**Table S C-1: Grammage of paper for newspaper**

Newsprint	Option 1	Option 2	Option 3	Option 4	Simple Average
Grammage [g/m <sup>2</sup> ]	40	45	50	52	46.75

Source: (2)

For reasons of consistency, we pick one sheet of the *New York Times* as a representative newspaper sheet, which corresponds to 13.5 inches (0.343 m) by 22.75 inches (0.578m)<sup>13</sup> (3), with an area equal to 0.1981 [m<sup>2</sup>]. This results in a weight of a sheet of periodical = 0.1981 [m<sup>2</sup>] \* 46.75 [g/m<sup>2</sup>] = 9.26 [g]. With this we calculate the [number of sheets] = ([tons consumed]/[weight per sheet]), which is multiplied by two to consider that each sheet is printed on both sides.

We consider the useful lifespan for periodicals to be a week on average; that is to say, we assume that after a week all newspapers are destroyed. In this sense, “periodical sheets” serve the same function as a large hard disk that is formatted and re-loaded with new content every week.

## C.1.2 Newspapers: performance

### C.1.2.1 Distribution of images and text

Given that we are not familiar with any historical statistics that reveals the average number of characters, words, and images per sheet, we opted to select a representative sample. The *New York Times* (the third largest circulating newspaper in the United States after *USA Today* and *The Wall Street Journal*) was chosen, after considering that the newspaper maintains a ratio between text and images a bit more representatively than *USA Today* (which is recognized for its large images) and *The Wall Street Journal* (a newspaper with a history of primarily economic news and traditionally less focus on culture and entertainment).

We created a mechanism for a stratified random sample (safeguarding against seasonal effects during the year and uneven distribution within the newspaper). Each one of the years 1975, 1985, 1995, and 2005 have been divided into four parts (each one 365/4 = 91 days), and a day was chosen that corresponds to the mid-point of each division (February 14, May 16, August 15, November 14). The newspapers on those days were then separated into three equal parts (depending on the number of pages in each specific newspaper). We considered the first page (the *cover-page*, the most important page) and pages that are in the

<sup>13</sup> Today, the *New York Times* no longer uses this format. On August 6, 2007, the size of the *New York Times* was reduced to 13.5 inches by 12 inches, equal to the standards of other US Periodicals (New York Times, 2006). However, for the period being studied (for the analyzed pages), the older size applies.

middle of the three parts that the newspaper consists of (after 1/6 of the total pages, 3/6 of the total, and 5/6 of the total). This process creates a sample of 16 newspapers between 1975 and 2005, of four pages each (see Table S C-2).

**Table S C-2: Sample of historical newspapers of the *New York Times* between 1975-2005.**

Date	14-Feb-75	16-May-75	15-Ago-75	14-Nov-75
Total # of pages	72	80	76	80
Pages sampled	1, 12, 26, 60	1, 13, 40, 67	1, 13, 39, 58*	1, 14, 41, 58*

Date	14-Feb-85	16-May-85	15-Ago-85	14-Nov-85
Total # of pages	120	112	96	120
Pages sampled	1, 20, 60, 100	1, 19, 56, 75	1, 16, 48, 80	1, 20, 60, 100

Date	14-Feb-95	16-May-95	15-Ago-95	14-Nov-95
Total # of pages	84	84	76	92
Pages sampled	1, 14, 42, 70	1, 14, 42, 70	1, 13, 38, 64	1, 15, 46, 77

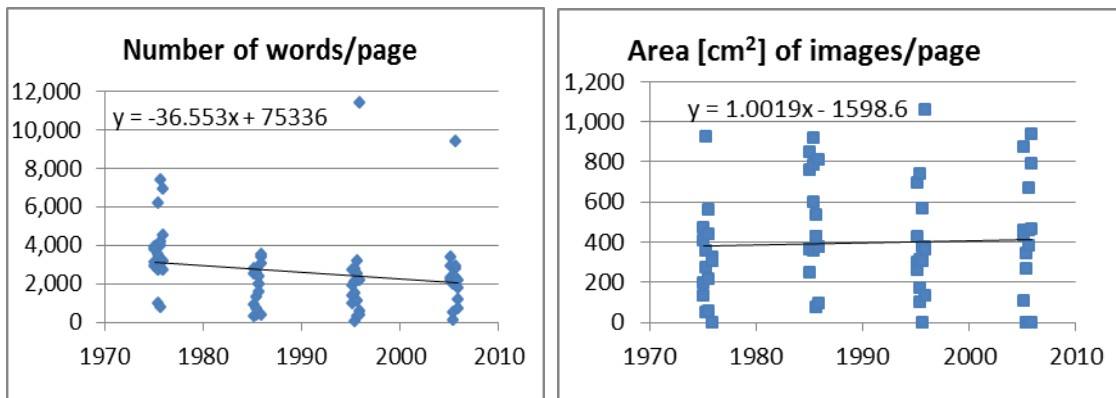
  

Date	14-Feb-05	16-May-05	15-Ago-05	14-Nov-05
Total # of pages	58	62	52	94
Pages sampled	1, 10, 29, 48	1, 10, 31, 52	1, 9, 26, 43	1, 16, 47, 78

Source: Previous explanation, based on (4). Note: \* means that the page that corresponds to the sampling mechanism was not scanned in the ProQuest photo database, for which we chose the page closest to the faulty page.

The 64 pages selected results in an average sample per page of 400 [cm<sup>2</sup>] for images and about 2600 words. However, as was expected, the quantity of images per page has increased with time, while the number of words has diminished. We adopt a linear approximation for general estimation of the distribution between text and images per page (see Fig. S C-3).

**Fig. S C-3: Quantity of words and images per newspaper page**



Source: Previous explanation, based on (4).

Since the source (4) only offers scanned pages in black and white, it becomes necessary to make an additional estimation regarding the proportion of images in color. *USA Today* is the newspaper credited with the introduction of color in printed newspaper printing, with its appearance in 1982, while the last important newspaper to adopt color printing is the *New York Times*, in 1997. Today it is estimated that approximately one-third of the images in the *New York Times* are printed in color (samples taken from the *New York Times* from Thursday July 30, 2008, Sunday August 3, 2008, Wednesday September 10, 2008, Friday November 7, 2008). It is supposed that, for the year 1981, 0% color images appeared in newspapers worldwide and, afterward, with a linear growth period of 15 years, we suppose that 35% of images are in color in 1997.

### C.1.2.2 Bit Estimation in gray-scale images

With regard to the printing of images on newspaper, we follow an idea similar to what we today recognize as the logic of “pixels”, where in reality the printed images in the pre-digital era are not determined by the number of pixels in them, but in the amount of “lines” (LPI: lines per inch) and “dots” (DPI: dots per inch). The standard is the technique known as “Half-tone printing”, in which the quantity of different tones and colors that can be printed depends on the number of dots (DPI) in each unit of LPI, and the granularity and clarity of the image depends on the amount of basic units (LPI) (5).

Reviewing the quality of printing during the last decades, we have decided to differentiate between gray-scale images of lower quality (which were used in the 1980s), which utilized around 135 DPI and 60 units (LPI) (6, 7), or images of higher quality (as in the end of the 90s), of 225 dots per inch (DPI), and 85 units (LPI) (5, 8, 9). This results in a bi-dimensional printing of  $(135/60)^2 = 5$  dots (lower quality), and  $(225/85)^2 = 7$  dots (better quality). With five dots per unit, one can produce 6 gray tones between total white and total black and with seven dots in one unit, one can produce 8 gray tones.

Translating this analog technology to a digital format implies that the six gray tonalities can be represented with 2.6 bits ( $2^{2.6} = 6$ ); whereas with eighty tonalities, with 3 bits ( $2^3 = 8$ ).

Given that it is impossible to utilize 2.6 bits in the digital realm, 3 bits are always necessary for each basic unit (LPI), whether high or low quality. With 60 LPI (lower quality) you have  $60 \times 60 = 3600$  basic units per inch<sup>2</sup>, and with 85 LPI (higher quality) you have  $85 \times 85 = 7225$  basic units per inch<sup>2</sup>. This results in  $3600 \times 3 = 10,800$  bits per inch<sup>2</sup> (equivalent to 4,252 [bits/cm<sup>2</sup>]) for images of lower quality and  $7225 \times 3 = 21,675$  bits per inch<sup>2</sup> (8,534 [bits/cm<sup>2</sup>]) for higher quality images. It is supposed that the transition between lower quality images and higher quality images in newspapers followed the same pattern of diffusion as the transition from black/white to color images.

### **C.1.2.3 Bits estimate per color image**

Newspaper printers normally use the four colors of CMYK (Cyan, Magenta, Yellow, Key = Black) (10). Assuming that one color can be printed in each dot, a total of 330 combinations can be produced on the 7 dots of each of the basic units in a good-quality image.<sup>14</sup>

By translating this analogous printing logic to a digital format, the 330 color combinations can be represented with 8.37 bits, which can be found between  $2^8 = 256$ ; and  $2^9 = 512$ . The lower value, 8, is selected with the consideration that an analogous impression is messy (i.e. the mixing of colors in the dots), which therefore lowers the quality of the resulting image. The assumption that 8 bits can adequately represent 256 colors rests upon the notion that the analogous color images in newspapers have the same image quality than digital images in GIF format (Graphics Interchange Format). GIF images have lower quality and are commonly found online (11), which validates the choice of 256. With 85 LPI we have  $85 \times 85 = 7225$  basic units per inch<sup>2</sup>, resulting in  $7225 \times 8 = 57\,800$  bits per inch<sup>2</sup> (22\,756 [bits/cm<sup>2</sup>]) for color images in printed newspapers.

### **C.1.3 Books and other paper for printing/writing/reprographics: quantity**

The ForeSTAT database (1) offers figures on the paper consumption (in tons) for different countries around the world<sup>15</sup>. FAO gives the following definition for this category: "Printing + writing paper: Paper, except newsprint, suitable for printing and business purposes, writing, sketching, drawing, etc. made from a variety of pulp blends and with various finishes. Included are such papers as those used for books and magazines, wallpaper base stock, box lining and covering calculator paper, rotonews, duplication, tablet or block, label, lithograph, banknote, tabulating card stock, bible or imitation bible, stationary, manifold, onionskin, typewriter, poster, etc." These classifications are simplified and distributed among a "books" category, and the sub-item "others printing/writing/reprographics" according to that data

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<sup>14</sup> 5 color possibilities exist for each dot (Cyan, Magenta, Yellow, Black, White = without impression). The order of the colors inside the seven dots does not matter, what matters are how many of the dots have which colors (the intensity):  $[(5+7-1)!] / [(7!) * (4!)] = 330$ .

<sup>15</sup> In 1980, for 119 countries, representing 91.24% of the global population of 1980; and in 2007 for 198 countries, representing 99.27% of the population.



drawn from the GreenPress Initiative (12), which indicates that between 6% and 10% of the paper production from forests in the United States is used for book production. Considering the average for these statistics, we conclude that 8% of paper production is for books and that 92% is for “other printing/writing/reprographics.”

The global figure for paper pages, measured in tonnage, is derived at using the following formula: [number of pages] = ([tons consumed] / [weight per page]). The weight of a page is calculated according to weight relative to the dimensions: grams per page = (length [m] x width [m]) x weight [g/m<sup>2</sup>]. The grammage [g/m<sup>2</sup>] is reported by (2) (see Table S C-3) and an average of the two common classifications is used.

**Table S C-3: Weight, printing and writing paper.**

Grammage [g/m <sup>2</sup> ]	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6 (Bible)	Simple Average
Books	60	75	90	105	120	45	82.5
Other paper	45	60	68	75	-	-	62

Source: (2)

The size of page most commonly printed in the United States is 25” x 38” (13), after which being divided into 16 equal sections, gives us a book size of 0.0383 [m<sup>2</sup>] (9 ½ “ x 6 ¼” or 0.241 x 0.159 [m]). For printing/writing/photocopying paper, the most common size format, A4, is considered (14), which has dimension of 0.0624 [m<sup>2</sup>] (0.21 [m] of width and 0.297 [m] of length) (see Table S C-4).

**Table S C-4: Page weight averages.**

Type of paper	Grammage [g/m <sup>2</sup> ]	Page Area [m <sup>2</sup> ]	Weight per Page [g/page]
Books	82.5	0.0383	3.16
General use	62	0.0624	3.87

Source: Authors’ own elaboration, based on (13, 14).

An average usefulness life span of 10 years is assumed for books (the average between 5 years (15), 10 years (16, 17) and 15 years (18)). For papers included in the category, “others printing/writing/reprographics” a life span of one month is considered. Based on these assumptions, the total amount of paper tonnage consumed by one country over the course of one year must be divided by 12 (months in a year). In this way, the paper for printing/writing/reprographics functions in the same way a hard disk does, whose content is updated on a monthly basis.

#### **C.1.4 Books and other paper for printing/writing/reprographics: performance**

Books are meant to contain only text (without images), and hold an average of 350 words per page (19) and 5.5 characters per word (20), which yields a total of 1925 characters per page.

In the case of paper used for “other printing/writing/reprographics,” it is assumed that half of the paper is used for printing and writing and the other half is used for reprographic purposes (this approximation is based on data corresponding to the United States in 1995 (21). For the half that is used for reprographic purposes, such as photocopiers, the same grey-scale image content as newspaper is assumed, following the same transition from lower quality images (4252 [bits/cm<sup>2</sup>]), to images of higher quality (8534 bits/cm<sup>2</sup>). The fact that a newspaper page is almost three times as large as an A4 format page (A4/newspaper = 0.0624 [m<sup>2</sup>] / 0.1981 [m<sup>2</sup>] ≈ 1/3) is taken into account. The other half used for printing and writing purposes is assumed to contain only printed text, with an average of 815 words per page (for an A4 size format), implying a total of 4482.5 characters per page (19). That average corresponds to the use of Times New Roman typeface, size 12 (the size most commonly considered most adequate for the human eye), and also assumed an average of 5.5 characters per word (20). Selecting a page that is densely printed, with a smaller typeface, is justified with the aim of estimating the “maximum technological capacity installed” in the world, and this same logic allows for the consideration of a double-sided printed pages.

The codification of characters is tracked with ASCII (American Standard Code for Information Interchange), which is compatible with UTF-8, and both are the dominant computer and communications codification systems in the world (22). In both cases, 8 bits represent each character, which allows for the possible representation of 256 different symbols, at maximum (see Table S C-5).

**Table S C-5: Bit and characters per page, for books and paper for general use.**

	Words per page	Characters per page	Bits per character	Impressions per page	Bits per page
Books	350	1,925	8	2	30,800
Paper for general use	815	4,482.5	8	2	71,720

Source: Authors’ own elaboration, based on various sources (see text).

### C.1.5 Content compression

For comparative purposes in the case of normalizing optimal compression, Table S C-6 presents figures for text and images. When considering the compression of images, GIF and JPEG measures are included in the calculation (more details in B.3.3). The “optimal” compression factors applied here are for high quality results obtained in 2007.

**Table S C-6: Compression factors for paper.**

“Optimal”

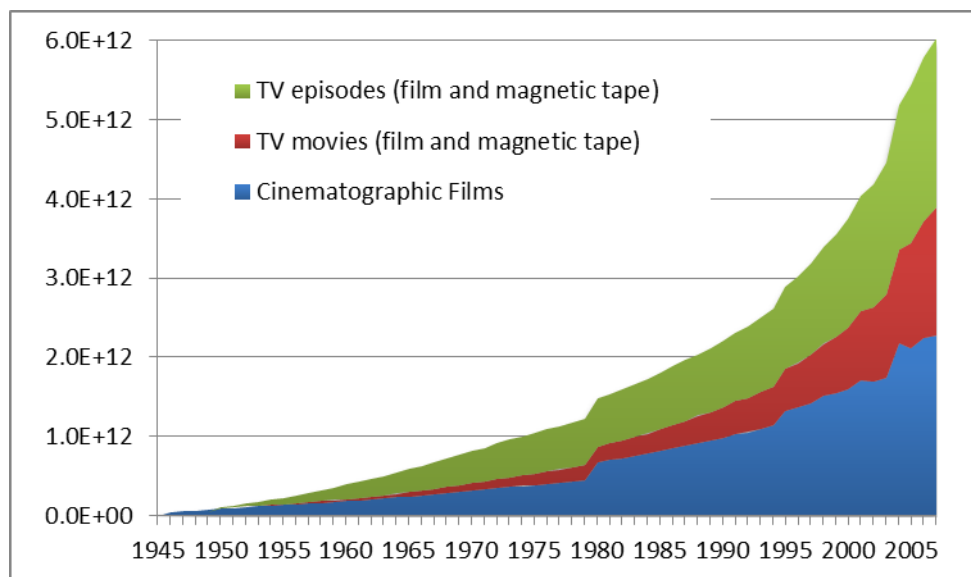
Text	6.6
Color Image	16
B&W Image	5.3

Source: Authors' own elaboration, based on B Compression.

## C.2 Films for cinema and TV

Films are essentially constructed from a series of individual frames that are shown in rapid succession (flip-book principal) (23). A certain quantity of frames with a specified size and the number of pixels relative to the size of the frames are required. The world of cinema and television has been slow to enter the digital age (i.e. May 2002, with the film, *Stars Wars Episode II: Attack of the Clones*). Even though digitalization has advanced quickly, it is assumed that in 2007 all film reels for movie theaters are still consisting of analog film (independently on how they were originally prepared for in the studio) (this assumption is confirmed by (24) in their 2009 assessment of the U.S.).

Fig. S C-4: Storage capacity provided for film (film and TV industries) (MB), without compression (hardware capacity).



Source: Author's own elaboration, based on various sources (see text).

### C.2.1 Motion Pictures: quantity

The figures denoting the quantity of films produced worldwide since 1888 were provided by (25). In order to separate cinematic film from movies on TV and video, we took a random sample (N=50) for 1946, 1965, 1985, 1995, 2000 and 2005, that identifies the quantity of the movies in each category. The result is that in 1946 almost all movies were produced for movie theaters. In 1965, 84% were produced for theaters, in 1985 about 74%, in 1995

approximately 66%, in 2000 about 53% and in 2005, roughly 42%. This trend is explained by the increase in production of films that are destined for the video niche of the market (including documentaries and pornography).

**Table S C-7: Quantity of films produced for theater release and preserved since 1888.**

1888	1889	1890	1891	1892	1893	1894	1895	1896	1897	1898	1899	1900	1901	1902
1	1	2	4	5	1	33	41	238	418	534	457	426	472	457
1903	1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917
861	369	218	314	331	477	729	1,270	2,463	3,856	7,001	1,043	1,034	975	840
1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932
389	474	714	772	563	557	702	940	1,002	951	825	863	777	875	1,019
1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947
1,077	1,213	1,277	1,560	1,675	1,714	1,670	1,582	1,675	1,774	1,674	1,635	1,646	1,784	1,900
1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
2,037	2,212	2,215	2,210	2,395	2,491	2,496	2,533	2,592	2,689	2,717	2,736	2,923	2,994	3,100
1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
3,046	3,337	3,438	3,461	3,786	4,097	3,706	3,892	3,901	3,734	3,623	3,620	3,731	3,669	3,515
1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
3,709	3,798	4,026	3,871	3,882	3,888	4,144	4,445	4,424	4,500	8,563	4,630	4,851	4,957	5,336
1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
5,550	5,850	6,096	6,023	6,127	6,611	6,799	7,107	7,371	7,622	8,432	9,417	9,973	9,321	8,572

Sources: (25, 26).

We consider the copies saved in production studios and in cinematographic archives. The majority of these films are “flops”. During the 1990s, only the 100 most popular films of the year were considered relevant movies (27), and normally the motion pictures industry does not monitor more than the 200 most popular films produced every year (28). This corresponds to no more than 5% of the films produced during the 1990s. Therefore, we estimate that the members of FIAF (International Federation of Film Archives), which houses the most important archives in the world (including the archives of the Academy of Motion Pictures Arts and Sciences that organizes the Oscars, among others) store one copy of 5% of the most outstanding motion pictures produced every year. FIAF (29) reports having four members in 1938, 33 in 1960, 77 affiliates in 1987, 85 in 2006 and 132 in 2008 (linear interpolation). Apart from these archives, production studios also store originals of all their films. It is an industry practice that a studio stores three original copies in three different geographical locations (for security reasons), as well as several extra copies in its studio library<sup>16</sup>. Therefore we assume that every motion picture film was copied five times and stored by the production company (beginning 1945). If a film was produced before 1945, it can be assumed there remains only one copy, if it has been preserved (see the linear assessment between 1928, when only a third of the films produced were kept) (26). The

<sup>16</sup> Personal interview with Sony Pictures Entertainment, Hollywood, April 2009.

accumulative stock of film material stored by the studios and the archives is equal to the total amount of film that is stored for the long-term. For these we suppose the original quality, without any kind of reduction in resolution.

Other than material in long-term storage, an estimate of the quantity of commercial copies can be made. Given that we did not find a statistic for the global number of movie theaters, we made an estimation based on the number of movie theaters in the U.S., and then extrapolated to the rest of the world comparing the income of the U.S. motion picture industry with that of industries in other countries. The quantity of movie theaters and the number of screens in the United States is derived from (28). First we consider the fact that the motion pictures industry in the U.S. has the capacity to show 100 films (27). We suppose that the top twenty most popular films are copied for all movie screens in the United States where the most popular films are shown during their opening week (28), which means that there is one copy per screen. For the remaining 80 films, it is suppose that one copy is sent to each theater. We suppose that other types of films that are not present in the mass market (alternative movies and short films) are sent to about 10 percent of the movie theaters in the U.S.

The relationship between the U.S. market and the rest of the world is based on the international distribution of the earnings from different films. ("Box Office" in US\$) (30). Before 1990, 2/3 of films distributed were from the U.S. and 1/3 from the rest of the world (this relationship was typical before India and China began to produce films in the mid-90s.). For the other years, see Table S C-8. Normally, these copies are distributed, collected and destroyed by the production studio, and thus they are only in active circulation for a year and do not have any accumulative effect on storage statistics.

Table S C-8: Box Office distribution in the U.S. and the rest of the world.

	1990	1991	1992	1993	1994	1995	1996	1997	1998
U.S.	63.9	61.3	63.5	62.5	61.4	44.4	46.7	47.1	45.6
Rest of World	36.1	38.7	36.5	37.5	38.6	55.6	53.3	52.9	54.4

	1999	2000	2001	2002	2003	2004	2005	2006	2007
U.S.	49	48	42.9	45.7	51.4	36.6	37	37.4	37.8
Rest of World	51	52	57.1	54.3	48.6	63.4	63	62.6	62.2

Source: (30),

## C.2.2 Cinematographic Films: performance

There are different types of film and format for movies that are to be shown in the cinema (33, 34, 43). Due to the lack of more detailed statistics, it will be assumed that all movies are filmed in 35 mm and for the ones from pre-1953 (introduction of *Cinemascope*), the aspect ratio was equal to 1.37:1 with the surface area equal to 22.05 x 16.03 [mm<sup>2</sup>], while afterwards (*wide screen*), the "common" selection in the United States is 1.85:1 (plain) with

a surface area of 20.96 x 11.33 [mm<sup>2</sup>], and in Europe it's 1.66:1, with a surface area of 20.96 x 12.62 [mm<sup>2</sup>] (31, 32).

In Table S C-9, the approximate resolutions in pixels of the four main formats used by the film industry are shown. Given their similarities, it was decided to use the average resolution of 142.42 [pixel/mm] for our purposes

**Table S C-9: Most-used film format resolutions in the film industry.**

Format	Period	Dimensions [mm <sup>2</sup> ]	Resolution [pixel/frame]	[pixel/mm]
Academy Sound	<= 1955	15 x 21	2160 x 2970	142.71
Academy US Widescreen	> 1932	11 x 21	1605 x 2970	143.65
Anamorphic Panavision (Scope)	> 1958	17.5 x 21	2485 x 2970	141.71
Super-35	> 1982	10 x 24	1420 x 3390	141.62

Sources: (33-35)

Using everything above, it is possible to estimate the resolution per frame (in pixels) for each one of the formats that are considered (see Table S C-10). For film copies (i.e. for their commercial distribution), it is considered that their resolution is reduced to one-sixth (35).

**Table S C-10: Resolutions in pixel for the different formats.**

Format 35 mm	AR	Dimensions [mm <sup>2</sup> ]	Resolution	
			[pixel/mm]	[pixel/frame]
PrD-1953	1.37:1	22.05 x 16.03	142.42	7 169 421
Wide screen EE. UU.	1.85:1	20.96 x 11.33	142.42	4 816 850

Source: Authors' own elaboration, based on various sources (see text).

A 90 minutes duration is assumed for cinema movies from between 1945-2007, which refers to a duration found between commercial movies (that are normally longer, "long films"), and the short films (normally defined as movies shorter than 30 minutes). For pre-1945 movies (many of them silent), an average of 30 minutes is assumed. One additional estimate is that all silent movies (those before 1926) were shot in black and white, with a depth of 8 [bits/pixel]. It follows the standard of 24 frames per second to give the illusion of continual motion (36), resulting in 129 600 frames for cinema movies from 1945-2007, and 43 200 frames for pre-1945. For cinema movies from 1926-2007, it is assumed that they have all been shot in color film with 24 bits per pixel (*True Color*).

Films also contain audio. It is assumed that each film contains only one audio format. The calculation of the bit rate for each analog technology is based upon the digitalization of the sound (B.4); the estimate of the frequency rate is based on the consideration that it is set 10% higher than the maximum frequency (Nyquist's Theorem) and the result corresponds to the product between this value and the number of bits that are assigned per sample.

**Table S C-11: bit rate for the different technologies for audio**

Tecnology	Analog/Digital	Period	Frequency Ranges. [kHz]	Sample Rate [kHz]	Bits/sample	Number of Channels	Bit Rate [kbps]
Vitaphone	A	1926–1930	0.03 - 4.3	10.32	8	1	82.56
Sound-on film	A	1930–1974	8	17.6	8	1	140.80
SVA (Dolby A)	A	1974–1980	0.031 - 12.5	27.5	16	2	880.00
SVA (Dolby SR)	A	1980–1990	0.031 - 12.5	27.5	16	4	1760.00
DTS	D	1993-	0.02 - 20	48	20	6	1440.00
Dolby Digital (compressed)	D	1991-	0.02 - 20	48	16	6	384.00

Source: Authors' own elaboration (37-39).

Regarding digital audio, consider the following: in accordance with (40), Dolby Digital is the most used system in theatres, while DTS takes second place (in 2004, 42,970 theatres were equipped for Dolby Digital, versus the more than 23,000 with DTS (41)). It is supposed that since 1991, all movies have included audio coded with Dolby Digital. The total capacity per movie is shown in Table S C-12. It should be noted that the weight decrease observed since 1991 is due to the sound that, apart from being stored digitally, uses a very efficient compression technique (AC-3).

**Table S C-12: Total performance in bytes of cinematographic films of distinct formats**

Period	Format	Audio [MB]	Original Films		Copies	
			Image [MB]	Total [MB]	Image [MB]	Total [MB]
1888 - 1926	PrD-1953	0	309,719	309,719	51,620	51,620
1926–1930		18.6	929,157	929,176	154,860	154,878
1931–1944		31.7	929,157	929,189	154,860	154,891
1945–1952		95.0	2,787,471	2,787,566	464,579	464,674
1953–1973	Wide screen EE. UU.	95.0	1,872,792	1,872,792	312,132	312,227
1974–1979	Wide screen EE. UU.	594	1,872,792	1,872,792	312,132	312,726
1980–1990	Wide screen EE. UU.	1,188	1,872,792	1,872,792	312,132	313,320
1991-2007	Wide screen EE. UU.	259	1,872,792	1,872,792	312,132	312,391

Source: authors' own elaboration, based on various sources (see text).

### C.2.3 TV Films and TV episodes: performance

For a lack of more concrete statistics, it is assumed that all movies and television episodes are recorded in analog film. It is supposed that the resolution is the same for the film used in original motion pictures, that is to say, 142.42 [pixel/mm] (42), but with an aspect ratio for the TV standard of 1.33:1 (43) with which the dimensions of film used for image storage is 24 x 18 [mm<sup>2</sup>]. Furthermore, the sound is registered in stereo format with SVA stored with a rate of 880 [kbps] and durations of 90 minutes for TV movies and some 45 minutes for TV episodes (between 30 and 60 minutes) (see Table S C-13).

**Table S C-13: Size in bytes of films and TV episodes stored on film.**

Type	Video				Audio [MB]	Total [MB]
	Resolution [pixel/frame]	[frame/s]	Duration [s]	Size [MB]		
Movie	8,762,454	24	5,400	3,406,842	594	3,407,436
Episode			2,700	1,703,421	297	1,703,718

Source: authors' own elaboration, based on various sources (see text).

As for commercial distribution copies (on magnetic film), these are stored –through a process called telecine<sup>17</sup>- on Betacam, films that since their appearance in 1982 (44) quickly turned into the standard of the television industry (45, 46). For a lack of information regarding the kind of magnetic film that was used before 1982, we may assume that since the appearance of the first TV movie or series since 1985, all have the same resolution as Betacam; and that since 1986, (the year in which Betacam SP was introduced) up to the present, all have Betacam SP resolution. (see Table S C-14 and Table S C-15).

**Table S C-14: Bit rate for video stored on Betacam film**

Type	Standard	Vertical Resolution	Horizontal resolution [lines]	Horizontal resolution [pixel]	Resolution [pixel/frame]	FPS	Pixel rate [pixel/s]	Bit rate [kbps]*
Betacam	NTSC	480	300	390	187,200	30	5,616,000	134,784
	PAL	576			224,640	25	5,616,000	134,784
Betacam SP	NTSC	480	340	422	202,560	30	6,076,800	145,843
	PAL	576			243,072	25	6,076,800	145,843

Sources: authors' own elaboration, based on (44, 47,48). Note: \*It is assumed that all TV series and films were filmed in color, with a depth of 24 bits per pixel.

**Table S C-15: Size in bytes of copies of films and TV episodes stored on magnetic film.**

Type	Duration [s]	<=1985	>=1986	<=1985	>=1986	<=1985	>=1986
		Video [MB]		Audio [MB]		Total Size [MB]	
Movie	5400	90,979	98,444	748	1,361	91,727	99 805
Episode	2700	45,489	49,222	374	680	45,864	49,902

Source: authors' own elaboration, based on various sources (see text).

<sup>17</sup> With this procedure, the stored information on a film is transferred to a magnetic film, adjusting the resolution and refresh rate (frames per second) so that they can be reproduced in a correct manner on a corresponding device.



## C.2.4 Content compression

For entropic normalization (the optimal rate as of 2007), a compression rate of 60:1 is used for video (with MPEG-4 AVC XviD), and for audio, 9.6:1 (MPEG-4 AAC, “excellent” quality), for both devices. Audio codified with Dolby Digital is already in an average compression rate of 12:1.

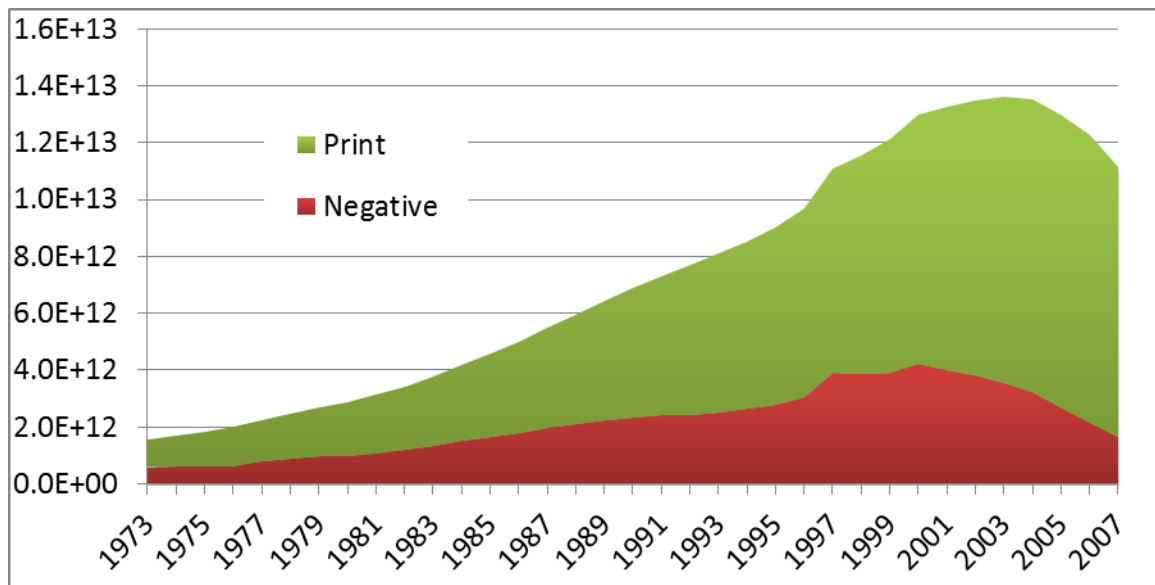
Table S C-16: Factors of compression for video and audio in a film

	Film (Optimal)	Magnetic Film (Optimal)
Video	60	60
Audio	9.6	9.6

Source: Authors’ own elaboration, based on B.4.3 and B.5.3.

## C.3 Analog Photography<sup>18</sup>

Fig. S C-5: Storage capacity of analog photographs, in MB, without standardized compression (hardware capacity).



Source: Authors' own elaboration, based on various sources (see text).

### C.3.1 Negatives: performance

<sup>18</sup> Storage concepts for digital photography are discussed in Memory Cards and Digital cameras and camcorders.

The quantity of bits per photo is directly related with the size of the film, the distribution of silver particles in the emulsion (49) (which is directly related to the “analogic” resolution of film, expressed in terms of pairs of millimeter lines [lp/mm]), and the number of bits per pixel.) According to (50), if we assume that the width of a pair of lines is two pixels, we can establish the following relationship between the two: Number of bits/photo = Resolution [pixels] x No. of bits per pixel = {Width x Height of film [mm] x Resolution [lp/mm] x 2 [pixel/lp]} x No. of bits per pixel.

Of all existing film formats, 35 mm (also known as 135 film) has succeeded as the most used and most popular since the 1960’s (33, 51). The standard size of a frame in this format is 24 x 36 [mm<sup>2</sup>] (approximately 0.9 x 13 [inches<sup>2</sup>]) (33).

The resolution of 35 mm films is 64.3 [lp/mm] (49). However, this does not correspond to the “theoretical maximum” of a film, given that we see a loss of 30% caused by the type of lens used (52, 53). Considering the size of a frame in a film, we find that the digital resolution is equal to 14 288 797 [pixels/frame]. For black and white film, with the same loss of 30%, the average resolution is 77 [lp/mm] (54), which results in 20 490 624 pixels/frame. This higher resolution, compared to that of color film, explains why primarily professional photographers use black and white film. As for disposable cameras, which also utilize the 35 mm format (55), the highest achievable resolution is 40 [lp/mm] (53), resulting in 5 529 600 [pixels].

To determine the quantity of bits per frame, an RGB *True Color* model is used for color images, with 24 [bit/pixel] (which reflects  $2^{24} = 16\,777\,216$  different colors); while an image in black and white (grayscale) has only 8 [bits/pixel] (which reflect  $2^8 = 256$  different shades of gray). The result is presented in Table S C-17 and is in agreement with the fact that a digital file of a quality color photo weighs around 2MB when it is compressed with JPEG, which has a compression ratio in the range of 16:1 – 32:1.

**Table S C-17: Quantity of bits contained in a roll of film**

	Resolution [pixels/ image]	Performance [bits/pixel]	Size [bits]	Size [MB]
B&W Film	20 490 624	8	163 924 992	20.5
Color Film	14 288 797	24	342 931 128	42.9
Disposable Camera Film	5 529 600	24	132 710 400	16.6

Source: Authors’ own elaboration, based on various sources (see text).

### C.3.2 Printed photos: performance

(56) reports that a resolution of around 400 [dpi] is required to produce a lossless scan of a photograph (52, 57). It makes no difference whether the original photo was analog or digital, given that the bottleneck of a photograph on paper depends on the printer. Considering that the standard size of printed photographs in the United States, Canada, and

many other countries is 6 x 4 [inch<sup>2</sup>] (15 x 10 [cm<sup>2</sup>]) (58), we may say that a photo of this size contains  $\{(6 \times 4)[\text{inch}^2] \times (400 \times 400)[\text{pixel}/\text{inch}^2]\} = 3\,840\,000$  [pixels]. Color photos are comprised of 24 [bit/pixel], while black and white photos are comprised of 8 [bits/pixel], resulting in 92 160 000 bits for a color photograph, and 30 720 000 for one in black and white. It is assumed that prints made from photos shot on disposable cameras are in color.

### C.3.3 Negatives and printed photographs: quantity

The following information on quantities of film and exposures (photographs that have been taken but not yet processed) has been received thanks to the kind assistance of Don Franz from Photofinishing News (59) (Table S C-18). The estimated amounts of disposable cameras are based on (60), and on the rate of growth in the United States between 1994-2006 (61). We can assume the same for exposures/film for conventional film (62).

Table S C-18: Quantity of film and exposures

	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Sales of Conventional Film (millions of rolls)	447.9	496.7	541.9	577.6	617.3	651.7	674.5	718.5	789.1	792.2	825.7
Exposures of Conventional Film (billions)	8.9	9.7	10.4	11	11.8	12.7	13.1	14.2	15.8	16	16.7
Exposures/Film	19.8	19.5	19.1	19	19.2	19.5	19.5	19.8	20	20.2	20.2
Disposable Cameras (millions)	0	0	0	0	0	0	0	0	0	0	0
	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Sales of Conventional Film (millions of rolls)	918.7	1013.4	1130.5	1184.2	1165.5	1246.3	1401.9	1544.4	1684.8	1816.7	1940.5
Exposures of Conventional Film (billions)	18.4	20.7	23.3	25	25.3	27.6	30.1	34.2	38.5	41.3	44.2
Exposures/Film	20.1	20.4	20.6	21.1	21.7	22.2	21.5	22.1	22.8	22.7	22.8
Disposable Cameras (millions)	0	0	0	0	0	0	0	0	0	0	0
	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Sales of Conventional Film (millions of rolls)	2125.5	2270.8	2424.1	2507.2	2551	2533	2570	2688	2795	3015	3404
Exposures of Conventional Film (billions)	49	51.9	55.2	56.9	58.2	58.9	60.4	62.8	65.9	71.9	91
Exposures/Film	23	22.8	22.8	22.7	22.8	23.3	23.5	23.4	23.6	23.9	26.7
Disposable Cameras (millions)	0	14	28	42	56	71	85	99	141	188	230
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	
Sales of Conventional Film (millions of rolls)	3332	3440	3788	3739	3595	3058	2764	2241	1779	1317	
Exposures of Conventional Film (billions)	89.3	90.3	96.9	91.3	86.1	79.8	72	59.1	47.3	35.5	

Exposures/Film	26.8	26.3	25.6	24.4	24	26.1	26.1	26.3	26.6	27
Disposable Cameras (millions)	264	298	332	366	400	449	443	410	349	297

Sources: Conventional Film: (59), Single-use, authors' own elaboration based on (60, 61). Note: Conventional films do not include instant film/Polaroid.

The estimates of the percentage of color and black and white films are based on the years 1963, 1964, 1969, 1974 for the United States, Japan, Germany, UK and France (63), and on Germany for the years 2001, 2002, and 2003 (64, 65); the others were calculated in a linear fashion (cursives in Table S C-19).

Table S C-19: Percentages of color film<sup>19</sup>.

Year	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
% Color	28.9	34.0	39.0	44.1	49.1	54.2	59.2	63.3	67.4	71.4
Year	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
% Color	75.5	79.6	80.65	81.30	81.94	82.59	83.24	83.89	84.53	85.18
Year	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
% Color	85.83	86.48	87.12	87.77	88.42	89.07	89.71	90.36	91.01	91.66
Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
% Color	92.31	92.95	93.60	94.25	94.90	95.54	96.19	96.84	97.49	97.53
Year	2003	2004	2005	2006	2007					
% Color	97.53	97.54	97.54	97.54	97.54					

Source: Authors' own elaboration, based on (63-65).

Each image is counted one time in the roll (where the base information and the resolution of the negative is stored), and one time once it is developed (either as a print or a slide, which applies the resolution of the printed photo). In theory, printed photos and negatives in particular have a very long shelf life (between 10 and 100 years) (66), however, according to online forums for photographers, the vast majority of persons do not keep them for long. Therefore, on average, we can consider a life expectancy of 10 years for printed photos<sup>20</sup>, and of 1 year for negatives (strongly influenced by the majority, who discard their negatives after having them printed).

### C.3.4 Content compression

To achieve the optimal level of compression, we can assume that printed images and images stored on film are to be compressed with high quality JPEG (to avoid affecting the

<sup>19</sup> (63) specifies the percentage of color photographs (exposures) that have not yet been processed.

<sup>20</sup> This average of ten years could be seen as a weighted average, for example as the result of that 5% of photos are saved "forever" (in our study equal to 40 years); 15% for 20 years; 40% for 10 years, 30% for 3 years, and 10% of photos are not saved for any longer than 1 year.

resolution), with compression factors equal to 16 and 5.3 for photos in color and black and white, respectively.

**Table S C-20: Comparison of sizes of photographs with and without compression.**

Type	Original size [bits]	Compression factor	Compressed size [bits]	Compressed size [MB]
Film	B&W	5.3	30,929,244	3.87
	Color	16	21,433,196	2.68
	Disposable	16	8,294,400	1.04

Source: Authors' own elaboration, based on various sources (see text).

**Table S C-21: Annual compression of content factors.**

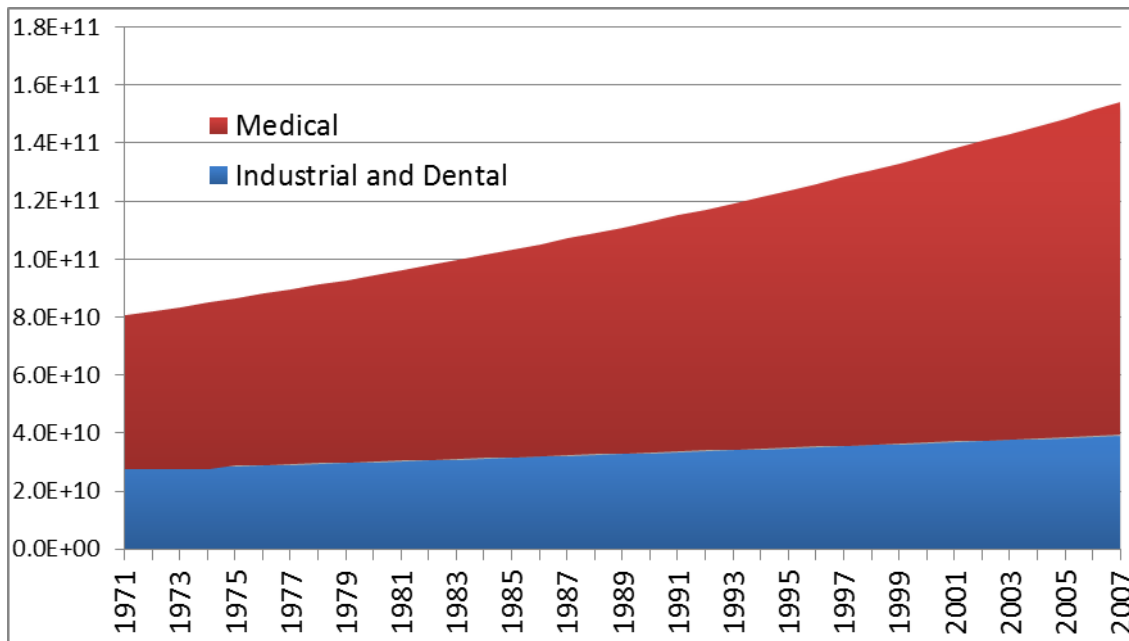
		Optimal
Film and print	Color	16.0
	B&W	5.3
Print	Color and disposable	16
	B&W	5.3

Source: Authors' own elaboration, based on B.3.3.

## C.4 Radiography

A radiograph is the result of a photographic films (films) exposure to a high-energy radioactive source (generally an x ray or gamma ray). In film, the dense areas of an object placed between a radioactive source and the film show up in a grey tones, whose intensity is an inverse function of the density of the object (the less density, the darker it appears and vice versa). The uses of radiography can be medical (to detect bone fractures, cancer, etc.) as well as industrial (for the detection of defective materials and welds that are unable to be seen by the naked eye.)

**Fig. S C-6: Storage provided by radiographs in [MB], without standardized compression (capacity hardware)**



Source: Authors' own elaboration, based on various sources (see text).

#### C.4.1 Radiographs: quantity

Concerning the number of units, we have the worldwide total of m<sup>2</sup> X ray images consumed in 1997 and 2002 for the medical, industrial, and dental industries (60). Throughout this period a CAGR growth rate of 2.2% was seen in medical X rays and of 1% in industrial and dental X rays. We may assume that this rate continued for the entire period, which is also in agreement with the development of sales of medical X ray films in North America between 1999 and 2005 (67) (the United States represents more than one third of the entire world consumption of X ray film.).

Table S C-22: Worldwide number of radiographs in millions of m<sup>2</sup>.

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
<b>Medical</b>	208	212	217	221	226	231	236	241	247	252	257	263	269
<b>Industrial &amp; Dental</b>	15.2	15.4	15.5	15.7	15.8	16.0	16.1	16.3	16.5	16.6	16.8	16.9	17.1
	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
<b>Medical</b>	275	281	287	293	299	306	312	319	326	333	340	348	355
<b>Industrial &amp; Dental</b>	17.3	17.4	17.6	17.8	18.0	18.1	18.3	18.5	18.7	18.9	19.0	19.2	19.4
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
<b>Medical</b>	363	371	379	388	396	405	413	422	431	441	450	460	470
<b>Industrial &amp; Dental</b>	19.6	19.8	20.0	20.2	20.4	20.6	20.8	21.0	21.2	21.4	21.6	21.8	22.1

Source: Authors' own elaboration based on 1997 and 2002 (60)

A radiograph can have a shelf life of from 20 to 30 years in optimum storage conditions (68), however; in normal conditions (such as in an office) its useful life will be shorter, from 1 to 10 years. On average, we can expect a shelf life of 5 years.

## C.4.2 Radiographs: performance

### Medical Radiographs

To determine the resolution of the films used in the capacity estimates, we have opted to use the specifications of pixel size in digital radiographic equipment. When put to practice, the linear size of the pixel in a digital medical radiograph varies between 0.1 and 0.2 [mm] – although there do exist special cases, like mammograms, where the pixel size can be as small as 0.05 [mm] (69), – this assumption is in agreement with other sources that specify the aforementioned variables for the three most common types of radiographs (as shown in Table S C-23).

Table S C-23: Size in pixels of the most common categories of medical radiographs.

Category	Thorax	Spine	Extremities	Others
Pixel size [mm]	0.1 – 0.2	0.1 – 0.14	0.1 – 0.16	0.14 (Supposed)
Percentage of images	40%	10%	20%	30%
Weighted average	0.14 mm/pixel			

Sources: (70-74)

The estimation of the average linear resolution (0.14 [mm/pixel]) is based on various studies that show the frequency with which different medical exams were carried out in Romania in 1995 and 2000 (75), France in 1982 and 1988 (76), Korea in 2006 (77) and Norway in 1993 and 2002 (78). From them we get the percentages shown in the table above, which allow us to calculate the average linear resolution. We can ascertain that the resolution is equal to 5 098 [pixel/cm<sup>2</sup>] (0.14 [mm/pixel] = 7.14 [pixel/mm] = 71.4 [pixel/cm] = 5 100 [pixel/cm<sup>2</sup>]). Expressed in [pixel/m<sup>2</sup>] makes: No. of pixels = (100 x 100 [cm<sup>2</sup>]) x (5100 [pixel/cm<sup>2</sup>]) = 51 000 000 [pixel/m<sup>2</sup>].

### Industrial and Dental Radiographs

A finer resolution is used in industrial and dental radiographs than in medical radiographs (a smaller pixel size); the typical values are summarized in Table S C-24. To estimate the amount of pixels, we have taken an average of the values found in the table, that is to say, a size of 0.0525 [mm], which is expressed in [pixel/m<sup>2</sup>]: 0.0525 [mm/pixel]= 19.05 [pixel/mm]= 190.5[pixel/cm]=36300[pixel/cm<sup>2</sup>] = 363 000 000 [pixel/m<sup>2</sup>]

Table S C-24: Size of pixels in dental and industrial radiographs.

Category	Industrial	Dental
Size of pixel [mm]	0.05 – 0.1	0.02 – 0.04

Sources: (79-84).

Finally, regarding the number of bits with which each pixel is coded (the number of tones), it is known that the dynamic range of the image in a film is less than that of digital (83). In the latter case, the depth of bits is usually 10 [bits/pixel] (70); so it would be reasonable to assume the use of 8 [bits/pixel] for analog film.

Table S C-25: Number of bits in medical radiographs.

	Resolution [píxeles/ m <sup>2</sup> ]	Performance [bits/píxel]	Size [kbits/m <sup>2</sup> ]
Medical Radiography	51,000,000	8	408,000
Industrial and Dental Radiography	363,000,000	8	2,904,000

Source: Authors' own elaboration, based on various sources (see text).

### C.4.3 Content compression

In agreement with (85-87), the JPEG standard (lossless) is used when digitalizing an analog image. For normalizing at the entropic level, we can resolve to use JPEG with excellent quality.

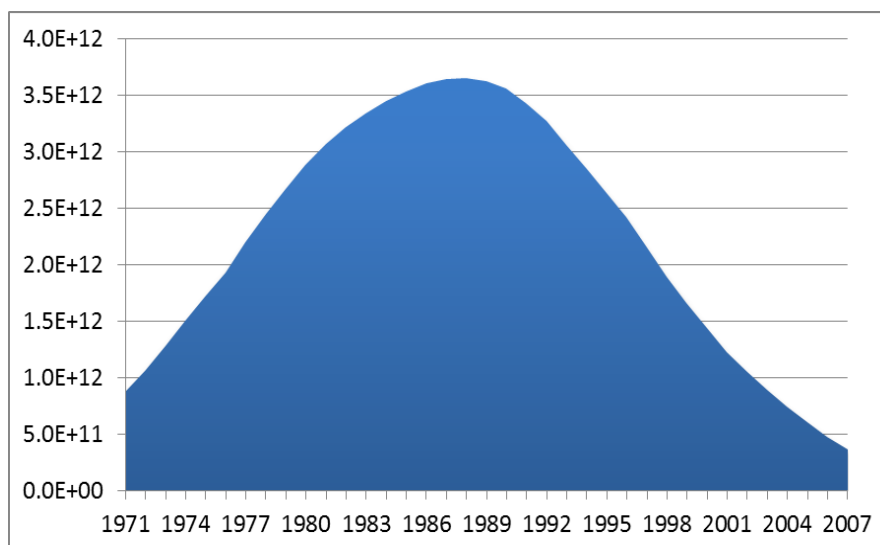
Table S C-26: Compression factors by content per year.

	Optimal
Medical	5.3
Dental and Industrial	5.3

Source: Authors' own elaboration, based on B.3.3.

## C.5 Vinyl

Fig. S C-7: Storage capacity provided by vinyl discs in MB, without compression (hardware capacity).



Source: Authors' own elaboration, based on various sources (see text).



### C.5.1 Vinyl LP: quantity

The quantity of LP vinyl is reported for the years 1984-1993 by (88) and for around 70 countries between the years 1994 and 2004 by (International Federation of the Phonographic Industry [IFPI]) (89-94). The years pre-1984 and post-2004 have been estimated based on the growth rate of vinyl in Japan (beginning in 1956; according to Recording Industry Association of Japan [RIAJ]) (95), United States (from 1973 on; Recording Industry Association of America [RIAA]) (96-98) and the United Kingdom (from 1973 on) (99) (weighted by the inhabitants of those three countries). A shelf life of 20 years is assumed for vinyl.

Table S C-27: Number of vinyl LPs sold, in millions.

1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
93.5	120.7	153.3	187.7	222.3	273.5	321.7	382.0	473.1	578.1	691.0
1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
825.9	969.1	1188.5	1194.6	1130.0	1191.7	1416.8	1392.7	1229.2	1227.4	1106.0
1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
935.2	826.0	800.0	730.0	690.0	590.0	510.0	450.0	338.0	157.0	115.0
1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
80.4	56.3	38.1	31.8	25.3	22.3	21.2	19.0	14.6	9.8	8.2
2004	2005	2006	2007							
7.8	5.9	5.6	6.3							

Sources: (88-99)

### C.5.2 Vinyl: performance

If we follow the logic of Nyquist's theorem and consider the specific information given regarding this technology by (100), we may assume that the performance of LP corresponds with the bit rate of 281.6 [Kbps]. We can suppose that LPs have duration of 45 minutes, resulting in 95.04 MB on both sides of the disk, the equivalent of 190.08 MB per LP.

### C.5.3 Content compression

An optimal compression factor is used to achieve excellent audio quality (Table S C-28). The table shows that about 45 minutes of vinyl compressed at the optimal level for the year 2007 (9.9 MB) contains approximately the same information as two long songs in MP3 format (typically around 5 MB), clearly demonstrating the inferior quality of vinyl.

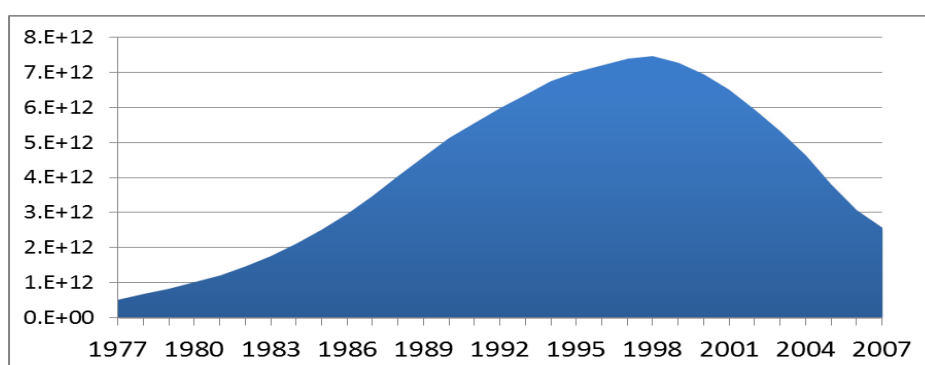
Table S C-28: Compression factors and resulting storage in [MB], for vinyl.

"Optimal"	
Compression factors	9.6
Performance [MB for 45 min]	9.9

Source: Authors' own elaboration, based on B.4.3.

## C.6 Audio Cassettes

Fig. S C-8: Storage capacity provided by cassettes in [MB], without compression (hardware capacity)

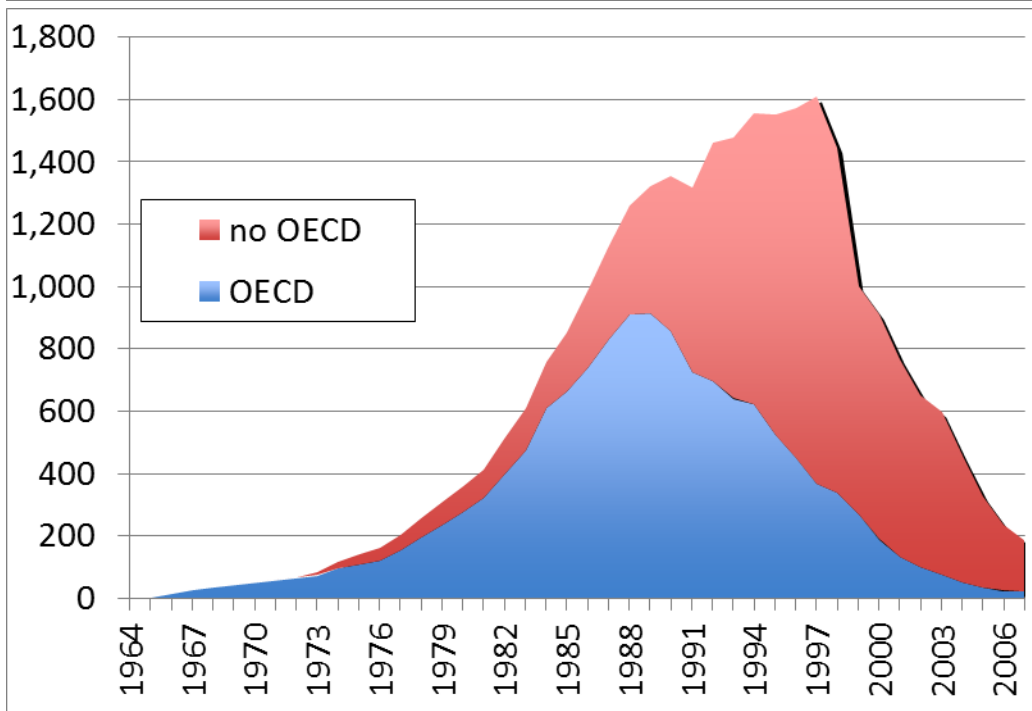
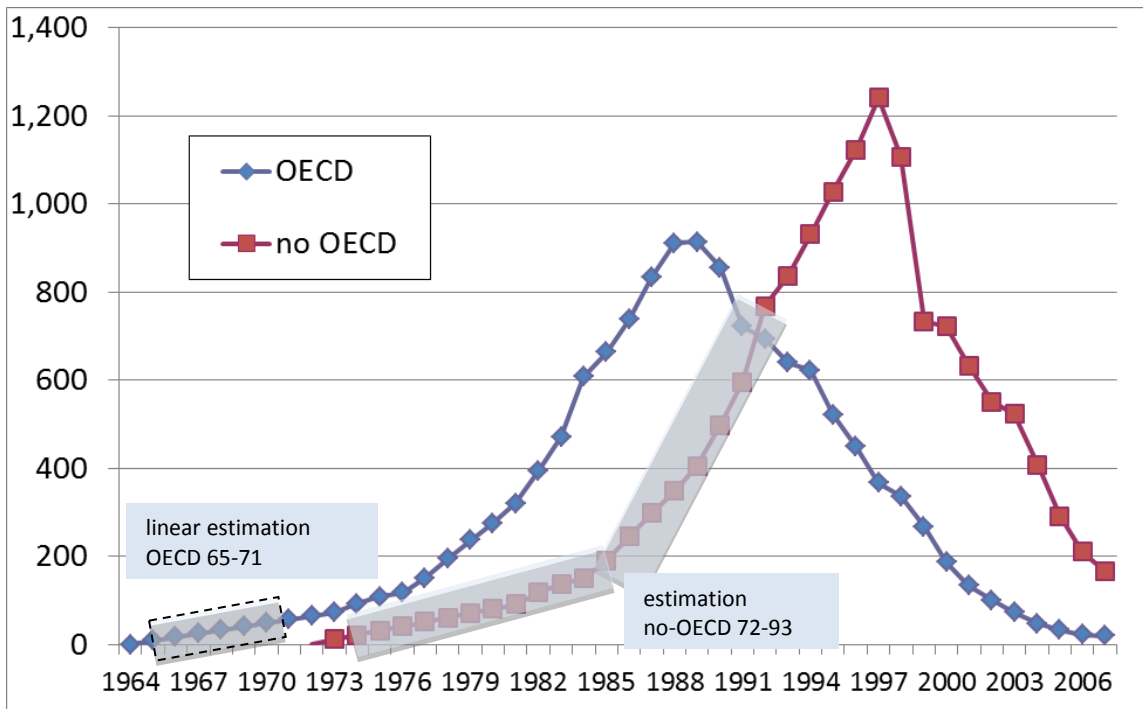


Source: Authors' own elaboration, based on various sources (see text).

### C.6.1 Audio Cassettes: quantity

The sales of cassettes by country (from a list of some 75 countries, representing 80% of the total global population of the year 2000) are reported between the years 1994 and 2004 by (89-94). For countries from the OECD (industrialized nations), the estimates for the period of 1973-1993 have been based on the growth rate of cassette sales in the United Kingdom (99), and the estimates for 1965-1972 have been calculated in a linear manner (based on the 9 million tapes sold worldwide in 1965 (101). For non-OECD countries, it may be assumed that cassettes arrived with the commercialization of music cassettes in 1973 (after the appearance of the Advent 201 model), and we consider a growth rate of the first 20 years of cassette distribution in OECD (1964-1984), adjusted for the levels of those countries. For the years 2005 to 2007, the total number of cassettes recorded at the worldwide level has been estimated using the sum of all units in Japan (95), the United States (between 1973 and 2007) (96-97); and United Kingdom (99, 102). Countries that are not registered in the statistics of the IFPI were estimated according to the ratio of [cassettes/inhabitant] of neighboring countries in the same region (Africa, Asia, Europe, Latin America, Oceania), with adjustments made for the amount of inhabitants in each country.

Fig. S C-9: Amount of recorded audiocassettes in OECD and non-OECD countries (above, showing separate estimates; below, accumulated).



Source: Authors' own elaboration, based on various sources (see text)

In the case of blank (unrecorded) cassettes, we unfortunately only have global statistics for the years 2002-2006 (Japan Recording-Media Industries Association [JRIA]) (103-108). The previous years and 2007 have been estimated according to the trend of recorded cassettes, which were registered by the music and entertainment industry. Audiocassettes have a technical duration of some 15 years (109, 110), and an average shelf life of 8 years<sup>21</sup>.

<sup>21</sup> This average follows a similar logic to that stated in footnote 13, and could be seen as the result of that 20% of analog video tapes are saved for 15 years; 40% for 10 years; 30% for 3 years; and 10% of tapes are not guarded for any more than 1 year.

## C.6.2 Audio cassettes: performance

(100) states that this medium stores sound in stereo (two channels, from 1971 on) and its frequency response is within the range of 0.04 – 18 [kHz]. This follows the logic of Nyquist’s theorem and defines a sampling frequency 10% higher than twice the maximum frequency (23), assuming 8 bits per sample per channel, multiplied by two, since two audio channels are contained on a stereo tape. The chosen time duration is 60 minutes, to estimate the total capacity of audio cassette tapes that are not singles.

Table S C-29: Capacity of audio cassettes

Type of cassette	Duration [minutes]	Sampling frequency [kHz]	Bit rate [Kbps]	Capacity per unit [MB]
Single	10	39.6	633.6	47.52
C60	60		633.6	285.12

Sources: Authors’ own elaboration, based on (100).

## C.6.3 Content compression

The most efficient algorithm in 2007 (MPEG-4 AAC) achieves “excellent” quality with a compression factor of 9.6. This implies that the capacities are reduced to 29.7 [MB], comparable to 5 or 6 songs in MP3 form.

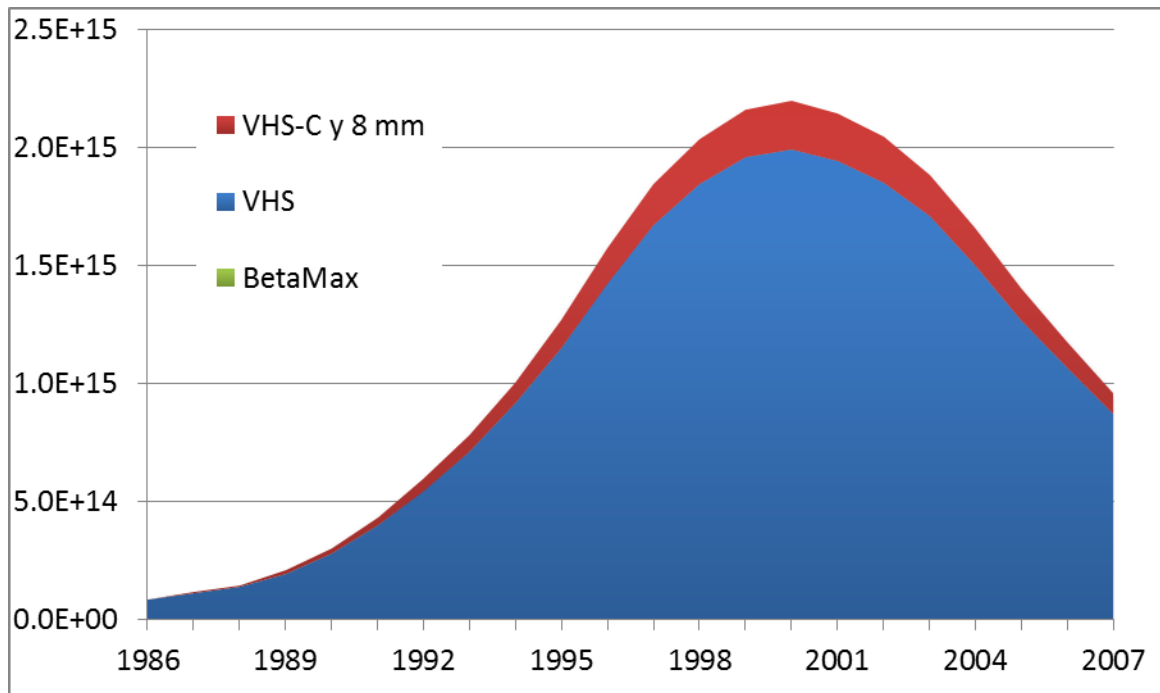
Table S C-30: Compression factors and resulting storage in [MB], audio cassettes.

	“Optimal”
Compression factor	9.6
Performance [MB for 60 min]	29.7

Source: Authors’ own elaboration, based on B.4.3.

## C.7 Analog video tapes

Fig. S C-10: Storage capacities of analog video tapes, in [MB], without compression (capacity hardware)



Source: Authors' own elaboration, based on various sources (see text).

### C.7.1 VHS tapes: performance

180 minutes may be considered the standard size for VHS tapes (an average of the three most marketed formats, together with 120 and 140 minutes). The performance of a tape that is played on a conventional television set is based on the numbers of lines that divide the screen and the pixels that make up each line (23). Along with this, using the number of frames per second (fps) defined in each of the standards (25 for the PAL/SECAM format and 30 for NTSC) (111) and the horizontal resolution of a VHS video film (240 lines), we may estimate the performance of a video tape (see also the chapter about TV in notes of Communication).

Table S C-31: Video resolutions of VHS tapes

	Vertical resolution [lines/frame]	Horizontal resolution [lines/mm]	Horizontal resolution [pixel]	Refresh rate [fps]
PAL/SECAM	576	240	312	25
NTSC	480	240	312	30

Sources: (23, 112)

A video image contains three fundamental components: one of luminance (Y) and two of chrominance ( $C_R$  y  $C_B$ ) (111). The chrominance components share the same number of pixels. It is maintained that the video is stored on the subsample structure 4:2:2, which implies that the luminance component is represented by 312 pixels per line, while each of the color components (the red and blue chrominances) are represented by only 156 pixels per line. It is worth noting that this differs from a TV transmission in broadcasting, where a structure of 4:2:0 is maintained to facilitate the transmission (by reducing the sharpness of the colors)

(113). With a digitalization of 8 bits per pixel (23) the following formula is used to reach Bitrate (PAL) = Bitrate (NTSC) = Bitrate (luminance) + Bitrate (Cr) + Bitrate (Cb) = 71.88 Mbps:  $N\# \text{ [bit/s]} = N\# \text{ [lines/frame]} * N\# \text{ [pixels/line]} * \text{refresh rate [frame/seconds]} * N\# \text{ [bits/pixel]}$ .

For an estimate of audio storage on VHS tapes (see Table S C-32), we follow the logic of Nyquist's theorem, while considering the change from mono to stereo in 1985, and the improvements in audio introduced by JVC in response to Sony's Betamax Hi-Fi technology.

**Table S C-32: Details of audio storage on VHS tapes and estimated bit rates.**

Technology	Mono/ stereo	Bandwidth [kHz]	Sample rate [kHz]	Bits per sample[bits]	Rate per channel [kbps]	Rate [kbps]
VHS Lo-Fi (pre-1985)	Mono	0.04 – 10	22	8	176	176
VHS Hi-Fi (post-1985)	stereo	0.02 – 20	44	8	352	704

Source: (113, 114)

Finally, with the bit rates obtained before, we conclude with the storage capacities of VHS video tapes (Table S C-33).

**Table S C-33: Estimated video capacity of VHS tapes.**

		Video Bitrate [Mbps]	Audio Bitrate [Mbps]	Bitrate Total [Mbps]	Capacity 180 minute tape [GB]
PrD-1985	PAL/SECAM	72.59	0.176	72.06	<b>98</b>
	NTSC	72.59	0.176	72.06	<b>98</b>
Post-1985	PAL/SECAM	72.59	0.704	72.58	<b>98</b>
	NTSC	72.59	0.704	72.58	<b>98</b>

Source: Authors' own elaboration

## C.7.2 VHS tapes: quantity

The number of units sold of pre-recorded VHS tapes was obtained from different sources (115-119). The numbers for the year 2000 are estimated in a linear fashion, and 2004-2006 is an estimation based on the growth rate of blank VHS film (103-108). For the number of blank VHS tapes, figures were obtained for the years 1985, 1994 and 2001-2006 (103-108, 120, 121). The figures for the missing years were estimated according to the growth rate of prD-recorded VHS tapes. Video tapes have a technical life of around 15 years (122), and a shelf life of an average of 8 years<sup>22</sup>.

<sup>22</sup> This average follows a logic similar to the one stated in footnote 21, and could be seen as the result of that 20% of analog video tapes are saved for 15 years; 40% for 10 years; 30% for 3 years, and 10% of tapes are not saved for any longer than 1 year.

Table S C-34: Global sales of VHS tapes in millions of units.

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Recorded VHS	0	0.1	0.3	0.9	1.3	2.9	6.5	9.4	13.6	23.5	41.0
Blank VHS	0	0.6	1.9	4.9	7.5	16.5	36.5	53.1	76.9	132.3	231.0
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Recorded VHS	29.6	39.8	44.8	131.9	219.1	306.3	393.5	480.6	567.8	655.0	742.2
Blank VHS	166.6	224.2	252.3	497.6	742.9	988.2	1233.4	1478.7	1724.0	2032.7	2341.5
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Recorded VHS	757.0	657.0	594.4	471.2	348.0	330.0	310.0	251.3	199.1	165.1	125.5
Blank VHS	2388.3	2072.8	1875.4	1486.7	1097.9	1054.0	903.0	732.0	580.0	481.0	365.6

Source: Authors' own elaboration based on: (103-108, 115-121).

### C.7.3 VHS-C and 8mm: performance

We consider 120 minutes as a standard size for VHS-C and 8mm tapes. VHS-C tapes have a resolution of 400 lines/mm (112), while for 8mm tapes it comes to 420 lines/mm (123). Therefore, the resolution of the two as a group is 410 lines/mm, the equivalent of 533 [pixel/line], resulting in 122.8 [Mbps]. Both formats take the same audio as VHS (Table S C-35).

Table S C-35: Capabilities of VHS-C and S-VHS tapes.

	Video	Audio	Total Bitrate [Mbps]	Capacity 120 minute tape [GB]
	Bitrate [Mbps]	Bitrate [Mbps]		
PAL/SECAM	122.80	0.704	123.50	111.15
NTSC	122.80	0.704	123.50	111.15

Source: Authors' own elaboration, based on various sources (see text).

### C.7.4 VHS-C and 8mm tapes: quantity

Regarding VHS-C and 8mm as a set during the period of 2001-2006, we have the source (103-108). For the previous years, an estimation was made according to the growth rate of conventional VHS, keeping in consideration that VHS-C was introduced to the market in 1982. These tapes have a useful lifetime of 8 years (124).

Table S C-36: Worldwide number of sales of VHS-C and 8mm in millions.

<b>1983</b>	<b>1984</b>	<b>1985</b>	<b>1986</b>	<b>1987</b>	<b>1988</b>	<b>1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>
5.2	8.9	15.5	11.2	15.0	16.9	49.9	82.9	115.9	148.9	181.9	214.9	247.9
<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	
280.9	286.5	248.6	225.0	178.3	131.7	125.0	113.0	96.0	77.0	61.0	24.8	

Source: Authors' own elaboration, based on various sources (see text).

### C.7.5 BetaMax tapes: performance

The standard size for BetaMax tapes is 120 minutes. The BetaMax format has a resolution of 260 lines/mm (125) and a structure of 4:2:2 (Table S C-37), which implies that the luminance component is represented with 338 pixels per line, while each of the color components (red and blue) are represented by only 169 pixels per line, resulting in the capacities shown in Table S C-37.

Table S C-37: Video resolutions of BetaMax tapes.

	Vertical resolution [lines/frame]	Horizontal resolution [lines/mm]	Resolution horizontal [pixel]	Refresh rate [fps]
PAL/SECAM	576	260	338	25
NTSC	480	260	338	30

Sources: (23, 125).

The audio performance of BetaMax tapes is presented in Table S C-38. It keeps in consideration that Sony launched a new version of the tape in 1983 that could store audio in high quality (a format called BetaMax Hi-Fi) (126).

Table S C-38: Detalles del almacenamiento del audio en las cintas Betamax y de la estimación de las tasas de bits.

Technology	Format	Frequency response [kHz]	Sample rate [kHz]	Bits per sample [bits]	Rate per cannel [kbps]	Rate [Kibps]
BetaMax	Mono	0.05 – 10	22	8	176	176
BetaMax Hi-Fi	Stereo	0.02 – 20	44	8	352	704

Sources: (113, 125).

Table S C-39: BetaMax tape capabilities.

		Video Bitrate [Mbps]	Audio Bitrate [Mbps]	Total Bitrate [Mbps]	Capacity: 120 Minute tape [GB]
PrD-1983	PAL/SECAM	77.88	0.176	78.06	<b>70.25</b>
	NTSC	77.88	0.176	78.06	<b>70.25</b>
Post-1983	PAL/SECAM	77.88	0.704	78.58	<b>70.72</b>



NTSC	77.88	0.704	78.58	<b>70.72</b>
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Source: Authors' own elaboration, based on various sources (see text).

### C.7.6 BetaMax tapes: quantity

The numbers reported of BetaMax units sold for the years 1975-1988 are by (115) and use a linear estimation for between 1989 and 2002. BetaMax tapes have a useful life of 8 years (124).

Table S C-40: Number of BetaMax tapes sold in millions of units.

1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
0.02	0.18	0.42	0.59	0.85	1.49	3.02	3.72	4.57	6.04
1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
3.39	1.11	0.67	0.15	0.14	0.13	0.12	0.11	0.10	0.09
1995	1996	1997	1998	1999	2000	2001	2002		
0.08	0.07	0.06	0.05	0.04	0.03	0.02	0.01		

Source: Authors' own elaboration based on (115)

### C.7.7 Content compression

The compression factors from 2007 (optimal) are 60:1 for video (with MPEG-4 AVC XviD) and 16:1 for audio (MPEG-4 AAC, "good" quality). This implies that the tape storage capabilities are lower than what is shown in Table S C-41. If we compare this result with a digital movie in MP4 (a 90 minute movie is about 1.6GB), we will find that a 180 minute VHS tape has only half the quality of its digital successor.

Table S C-41: Storage capability by tape in [MB] with "optimal" compression applied.

Tape	VHS		VHS-C	BetaMax	
Period	< 1985	>=1985	1983-2007	<1983	>=1983
[MB]	1,632	1,677	1,882	1,178	1,208

Source: Authors' own elaboration.

Table S C-42: Compression factors for both contents of a video tape.

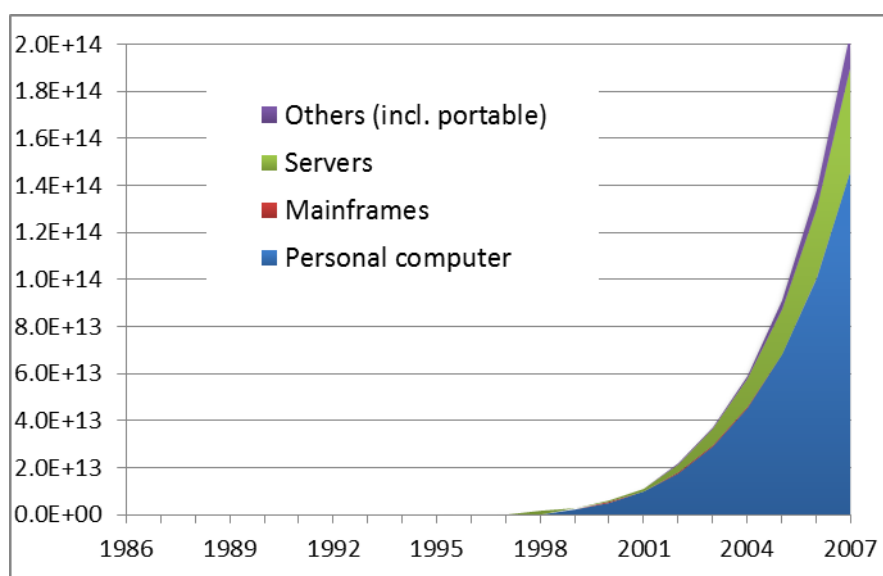
	"Optimal"
Video	60
Audio	9.6

Source: Authors' own elaboration, based on B.4.3 y B.5.3.

## C.8 Hard Disk Drives (HDD)

Hard disks are used for many different applications: computer systems (including desktop and portable computers, high performance servers, supercomputers, mainframes, etc.), PVR/DVR (personal/digital video recorder), video game consoles, iPods, digital cameras, etc. We present a distribution estimate of HDD for different types of devices. This distribution is not necessarily important in relation to the number of bits stored *per sé*, but it is significant to the estimation of the compression of content, and for the estimation of the respective computing power, both of which vary for different types of equipment (see E Computation).

Fig. S C-11: Storage capacity provided by hard disks, in [MB], without normalizing by compression (capacity hardware).



Source: Author's own elaboration, based on various sources (see text).

### C.8.1 Hard Disks: quantity

The quantity of units shipped between 1976 and 1998 was obtained from (127-138), between 1999 and 2004 from (139-144), for 2005 and 2006 from (145), and for year 2007 from (146-148) (see Table S C-43).

Table S C-43: Quantity of hard disks shipped between 1976 - 2007 worldwide.

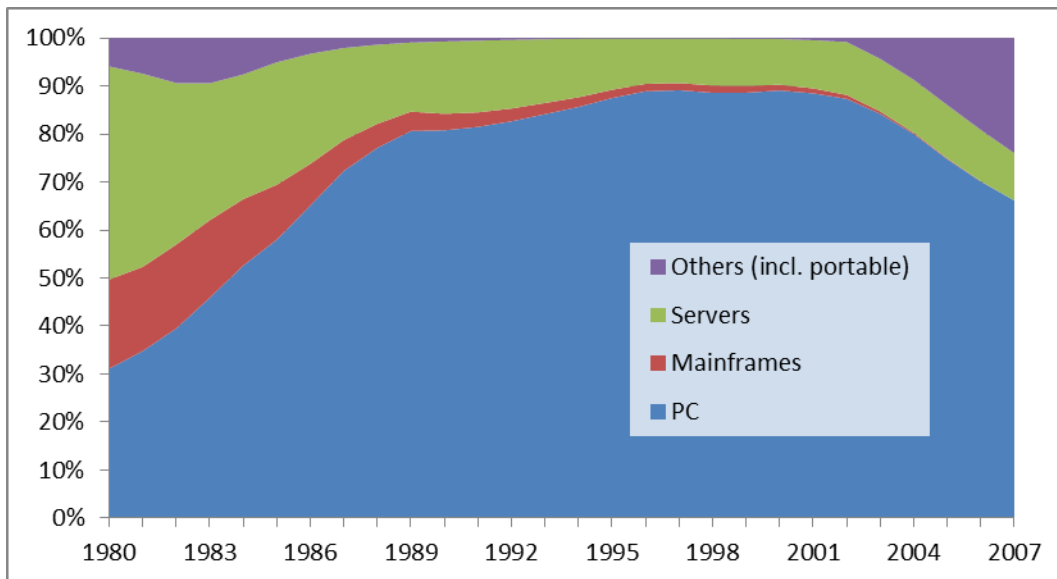
Years	Units [x1000]	Years	Units [x1000]	Years	Units [x1000]
1976	175.7	1987	13,191.9	1998	144,966.8
1977	235.2	1988	17,766.5	1999●	165,290.0
1978	306.1	1989	22,180.5	2000●	195,451.0
1979	386.3	1990	27,879.1	2001●	196,400.0
1980	493.5	1991	32,587.3	2002●	210,500.0
1981	700.7	1992	43,907.1	2003●	261,400.0
1982	950.3	1993	51,857.6	2004●	295,900.0

1983	1,964.7	1994	69,998.8	2005■	358,881.0
1984	3,649.1	1995	89,556.9	2006■	437,028.0
1985	4,855.0	1996	105,017.6	2007⊕	501,800.0
1986	7,941.9	1997	130,498.1		

Sources: No symbol: (127-138), ●: (139-144); ■: (145); ⊕: (146-148).

To determine the shelf life of hard disks, the total number of yearly shipments of HDDs for PCs from Porter (127-138) was compared with the amount of installed PCs reported by the ITU (149). The difference between the two sources is minimized by assuming a shelf life of 10 years for HDDs produced between 1976 and 1986; of 7 years for the period between 1987 and 1989; and a shelf life of 5 years for between 1990 and 2007. This was a period of transition that coincides with the points in time when the Windows operating systems 2.0 (1987) and 3.0 (1990) were put on the market (150). This resulted in the break-up of IBM and Microsoft in 1990, owing to differences between them over which operating system was to be used in the PC (151, 152). It seems reasonable to assume that this development had an impact on the possible shelf life of computers. Considering this shelf life, the estimate of the total distribution according to different technologies (PC, mainframes, servers, portables and others) is presented in the following figure.

Fig. S C-12: Quantity of hard disk distribution (with accumulation).



Sources: (127-138, 139-148).

## C.8.2 Hard disks: performance

From the information reported in the “Disk TrendReport” (127-138) and by Gartner (153, 154), we were able to put together the amount of capacity sent, in terabytes (TB = 1 000 000 000 000 bytes), for 1988-1999, and for 2000 – 2002 and 2006, respectively. The three years between 2003-2005 are estimated with a constant annual growth rate of (48%). Given

that the Disk Trend reports do not show the total number of TB for the years between 1976-1987, an estimate for those years has been created based on the statistics of the number of devices and their performance, both presented in the same reports (127-138).

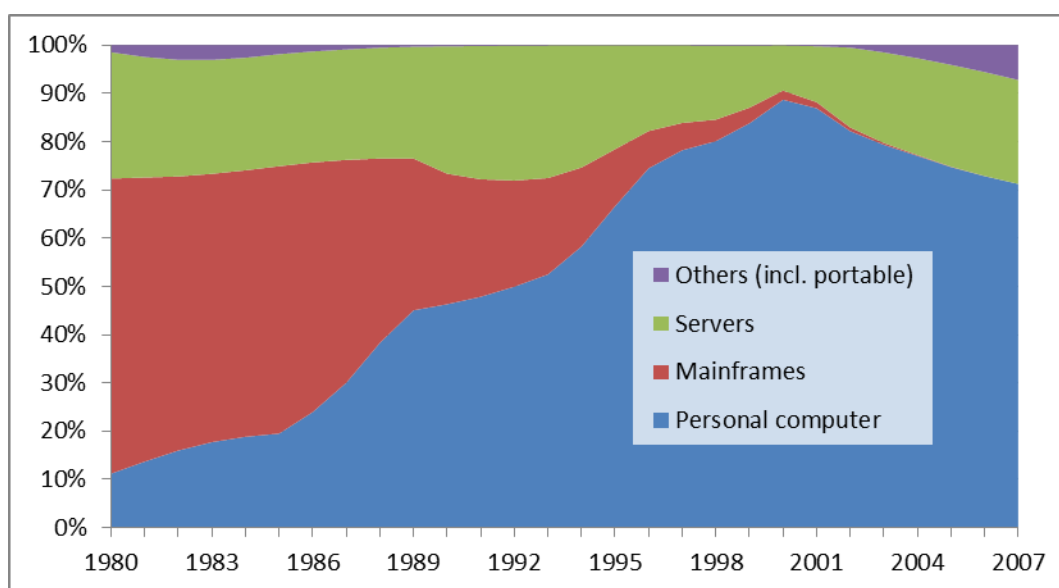
Table S C-44: Capacity sent per year, in terabytes 1980 - 2007.

Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]
		1981+	74.3	1990	3,727.1	1999	1,393,433.8
		1982+	92.5	1991	4,710.8	2000♦	3,194,000.0
		1983+	157.9	1992	8,180.4	2001♦	5,340,000.0
		1984+	242.6	1993	14,855.5	2002♦	10,788,000.0
1976+	10.7	1985+	365.6	1994	32,966.0	2003#	15,999,050.4
1977#	16.2	1986+	492.7	1995	80,677.2	2004#	23,727,253.7
1978#	23.7	1987+	779.1	1996	160,623.4	2005#	35,188,499.0
1979#	33.3	1988	1,769.9	1997	338,061.4	2006♦	52,186,000.0
1980+	55.4	1989	2,435.9	1998	694,338.2	2007#	77,393,997.3

Sources: No symbol: (127-138), #: Estimate of constant growth rate, ♦: (153, 154), +: Estimate based on data on number of devices and their performance

For the estimates on the capacity used by different types of computer systems, we consider the data given by Porter (127-138) concerning the percentage of hard disks sent to computer manufactures for each type of computer (PCs, mainframes, servers and others), and the average capacity of each respective category. The years without data (1988, 1992, 1994, 1995, 1997, 1999, 2001) were estimated in a linear manner; and as for the period of 2003-2007, the estimations were based on diverse estimates from (153, 154), IDC (155) and Coughlin (147) (Fig. S C-13).

Fig. S C-13: Hard disk storage capacity distribution, in MB, without normalization by compression (hardware capacity) in different areas of application (with accumulation).



Source: Authors' own elaboration based on (127-138, 147, 153-155).

## Personal Computers

**Table S C-45: Capacity sent for personal computers in [TB].**

Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]
1980	6.2	1989	1 359.4	1998	564 450
1981	13.7	1990	1 788.6	1999	1 209 626
1982	19.7	1991	2 387.7	2000	2 948 856
1983	33.4	1992	4 336.9	2001	4 528 747
1984	50.8	1993	8 330.9	2002	8,338,167
1985	76.0	1994	21 165.3	2003	12,106,560
1986	164.4	1995	58 351.9	2004	17,569,998
1987	325.1	1996	129 224.2	2005	25,486,757
1988	863.1	1997	273 398.5	2006	36,952,171
				2007	53,547,326

Sources: *No symbol*: Estimation based on (127-138, 147, 153-155).

## Mainframes

Most available statistics stopped tracking mainframes after 2002. We assume that the remaining number of mainframes was incorporated into statistics on mid-range and high-end enterprise servers. We therefore often group mainframes with servers.

**Table S C-46: Capacity sent for mainframes [TB].**

Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]
1980	33.9	1989	503.2	1998	25 551.7
1981	40.6	1990	741.8	1999	32 425.8
1982	48.1	1991	895.0	2000	31 112.0
1983	84.1	1992	1480.1	2001	35 741.4
1984	132.2	1993	2 553.4	2002	39 327.9
1985	203.9	1994	4 288.5	2003	-
1986	216.6	1995	7 123.5	2004	-
1987	276.1	1996	7 469.5	2005	-
1988	496.5	1997	14 080.8	2006	-
				2007	-

Sources: *No symbol*: Estimation based on (127-138, 147, 153-155).

## Servers

**Table S C-47: Capacity sent for servers [TB].**

Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]
1980	14.5	1989	572.6	1998	102 866.0
1981	16.9	1990	1 192.5	1999	149 815.3
1982	20.6	1991	1 423.4	2000	213 617.0
1983	35.6	1992	2 326.2	2001	753 739.6
1984	55.2	1993	3 960.0	2002	2,323,938
1985	84.1	1994	7 494.8	2003	3,446,496

1986	111.4	1995	15 178.2	2004	5,111,296
1987	177.0	1996	23 919.8	2005	7,580,263
1988	409.0	1997	50 213.7	2006	11,241,844
				2007	16,672,120

Sources: *No symbol*: Estimation based on (127-138, 147, 153-155).

*Others (external, portable, etc)*

**Table S C-48: Capacity sent for other computation systems [TB].**

Year	Capacity [TB]	Year	Capacity [TB]	Year	Capacity [TB]
1980	0.8	1989	0.7	1998	1 470.8
1981	3.2	1990	4.2	1999	1 566.4
1982	4.1	1991	4.7	2000	415.1
1983	4.9	1992	7.2	2001	21 772.2
1984	4.3	1993	11.3	2002	86,567
1985	1.7	1994	17.3	2003	445,994
1986	0.4	1995	23.7	2004	1,045,960
1987	0.9	1996	9.9	2005	2,121,478
1988	1.3	1997	368.5	2006	3,991,985
				2007	7,174,552

Sources: *No symbol*: Estimation based on (127-138, 147, 153-155).

### C.8.3 Content Compression

In the case of hard disks, just as for magnetic tape data, it is assumed that information that is communicated in real time (voice, video conferences, etc.) is not stored. The remaining contents are stored in accordance with the percentages shown in Table S C-56. Regarding personal computer storage and the hard disks classified as “other”, we have resolved that the content is distributed in the same way as Internet traffic was in 1986 and 1993, while in 2000 and 2007, as the average between the web and P2P<sup>23</sup>. As for servers, we will assume that they always behave in accordance with web traffic (see the content section in the notes on Internet for further details). The case of mainframes is different, as they are in general only used by large organizations (military, governmental, scientific, corporative) for critical applications for the processing of data, such as censuses and industrial/consumer statistics, the planning of business resources, and for the processing of financial transactions (156, 157). It so becomes necessary to make assumptions that depart from the context of Internet traffic. We assume that in 1986, 100% of the capacity contained text, where as in 2000 we assume two thirds as text data, and one third as images (see data from Martino Neuroimaging Center and Center for Climate Change Study at MIT in (158)).

**Table S C-49: Distribution of different contents in hard disks according by type of computational system (Personal Computers, Servers, Mainframes).**

	1986	1993	2000	2007
--	------	------	------	------

<sup>23</sup> We add the “compressed” part to audio, which turns out to bring the share of audio for PC hard-disks equal to the share of audio in P2P.

% Text	PC	100	43.1	22.9	22.9
	SV	100	43.1	43.5	34.9
	MF	100	83.3	67.7	-
% Image	PC	0	42.5	20.4	17.1
	SV	0	42.5	40.2	32.3
	MF	0	16.7	33.3	-
% Audio	PC	0	2.2	45.6	9.3
	SV	0	2.2	3.6	3.8
	MF	0	0	0	-
% Video	PC	0	2.8	8.2	50.7
	SV	0	2.8	8.0	29.1
	MF	0	0	0	-
% Compressed	PC	0	9.4	3.0	0.0
	SV	0	9.4	4.7	0.0
	MF	0	0	0	-

Source: Authors' own elaboration, based on various sources (see text).

The mainframe compression factors are considered to be equal to those for the PC and "others", given that in both cases the type of compression that is usually used causes minimal losses. In general a very good quality is seen, with the exception of servers, which store web content. Here, a higher compression factor is applied for web images of medium quality (Table S C-71).

Table S C-50: Compression factors for different types of PC and server content.

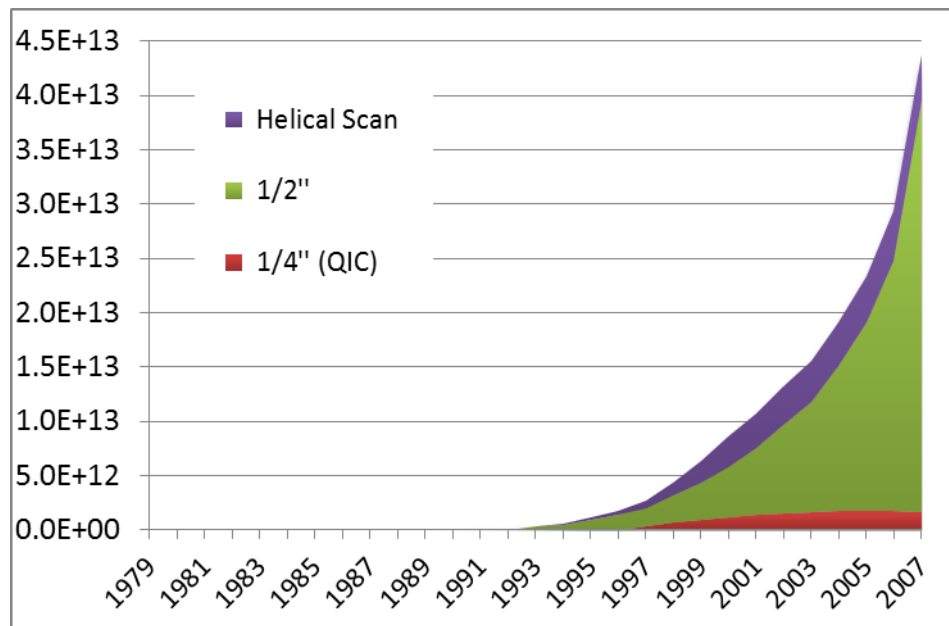
		1986	1993	2000	2007	Optimal
Text	PC = SV	2.2	2.9	4.6	4.7	6.6
Image	PC	1	7	8.5	11.3	16
	SV	1	7	14.3	27.6	48
Audio	PC = SV	1	1	6.8	6.8	12
Video	PC = SV	1	20	27	60	60
Compressed	PC = SV	2.2	2.9	4.6	4.7	6.6

Source: Authors' own elaboration, based on B Compression.

## C.9 Magnetic Data Tapes

These tapes are mainly used for the backup of data, and are often put together in what are called *Tape Libraries* (Fig. S C-14).

Fig. S C-14: The total storage capacity provided by digital data storage tapes, in [MB], without normalization by compression (capacity hardware).



Source: Authors' own elaboration, based on various sources (see text).

### C.9.1 Data Tapes: quantity

The data tapes considered include: QIC (Data Cartridge and Minicartridge/TRAVAN); Tapes and cartridges of 1/2" [DEC 1/2" 1/2" Reel, format IBM (3480, 3490E, 3590); and Sun-StorageTek/Imation format (9840); DLT/SDLT; LTO; *helical scan tapes* (8 mm and 4 mm DAT). The quantity of units sold per year comes from different sources, among them the following: (139-144, 159-166). These list the number of units sold for 1990 and 1991 (all models except: DLT and IBM 3590, which were estimated in a linear fashion, keeping in mind the year they were both introduced to the market (1984)), 1998 – 2001 (all models with the exception of, 1/2" Reel<sup>24</sup>) and for 2002 (all models). For the period from 2003-2005, the estimate was made using the percentages represented by each model's total in 2002; while in 2007 the participations of the market reported by (167) were used (Table S C-51). A 10 year shelf life is assumed (168), twice that of a hard disk.

Table S C-51: Total quantity of data tapes sold worldwide, in millions.

<sup>24</sup> While this tape model began to be sold in 1969, the data is only available from 1990 and already shows a clear decrease. Because it is impossible to know how it performed before this time, (for example, it is not known in which year the tape hit its highest sales), it is not possible to make a realistic estimate. Following this logic, we only consider the data from 1990 forward.



		1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
	data														
<b>1/4"</b> <b>(QIC)</b>	cartridge	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5	15.0	16.5	18.0	19.5	20.4
	minicartr. /travan	0.4	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.2	3.5	3.9	4.2	5.8	7.7
	DEC 1/2"														
	cartridge	-	-	-	-	-	-	-	-	-	-	-	2.5	2.3	2.1
	1/2" Reel	-	-	-	-	-	-	-	-	-	-	-	23.7	20.8	18.1
	DLT	0.0	0.0	0.0	0.0	0.0	0.7	1.3	2.0	2.7	3.4	4.0	4.7	5.4	6.0
<b>1/2"</b>	3480/ 3490e	0.0	0.0	0.0	0.0	0.0	5.6	11.1	16.7	22.2	27.8	33.3	38.9	37.6	32.6
	9840	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3590	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3
	LTO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	<b>Helical</b>	8mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.6	2.7	4.3
<b>scan</b>	4mm DAT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	1.3	2.9
<b>Data Cassette</b>		-	-	-	-	-	-	-	-	-	-	-	1.9	2.2	2.4
<b>TOTAL</b>		1.8	3.7	5.5	7.4	9.2	17.5	25.7	33.9	42.1	50.9	59.8	96.8	98.6	97.7

		1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
	data															
<b>1/4"</b> <b>(QIC)</b>	cartridge	18.0	15.6	13.2	10.8	8.4	6.0	5.9	6.2	6.1	4.3	3.5	2.7	1.9	1.1	0.4
	minicartr / travan	9.4	11.1	12.8	14.5	16.3	18.0	15.5	11.1	11.7	6.0	4.9	3.8	2.7	1.6	0.6
	DEC 1/2"															
	cartridge	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1/2" Reel	16.2	14.4	12.6	10.8	9.0	7.2	5.4	3.6	1.8	0.0	0.0	0.0	0.0	0.0	0.0
	DLT	6.7	7.4	8.1	8.7	9.4	10.1	12.6	17.1	12.8	10.5	9.4	8.4	7.3	6.3	5.5
<b>1/2"</b>	3480/ 3490e	29.5	26.4	23.3	20.2	17.1	14.0	7.9	4.7	1.8	0.9	0.8	0.7	0.6	0.5	0.3
	9840	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.1	1.4	1.5	1.4	1.2	1.1	0.9	0.5
	3590	1.5	1.6	1.8	1.9	2.1	2.2	2.9	3.2	3.2	3.4	3.0	2.7	2.3	2.0	1.2
	LTO	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.2	6.3	6.8	5.0	9.3	10.7	20.0	30.0
<b>Helical</b>	8mm	5.9	7.5	9.0	10.6	12.2	13.7	14.4	15.7	2.9	2.8	2.8	2.7	2.7	2.7	0
<b>scan</b>	4mm DAT	6.6	10.4	14.1	17.8	21.5	25.2	24.8	25.4	22.7	18.7	18.8	18.8	18.9	18.9	11.5
<b>Data Cassette</b>		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<b>TOTAL</b>		93.8	94.3	94.9	95.4	95.9	96.5	90.1	89.3	70.7	54.8	49.5	50.3	48.2	54.1	50.0

Source: Authors' own elaboration, based on various sources (see text).

## C.9.2 Data Tapes: performance

The performance of data tapes is shown in the following tables. The estimate is in agreement with the total capacity of TB shipped reported by (167).

Table S C-52: Storage capacity of 1/4" tapes (QIC), in [GB].

	1979-	1989-	1991-	1993-	1996	1997	1998-
--	-------	-------	-------	-------	------	------	-------

	1988	1990	1992	1995		2007	
Data Cartridge	0.02	0.11	0.24	0.50	0.97	4.13	10.53
Minicartridge/TRAVAN	0.02	0.11	0.21	0.87	2.47	7.67	15.33

Sources: Authors' own elaboration based on (169, 170)

Table S C-53: Storage capacity of ½" tapes in [GB].

	1979- 1986	1987- 1988	1989- 1990	1991- 1992	1993	1994- 1995	1996- 1997	1998- 2001	2002- 2003	2004- 2007
DEC ½"	0.13	0.26	0.26	1.01	2.30	2.30	2.30	2.30	2.30	2.30
½" Reel	0.18	0.18	0.18	0.23	0.23	0.23	0.23	0.23	0.23	0.23
DLT	0.10	0.20	1.00	2.97	6.20	12.00	21.67	55.00	101.67	190.00

Sources: Authors' own elaboration based on (171-174)

Table S C-54: Storage capacity of IBM and StorageTek\* tapes in [GB].

	1984- 1985	1986- 1988	1989- 1990	1991- 1992	1993- 1994	1995- 1999	2000- 2001	2002	2003- 2004	2005- 2007
3480/3490e	0.20	0.30	0.47	0.93	1.60	11.33	11.33	30.80	196.67	196.67
9840*	-	-	-	-	-	50.00	55.00	103.33	103.33	103.33
3590	-	-	-	-	-	30.00	30.00	45.00	45.00	96.67
LTO	-	-	-	-	-	100.00	100.00	100.00	150.00	233.33

Sources: Authors' own elaboration based on (171-174)

Table S C-55: Storage capacity of HelicalScan tapes en [GB].

	1987- 1988	1989- 1990	1991- 1992	1993	1994- 1996	1997	1998	1999- 2007
8mm	2.40	2.45	3.30	5.83	5.83	11.67	21.67	35.00
4mm DAT	-	1.30	1.65	1.65	2.43	9.00	9.00	12.00

Sources: Authors' own elaboration based on (175-180)

### C.9.3 Content Compression

Regarding servers, we can assume that they behave about the same as web content (see Table S C-56). The compression methods used are between the quality of servers (highly compressed for web content) and PCs (less compressed, which is to say, higher quality).

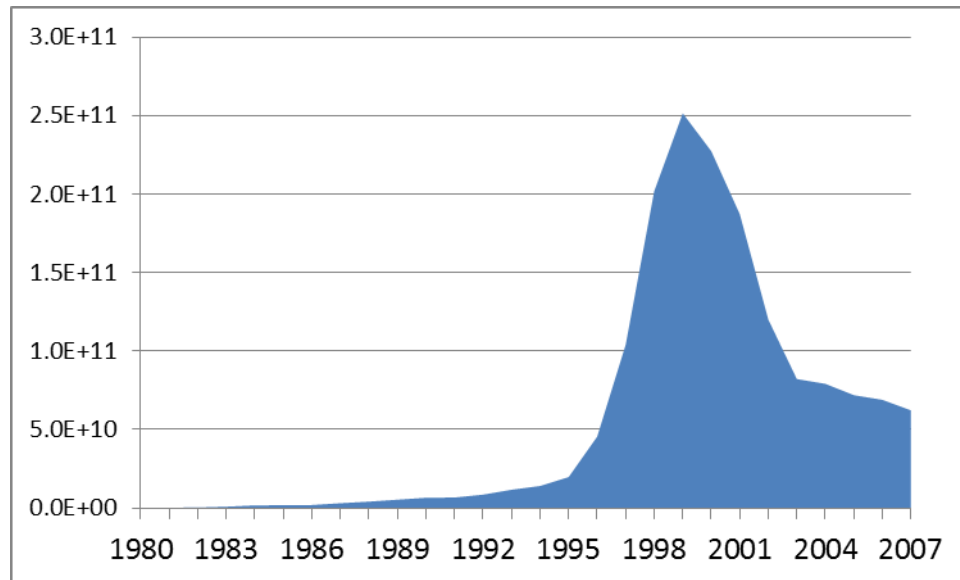
Table S C-56: Compression factors for different types of digital tapes by content.

	1986	1993	2000	2007	Optimal
Text	2.2	2.9	4.6	4.7	6.6
Image	1.0	7.0	10.7	17.6	32.0
Audio	1.0	1.0	6.8	6.8	12.0
Video	1.0	20.0	27.0	60.0	60.0
Compressed	2.2	2.9	4.6	4.7	6.6

Source: Authors' own elaboration, based on B Compression.

## C.10 Flexible Disks (FD, Floppy Disks)

Fig. S C-15: Storage capacity provided by floppy disks in [MB], without compression (capacity hardware).



Source: Authors' own elaboration, based on various sources (see text).

### C.10.1 Floppy Disks: quantity

The global production of Floppy Disks is reported for the years 1990 and 1991 by (181) and for 2002-2007 by (103-108). For the years between 1969-1989 and 1992-1998, the global figure is estimated in proportion to the growth of the number of Floppy Disk Drivers indicated by Disk/Trend Report from Porter (182-191) for the years 1976 to 1998, assuming that the growth rate between such disks and their drives is similar. A linear estimation is made for the years 1998-2000. Given the fragility of floppy disks, we assume a useful lifetime of 2 years. (124, 193, 194).

Table S C-57: Global quantity of floppy disks produced (units in millions).

1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
13	26	47	86	129	231	335	800	1,215	1,101	1,478
1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1,856	2,243	2,452	2,845	3,052	3,767	4,201	4,812	5,279	5,907	6,766
1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	
8,020	6,344	4,668	2,992	1,316	1,250	987	858	764	592	

Source: Authors' own elaboration, based on (103-108, 181-191).

## C.10.2 Floppy Disks: performance

To calculate the performance of floppy disks, we have worked with the average performances of random sample disc diameters (8", 5.25", <3.5" y HC) presented in the inventory of the Disk/Trend Report for the period of 1976-2002 (182-191) (Table S C-59). They are weighted by the distribution of floppy disc readers (195), assuming that there is a similar relationship between the readers and the discs. The figures are interpolated linearly for the years 2003-2007.

**Table S C-58: Weighted capacity per floppy disk [MB].**

<b>1976</b>	<b>1977</b>	<b>1978</b>	<b>1979</b>	<b>1980</b>	<b>1981</b>	<b>1982</b>	<b>1983</b>	<b>1984</b>	<b>1985</b>	<b>1986</b>	<b>1987</b>
0.63	0.63	0.87	0.67	0.71	0.60	0.56	0.80	0.80	0,72	0,78	0,78
<b>1988</b>	<b>1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1989</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>
1.01	0.97	0.97	1.27	1.27	1.20	0.97	1.59	2.29	5,65	10,45	16,36
<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>			
18.96	22.93	26.80	30.31	33.82	37.33	40.84	44.35	47.86			

Source: Authors' own elaboration, based on (182-191, 195).

**Table S C-59: Percentage of different diameters of floppy disk readers and average capacity.**

Year	Percentage [%]				Average Capacity [MB]			
	8"	5.25"	<3.5"	HC	8"	5.25"	<3.5"	HC
1976	99.50	0.50	0.00	0.00	0.64	0.15		
1977	89.27	10.73	0.00	0.00	0.67	0.24		
1978	82.54	17.46	0.00	0.00	0.97	0.39		
1979	63.27	36.73	0.00	0.00	0.90	0.27		
1980	57.07	42.93	0.00	0.00	0.97	0.36	0.01	
1981	39.12	60.75	0.14	0.00	1.08	0.29	0.05	
1982	31.03	68.48	0.49	0.00	0.95	0.39	0.09	
1983	12.85	83.63	3.49	0.02	1.92	0.65	0.15	
1984	7.47	81.95	10.35	0.24	1.92	0.78	0.17	10.26
1985	5.24	75.26	18.93	0.58	1.92	0.58	0.41	18.20
1986	2.48	70.28	26.75	0.49	1.92	0.66	0.71	15.72
1987	1.49	55.75	42.37	0.38	1.92	0.86	1.07	13.23
1988	1.03	47.11	51.49	0.36	1.92	0.83	1.01	10.75
1989	0.64	38.71	60.37	0.28	1.92	0.83	1.48	16.08
1990	0.32	33.50	66.00	0.18	1.92	0.83	1.33	21.40
1991	0.16	31.28	68.35	0.21	1.92	0.83	1.12	21.00
1992	0.09	29.17	70.51	0.23	1.92	0.83	1.48	44.60
1993	0.04	22.26	77.39	0.32	1.92	0.83	1.48	58.45
1994	0.03	12.96	86.74	0.27	1.92	0.83	1.48	72.30
1995	0.03	6.44	92.54	1.00	1.92	0.83	1.48	86.15
1996	0.00	1.28	94.47	4.24	1.92	0.83	1.48	100.00
1997	0.00	0.17	92.26	7.57	1.92	0.83	1.48	120.00

1998	0.00	0.03	89.85	10.11	1.92	0.83	1.48	148.57
1999	0.00	0.02	86.49	13.50	1.92	0.83	1.48	131.00
2000	0.00	0.01	83.43	16.56	0.00	0.83	1.48	131.00
2001	0.00	0.00	80.46	19.54		0.00	1.48	131.00
2002	0.00	0.00	77.75	22.25			1.48	131.00
2003	0.00	0.00	75.04	24.96			1.48	131.00
2004	0.00	0.00	72.33	27.67			1.48	131.00
2005	0.00	0.00	69.62	30.38			1.48	131.00
2006	0.00	0.00	66.90	33.10			1.48	131.00
2007	0.00	0.00	64.19	35.81			1.48	131.00

Source: Authors' own elaboration, based on (182-191, 195).

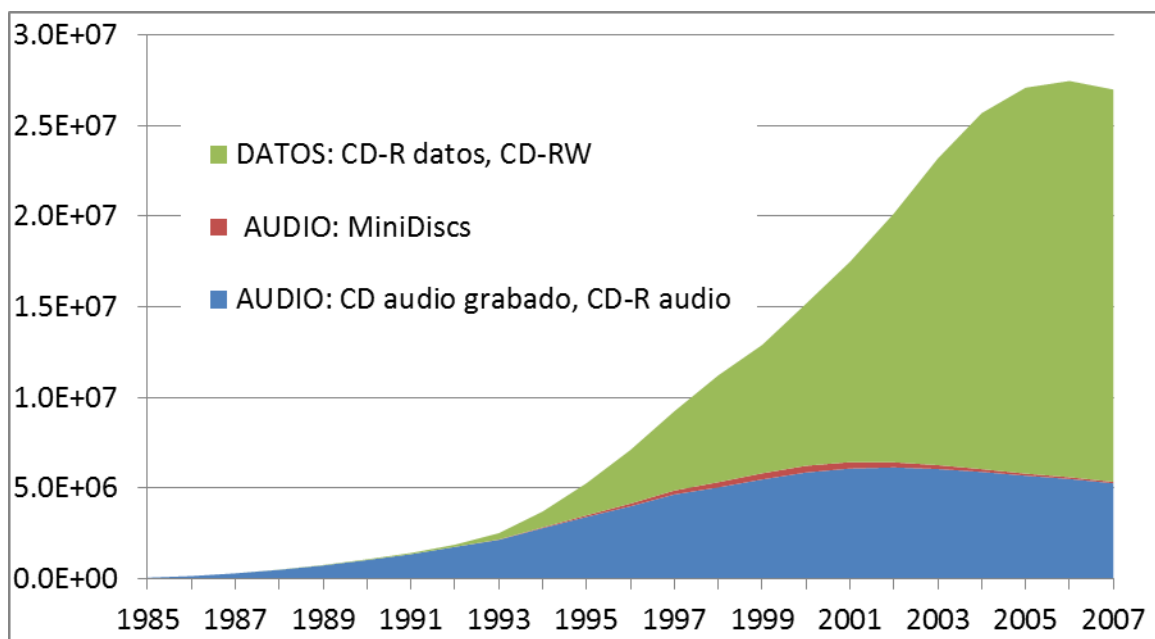
### C.10.3 Content compression

Regarding their respective compression rates, we assume that:

- Floppy disks of 8", 5.25" and <3.5" only store text. Considering their capacity, they could almost store a JPEG photograph, but not an audio or video file.
- High capacity disks (HC) can store images, text, and sound, but because of their small size, not video. For lack of a better statistics, it is assumed that these contents are distributed equitably.

## C.11 CD (Compact Disc) y MiniDisc

Fig. S C-16: Total storage capacity of CDs and MiniDiscs in [MB], without compression (capacity hardware).



Source: Authors' own elaboration, based on various sources (see text).

### C.11.1 CD and MiniDisc: quantity

The number of units sold of CDs with recorded audio content was obtained using the information reported by (89-94) (data for 70 countries, with estimates for missing countries based on the figures of neighboring countries of similar socio-economic standings, as in (196). There are also statistics on blank audio CDs and data CDs (audio CD-R; CD-R and data CD-RW, respectively), which are based on reports published by the *Japanese Recording-Media Industries Association (103-108, 197)*. These reports contain a global estimate, and individual estimates for Japan, North America, and Europe. For previous years, in the case of audio CD-Rs (1993-2001), the figures were extrapolated with the growth rate of audio CDs. To estimate the quantity of data CD-Rs and CD-RWs for the years 1985-2001, we look to the growth rate of Optical Disc Drives which is registered and estimated by Porter (192). Furthermore, some information is included on the number of Mini Discs (MDs) (103-108). For the previous period (1993-2001), estimates were made based on the growth rate of Optical Disc Drives (192).

Table S C-60: Number of CDs in millions of units.

	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Recorded audio CDs	2	31	81	154	258	376	503	671	817	1,076	1,183	1,789	1,885
Audio CD-Rs	-	-	-	-	-	-	0	0	0	0	0	1	9
MiniDiscs	-	-	-	-	-	-	-	-	-	-	101	201	302
Data CD-Rs	-	-	0	0	1	4	11	13	27	47	207	450	781
CD-RW	-	-	0	0	1	3	7	8	17	30	131	285	495
<b>TOTAL</b>	<b>2</b>	<b>31</b>	<b>82</b>	<b>155</b>	<b>260</b>	<b>383</b>	<b>521</b>	<b>693</b>	<b>860</b>	<b>1,154</b>	<b>1,623</b>	<b>2,726</b>	<b>3,470</b>
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	
Recorded Audio CDs	2,071	2,262	2,384	2,499	2,556	2,441	2,324	2,213	2,186	2,055	1,981	1,819	
Audio CD-Rs	25	60	84	150	210	262	246	285	303	289	273	263	
MiniDiscs	402	540	666	687	599	411	219	206	196	144	107	98	
Data CD-Rs	1,040	1,396	1,722	1,777	3,270	4,500	6,120	6,940	7,683	7,144	7,015	6,771	
CD-RW	659	885	1,091	1,126	982	674	359	327	303	290	243	201	
<b>TOTAL</b>	<b>4,198</b>	<b>5,143</b>	<b>5,946</b>	<b>6,239</b>	<b>7,618</b>	<b>8,288</b>	<b>9,268</b>	<b>9,971</b>	<b>10,671</b>	<b>9,922</b>	<b>9,619</b>	<b>9,152</b>	

Source: Authors' own elaboration, mainly based on (89-94, 103-108, 197).

In technical terms, some sources argue that CDs have a useful life of more than 20 years if properly kept (198), but experts insist that the real shelf life is between 2 and 5 years (199, 200). We will assume a lifetime of 4 years, a little less than that of hard-disks.

### C.11.2 CD and MiniDisc: performance

CDs have a performance of 730 [MB], which corresponds to 700 [MiB]. For MiniDiscs, we consider a performance of 150 [MB], which makes 143,05 [MiB]<sup>25</sup>. CDs with recorded music frequently do not use all of this potential. Considering an average of the most-sold recorded music CDs from the years 200-2005, we consider 575 [MB] for music CDs recorded commercially.

### C.11.3 Content compression

Audio CDs store audio digitally, without using any compression algorithm. Other types of applications for CDs exist as well, which do use compression; for example, VCD (MPEG-1), SVCD (MPEG-2), PicturD-CD (JPEG) and CD±R (various, depending on the user), but as only separate statistics are available for audio CDs (recorded and to be recorded) and data CDs (-R and-RW), it is assumed that:

- Audio CDs and MiniDiscs only store audio
- CD-Rs and CD-RWs can store any kind of content, distributing it the same way as do PCs (see Table S C-49).

Table S C-61 reports the compression factors considered for audio CDs and MiniDiscs. For data CD-R and CD-RWs, we can assume the same compression rates as PC (Table S C-50).

**Table S C-61: Most common compression factors of CD and MiniDisc.**

		1986	1993	2000	2007	Optimal
CD Audio <sup>26</sup>	Sound	1	1	1	1	9.6
MiniDisc	Sound	-	5 (ATRAC)	10 (ATRAC3)	15 (ATRAC3plus)	16

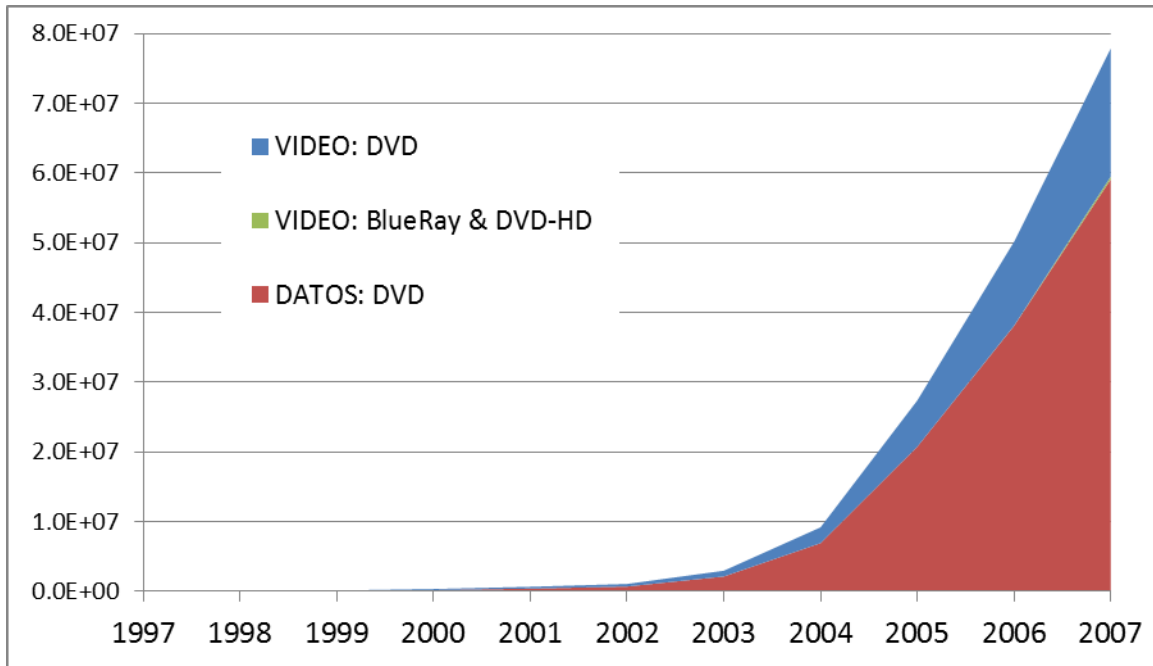
Source: Authors' own elaboration, based on B.4.3. Note: The family of compression algorithms with losses used in MiniDisc is known as ATRAC (*Adaptive Transform Acoustic Coding*); and in previous versions: ATRAC3 (1999), ATRAC3plus (2002) y ATRAC Advanced Lossless (2006) (201-203).

## C.12 DVD, HD-DVD, DVD 8cm and Blu-Ray

**Fig. S C-17: Storage capacity of DVDs and Blu-ray Disks, in [MB], without compression (capacity hardware).**

<sup>25</sup> Contrary to other storage solutions, the CD industry usually presents the capacity of devices in binary units – meaning  $2^{10} = 1024$  bits, which is referred to as kibit— and not in decimal units, which define that one kb = 1000 bits. This particularity comes from the closeness of the optical storage industry to the computer and software industry, which tends to count bits in binary units.

<sup>26</sup> These compression factors are valid for recorded audio CDs and audio CD-Rs.



Source: Authors' own elaboration, based on various sources (see text).

### C.12.1 DVD, D-DVD, DVD 8cm y Blu-Ray: performance

DVDs (*Digital Versatile Disc*) were commercialized in 1996 and have a capacity of 4.7 GB (4.38 GiB). MiniDVDs (8cm) have a capacity of 1.4 GB. For Blu-Ray Discs, we used a figure of 25 [GB] (23.28 [GiB]), while for HD-DVDs we assumed 15 [GB] (13.97 [GiB]).

### C.12.2 DVD, HD-DVD, DVD 8cm y Blu-Ray: quantity

(103-108) reports on the write-once and the re-writable DVD for the period of time of 2002-2007. The amounts for 1996 and 2001 are based on the growth rate of DVD players and recorders during that time, drawn from (204). The worldwide number of units was taken from (108), following the same logic of CDs (199, 200). Blu-Ray is mainly used for videogames (i.e. Sony's Playstation 3). A 4 year shelf life is assumed.

Table S C-62: Quantity of DVD, DVD-HD, Blu-Ray in millions.

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Video: DVD	0.6	2.7	10.3	17.9	23.3	26	109	325	943	1,165	1,431
Datas: DVD	0.6	3.1	11.2	27.5	44.6	65	318	1,044	2,989	3,750	4,791
Datas: DVD 8cm									22	43	74
Datas: DVD-HD										0.5	5
Datas: Blu-Ray										1	12
<b>TOTAL</b>	<b>1.2</b>	<b>5.8</b>	<b>21.5</b>	<b>45.5</b>	<b>68.0</b>	<b>91</b>	<b>427</b>	<b>1,369</b>	<b>3,954</b>	<b>4,959</b>	<b>6,313</b>

Source: Authors' own elaboration, based on various sources (see text)



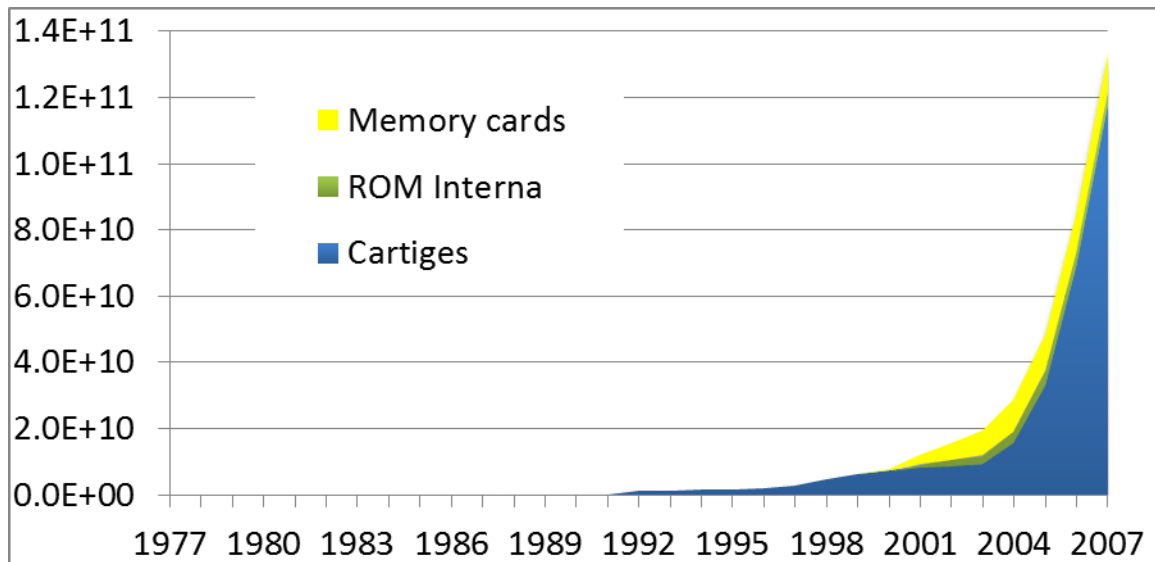
### C.12.3 Content compression

Given that we lack statistics which indicate what percentage of DVD-Rs and DVD-RWs are used exclusively in video and which may serve for all types of data, we make an estimation based on the content of their analog equivalents. Since we know that 96.5% of the compressed content of VHS and BetaMax is dedicated to video and the rest to audio, we assume the same distribution for DVD. As for DVD video content, we use the compression method of MPEG-2 with a compression rate of 41.1:1 (for 2000 and 2007) and for the optimum level we will assume MPEG-4, with a compression factor of 60. In audio we suppose factors of 5.36 for 2000 and 2007 (excellent MP3 quality) and 9.6 for optimal compression (excellent MPEG-4 quality). For all types of data on DVDs, we assume the same content as for PCs (Table S C-49), as well as the same compression rate (Table S C-50). As for Blu-Ray discs and HD-DVDs that are not videogames, we assume that the complete number sold are video “originals” and therefore, the compression algorithm that is used is MPEG-4 AVC for video, with a compression rate of 12.6:1, which is also the optimal rate at this level of quality. Audio compression factors are assumed at 5.36 for 2000 and 2007 (excellent MP3 quality), and 9.6 for optimal compression (excellent MPEG-4 quality).

## C.13 Video-Game Consoles

The storage technology used by video-game consoles considered is broken up into two groups: those that store only games (mainly cartridges in this section, given that optical devices are already included in the respective sections on CD and DVD), and those that store another type of information directly linked to the console (mainly ROM memories and proprietary external memories or memory cards, since hard disks and generic memory cards are already counted in the respective sections).

**Fig. S C-18: Video game storage capacity that has not been included in hard-discs and optical device sections (CD and DVD), without compression (capacity hardware).**



Source: Authors' own elaboration, based on various sources (see text).

### C.13.1 Videogame software: performance

Table S C-63 presents the different consoles included in the study with their respective storage technologies as well as their associated storage capacity. Modern day consoles support more than just one type of storage technology, such as CD-ROM, DVD-ROM, BD-ROM, and proprietary formats (like Nintendo).

Table S C-63: Storage Capacity. Video-game software.

Make	Platform	Technology	Capacity
Nintendo	Wii	Wii Optical Disc	4.7 GB
Sony	PlayStation 3	DVD & Blu-Ray-ROM	4.7 GB
Microsoft	Xbox 360	DVD & HD-DVD	4.7 GB
Nintendo	Nintendo DS	Nintendo DS Game Card	256 MB
Sony	PlayStation Portable	UMD™	1.8 GB
Nokia	N-Gage	MMC	1 GB
Nintendo	Game Boy Advance	Flash Cartridge	32 MB
Microsoft	Xbox	DVD-ROM	4.7 GB
Nintendo	GameCube	GameCube Disc	1.4 GB
Sony	PlayStation 2	DVD-ROM	4.7 GB
Sega	Dreamcast	GD-ROM	1.4 GB
SNK	Neo Geo Pocket and Neo Geo Pocket Color	Cartridge	4 MB
Nintendo	Nintendo 64	Cartridge	32 MB
Sega	Nomad	Cartridge	4 MB
Sony	PlayStation	CD-ROM	730 MB
Sega	Saturn	CD-ROM	730 MB
Panasonic	3DO Interactive Multiplayer	CD-ROM	730 MB
Sega	Mega-CD	Sega CD	730 MB
Nintendo	Super Nintendo Entertainment System	Cartridge	4 MB
Sega	Game Gear	Cartridge	64 KB
NEC	TurboExpress	HuCard	512 KB

Nintendo	Game Boy and Game Boy Color[2]	Cartridge	64 KB
Sega	Mega Drive/Genesis	Cartridge	64 KB
NEC	TurboGrafx-16	HuCards	2.5 MB
Sega	Master System	Cartridge	512 KB
Nintendo	Nintendo Entertainment System	Cartridge	512 KB
Coleco	ColecoVision	Cartridge	24 KB
Mattel	Intellivision	Cartridge	16 KB
Atari	Atari 2600	Cartridge	4 KB

Sources: Authors own elaboration, based on (204-207).

### C.13.2 Consoles: performance

For reasons of completeness, the table shows the storage capacity of a hard drive, an internal ROM memory drive, and external memory drive for each one of the systems studied. Some of the consoles, marked by an asterisk (\*), use the same memory card as other equipment. (SD, memory stick, Compact flash, SmartMedia, MMC, xD), which are included in the worldwide total reported in the respective section on Memory Cards. However, in other cases, companies have developed their own memory card formats, which were sold separately. They are considered below.

Table S C-64: Storage performance of video game consoles.

Make	Platform	HDD	Internal ROM Memory	External Memory
Nintendo	Wii	No	512 MB	*
Sony	PlayStation 3	60 GB	No	*
Microsoft	Xbox 360	60 GB	No	256 MB
Nintendo	Nintendo DS	No	256 KB	*
Sony	PlayStation Portable	No	32.7 MB	*
Nokia	N-Gage	No	3.4 MB	*
Nintendo	Game Boy Advance	No	32 MB	64 MB
Microsoft	Xbox	8 GB	No	8 MB
Nintendo	GameCube	No	40 MB	2 MB
Sony	PlayStation 2	No	4.2 MB	8 MB
Sega	Dreamcast	No	128 KB	128 KB
SNK	Neo Geo Pocket and Neo Geo Pocket Color	No	8 KB	No
Nintendo	Nintendo 64	No	64 KB	256 KB
Sega	Nomad	No	2.5 KB	8 MB
Sony	PlayStation	No	64 KB	128 KB
Sega	Saturn	No	64 KB	256 KB
Panasonic	3DO Interactive Multiplayer	No	1 MB	No
Sega	Mega-CD	No	133 KB	125 KB
Nintendo	Super Nintendo Entertainment System	No	48 KB	No
Sega	Game Gear	No	2.5 KB	No

NEC	TurboExpress	No	4 KB	No
Nintendo	Game Boy and Game Boy Color[2]	No	32 KB	No
Sega	Mega Drive/Genesis	No	512 KB	No
NEC	TurboGrafx-16	No	4 KB	No
Sega	Master System	No	128 KB	No
Nintendo	Nintendo Entertainment System	No	48 KB	No
Coleco	ColecoVision	No	No	No
Mattel	Intellivision	No	7.2 KB	No
Atari	Atari 2600	No	No	No

Sources: Authors' own elaboration, based on (204-209)

### C.13.3 Videogame software: quantity

To find the total number of gaming units, we multiply the number of consoles sold per year (see Game consoles: quantity in E.5.2) by the *tie ratios* of the consoles (the number of cartridges) which are portable (handheld) and those that are not (210-217). A shelf life of 5 years is assumed (124). It is important to take note that the total number of optical devices which store video games are reported in write-once CD and DVD in the section CDs and DVDs.

Table S C-65: Tie Ratios, number of games per console.

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Cartridge non-portable	3,3	3,3	3,3	3,3	3,3	3,7	4,0	5,0	3,8	4,9	5,5
	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Cartridge non- portable	5,8	6,0	5,6	5,9	6,0	5,6	6,2	5,1	5,3	4,7	4,1
Cartridge - portable	-	4,8	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,8	4,1
	1999	2000	2001	2002	2003	2004	2005	2006	2007		
Cartridge non- portable	4,7	4,8	5,8	5,8	-	-	-	-	-		
Cartridge portable	5,2	4,4	1,8	2,3	-	-	-	-	-		
Flash Cartridge portable	-	2,6	2,8	3,8	4,3	3,7	5,6	5,8	4,8		

Source: Authors' own elaboration based on (210-217).

### C.13.4 Consoles: quantity

Just as we presented in Table S C-64, video game consoles have only a hard drive or a ROM memory (332); in the case of memory cards, we can assume that every console sold (see E.5.2) has one of them (218). A shelf life of 5 years can be assumed (124). Regarding hard disks, the total used for the consoles can be found in the section on disk drives.

### C.13.5 Content compression

There are five different types of storage devices used by consoles. Since no information is available on how different types of information are distributed on them, we can presume that the device contains all content types. These are distributed out equally on the PC (see Table S C-49). If the content is less diverse, the storage capacity will be divided equally (see Table S C-66). Finally, for compression factors used (Table S C-56) the same rate as for digital tapes is assumed.

**Table S C-66: Assumptions about the distribution of content storage devices used by video game consoles.**

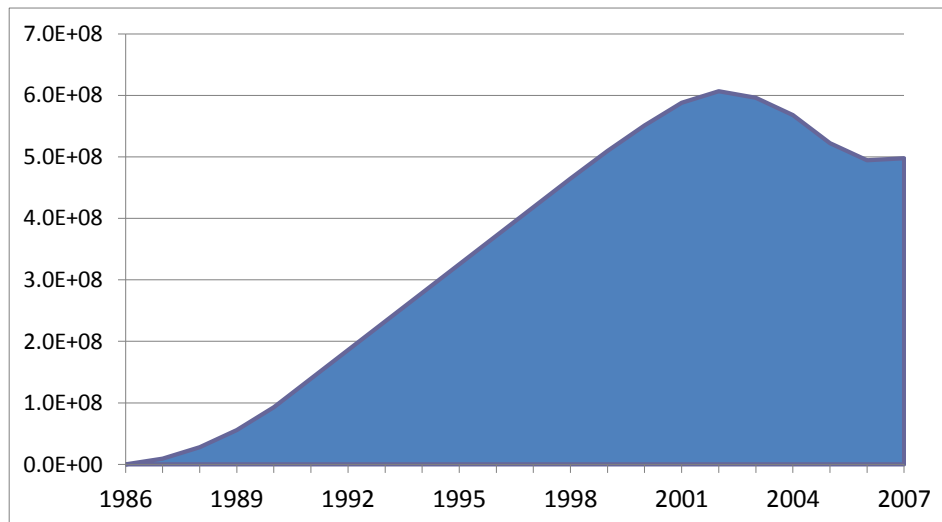
	1986	1993	2000	2007
HDD	-	-	-	All equals to PC
Memory Card	Text	Text	Text + Image	Text + Image
ROM- Internal	Text	Text	Text	Text
Cartridge	Text + Image + Sound	Text + Image + Sound	Same as PC	Same as PC
Optical	-	Same as PC	Same as PC	Same as PC

Source: Authors' own elaboration, based on B Compression.

### C.14 Chip Card

*Chip Cards* are used for identification purposes, as in credit cards, consumer aspects, mobile phone SIM cards and in the encryption of personal information. Use of plastic cards with identification information dates back to the early 1950s, when Diners Club began to give out magnetic cards for commercial transactions (219). For lack of information on the subject we only considered cards with integrated circuits that operated inside the card and whose use began in 1986 (220).

**Fig. S C-19: Chip card storage capacity in, MB, without compression (capacity hardware).**



Source: Authors' own elaboration, based on various sources (see text).

### C.14.1 Chip cards: performance

The average capacity of chip cards manufactured yearly is an average of the performance of different cards weighted by their importance in each area of use (Table S C-67).

Table S C-67: Percentage distribution of chip card applications and their weighted performance

	Performance [KB] (+)	1986-1998 % (*)	1999 % (+)	2000 % (+)	2001 % (+)	2002 % (+)	2003 % (+)	2004 % (+)	2005 % (+)	2006 % (+)	2007 % (+)
<b>Telecom</b>	128	77,2	77,9	86,7	82,2	77,3	77,4	76,1	75,0	70,4	43,6
<b>Healthcare</b>	128	8,6	4,0	2,3	1,8	3,5	3,2	2,8	3,2	9,5	29,7
<b>Others</b>	128	3,7	5,4	2,1	1,7	2,0	1,6	1,9	2,2	1,5	7,9
<b>Transport</b>	120	1,9	3,0	0,8	2,0	4,2	3,3	3,2	3,5	4,5	15,8
<b>Banking</b>	4	4,9	7,6	6,9	8,1	*	*	*	*	*	*
<b>Pay TV/IT</b>	4	2,5	2,1	1,2	1,4	2,0	1,8	2,4	2,1	1,8	-
<b>Royalty</b>	4	1,2	**	**	2,7	11,1	12,6	13,6	13,9	12,3	3,0
<b>Weighted performance in KB</b>		117,2	115,7	117,9	112,6	111,5	109,8	107,9	107,8	110,2	123,0

Sources: (\*) (221); (+) (222-226); Note: \*Royalty is considered together with Banking \*\* Banking is considered together with Royalty.

### C.14.2 Chip cards: quantity

The number of chip card units is reported for the years 1986 and 1999-2006 by (208, 209, 221-227). For the remaining years (1987-1998) a linear growth rate is applied. A shelf life of five years can be assumed (228, 229).

Table S C-68: Quantity of Chip Cards (thousands).

1986	1987	1988	1989	1990	1991	1992	1993
64	79,367	158,670	237,972	317,275	396,578	475,881	555,183
1994	1995	1996	1997	1998	1999	2000	2001
634,486	713,789	793,092	872,394	951,697	1,031,000	1,062,000	1,152,000
2002	2003	2004	2005	2006	2007		
1,085,000	919,000	845,000	738,000	925,000	1,010,000		

Sources: Authors' own elaboration, based on various sources, 208, 209, 221-230).

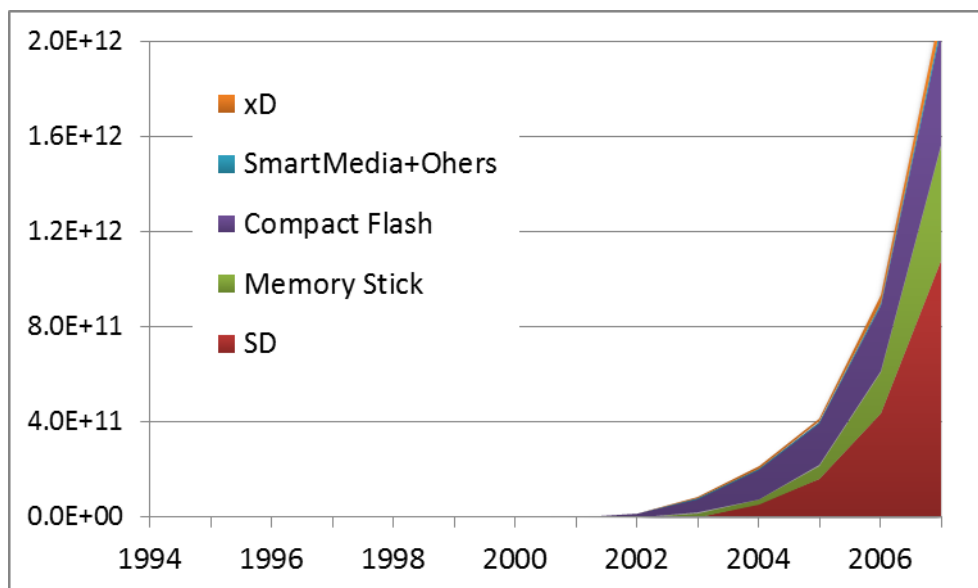
### C.14.3 Content compression

As the information which is stored is only text, the same rates are assumed as those for text compression on hard disks (Table S C-50).

## C.15 Memory Cards

Memory cards are used in many electronic devices, including digital cameras, mobile phones, MP3 players, digital picture frames, and video game consoles. The formats considered in this study are as follows (with year of commercialization): Compact Flash (1994); SmartMedia (1995); Multimedia Card (MMC) (1997); Memory Stick (1998); Security Digital (SD) y MicroSD (1999); xD (2002).

Fig. S C-20: Cumulative storage capacity provided by flash memory cards, in [MB], without compression (capacity hardware).



Source: Authors' own elaboration, based on various sources (see text).

### C.15.1 Memory Cards: quantity

To calculate the world wide number of units, we combine the figures for the total number of Memory Cards (which show six formats already included) reported by different sources (231-234) and the number of memory sticks (a special format developed by Sony (235-239)). The estimated worldwide total of units of SD, Compact Flash, SmartMedia y MMC, and xD is based upon the percentage of each format of all memory cards sold in Japan (103-108), weighting these percentages with the global total of memory cards.

Table S C-69: Memory Card manufactured worldwide.

Nº units worldwide [millions]						
year	SD	Memory Stick	Compact Flash	SmartMedia + MMC	xD	Total
1994	0.0	0.0	0.8	0.0	0.0	0.8
1995	0.0	0.0	0.9	0.6	0.0	1.5
1996	0.0	0.0	1.5	1.0	0.0	2.6
1997	0.0	0.0	2.7	1.8	0.0	4.5
1998	0.0	1.0	3.2	3.7	0.0	7.9
1999	0.2	3.0	4.3	5.2	0.0	12.7
2000	0.3	8.0	5.5	6.6	0.0	20.4
2001	0.5	10.4	9.9	12.0	0.0	32.8
2002	9.2	13.5	17.3	10.8	1.9	52.7
2003	76.1	20.3	52.9	19.9	30.9	200.0
2004	140.5	34.5	42.8	16.4	35.2	270.0
2005	207.4	58.6	28.4	9.9	36.2	340.6
2006	278.9	99.6	34.5	12.1	44.9	470.0
2007	362.5	1144.7	39.7	13.9	51.7	541.0

Sources: (103-108, 231-239); Cursive: Authors' own estimates.

With proper care, memory cards can last up to 10 years (240-246), but the years under warranty that the manufactures offer vary between 5 and 10 years. To be consistent with other digital equipment, we will suppose a shelf life of 5 years.

### C.15.2 Memory Cards: performance

We used 77 reference models (Memory Stick: 12 models, SD: 11 models; xD: 8 models; CF: 32 models and SmartMedia/MMC/Others: 15 models) (247-285). Considering that there is more than one capacity per format, the estimation was based on the format in Japan in 2007, we make an estimation based on the distribution per capacity in Japan in 2007, which consists



of: 8.8% low performance; 23.2% medium to low performance; 25% average performance; 38% medium-high; and 5% High performance (108). The result of this estimate is shown in Table S C-70 and is in agreement with the independent estimates by Coughlin for 2006 (286).

**Table S C-70: Performance by unit of Memory Card formats**

Estimated Performance by Unit [MB]					
Year	SD	Memory Stick	Compact Flash	SmartMedia + MMC	xD
1994	0.0	0	5.5	0	0
1995	0.0	0	5.9	0.6	0
1996	0.0	0	7.7	2.0	0
1997	0.0	0	8.7	2.9	0
1998	0.0	5.7	38.7	10.7	0
1999	8.0	19.6	72.1	19.4	0
2000	31.5	21.6	137.9	22.5	0
2001	43.1	24.4	222.2	30.8	0
2002	85.9	43.0	479.7	38.8	32.2
2003	240.1	226.0	939.2	60.7	92.7
2004	379.8	371.3	1 552.9	147.7	123.4
2005	890.0	650.0	1 867.9	289.2	188.7
2006	1 297.0	1 196.3	2 927.1	510.8	334.6
2007	2 396.6	2 367.8	4 856.0	818.5	600.4

Source: Author's own elaboration based on (108, 247-286).

### C.15.3 Content compression

Memory cards are used for storage purposes in many different kinds of devices, such as mobile phones, PDAs, digital cameras (video and photography), digital media players, handheld computers, netbooks, GPS systems, video games, navigation devices, and more. Memory cards store many kinds of content, with the exception of xD memory cards, which are used mainly in digital cameras that store only images. Given that there is scarce information regarding content distribution, we assume that it is distributed in the same fashion as PCs for the years 2000 and 2007 (Table S C-49).

Regarding compression factors, the same compression factors are used in PCs as for all cards (Table S C-50) except for image cards. For these, given that after reviewing the technical specifications of 20 different camera models produced in 2000, and 86 models from 2007 (287, 288), it was seen that in 2000 only three models supported the GIF format and none in 2007 (all use JPEG), high quality JPEG and color were selected. The next table shows the compression factor used.

**Table S C-71: Compression factors for still images**

	2000	2007	Optimal

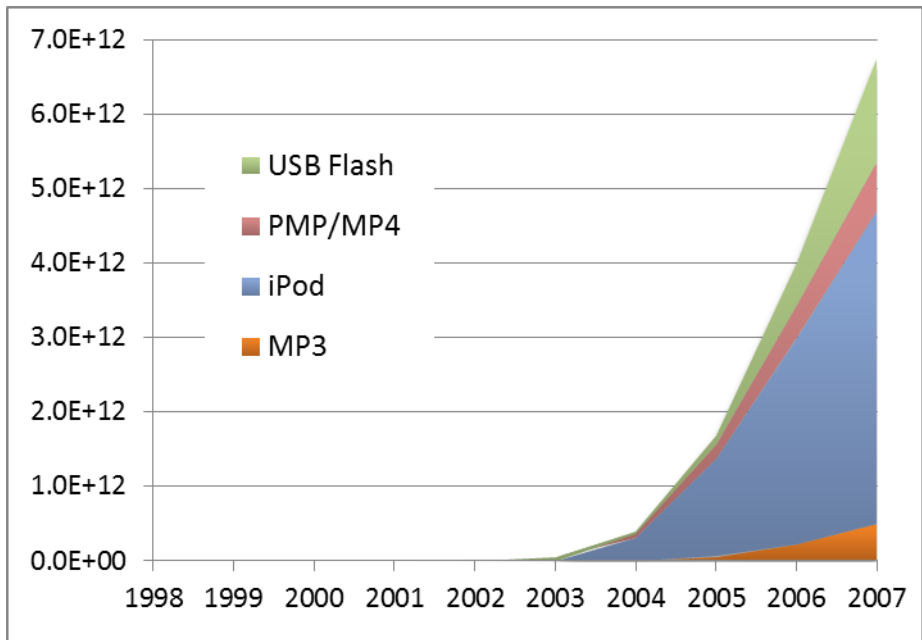
JPEG high quality	14.0	14.0	16.0
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Source: Authors' own elaboration, based on B.3.3.

### C.16 Portable Media Player and USB Flash

Portable media players and flash drives (USB flash) correspond to devices without connectivity that store information using semiconductors (just as in mobile phones and digital cameras). These are known as “flash” memories.

Fig. S C-21: Storage capacity provided by portable media players and USB flash, in MB, without compression (capacity hardware)



Source: Authors' own elaboration, based on various sources (see text).

#### C.16.1 iPod, MP3, MP4, USB flash: quantity

(204) reports the number of MP3 players sold worldwide from 2003-2006. We know the number of sold units in 1998 (289), and the increase in sales (in dollars) of Diamond Multimedia, the first company to commercially manufacture portable MP3 players. The sales are converted into units according to the average price of an MP3 player for that year (the most popular MP3 player in 1998 was the Rio PMP300, valuing US\$200 in the U.S. market (290)), and in this way we can estimate the total units sold for the period 1998-2002. iPods have a better performance than traditional MP3 players, and are reported by (291-307). MP4 players are reported by (308). Regarding USB flash pendrives, the number of units sold is

reported by (308) for the years 2005-2006; and for 2007 by (309, 310). The assumed useful lifetime of these technologies is 3 years (the same as for mobile phones (311)).

**Table S C-72: Worldwide number of manufactured portable devices (millions).**

	MP4	MP3 (without iPod)	USB flash	iPod
1998	0	0.8	0	0
1999	0	3.7	0	0
2000	0	6.6	0.8	0
2001	0	9.4	2.0	0.1
2002	0.2	11.9	5.0	0.5
2003	0.5	14.2	13.0	1.1
2004	3.4	26.7	54.0	8.3
2005	5.5	96.7	93.5	32.0
2006	9.8	172.2	150.0	46.4
2007	10.8	186.2	171.0	52.7

Sources: (289-313).

### C.16.2 iPod, MP3, MP4, USB flash: performance

The performance of MP3 players is estimated based on 9 different models. For iPod, we focus on the storage capacity that comes from flash memories, without considering those that use 2.5' inches hard drives (*microdrives*); considering 24 different models (314); for MP4 players we have based our estimations on 8 models (315); and for USB pendrives on 10 IBM models (316).

**Table S C-73: Performance of portable media players and USB flash drives in (MB).**

	MP3 (without iPod)	USB flash	iPod	MP4
1998	32	0	0	0
1999	32	0	0	0
2000	64	8	0	0
2001	64	32	5000	0
2002	128	128	15000	5000
2003	128	160	23000	5000
2004	256	384	32000	17000
2005	512	1000	32000	25000
2006	1000	3000	32000	25000
2007	1488	5000	32000	25000

Sources: (314-316)

### C.16.3 Content compression

The stored contents in each of the devices considered in this section are in agreement with the storage of the device and its area of application (Table S C-74).

Table S C-74: Types of content stored on portable devices. <sup>27</sup>

		MP3		
	PMP/MP4	(without iPod)	USB flash	iPod
1993	-	-	-	-
2000	-	Audio	Text + Image	-
2007	Audio + Video	Audio	All	All

Source: Authors' own elaboration.

For devices that only use two types of content, we assume that each occupies 50% of the total capacity. For devices that are used to store all kinds of contents, we can assume that they are spread out just as the contents in a PC (see Table S C-49). With regard to compression rates, those used are shown in Table S C-75.

Table S C-75: Compression rate by content, per year.

	1993	2000	2007	Optimal
Text	2.9	4.6	4.7	6.6
Image	7.0	8.5	11.3	16.0
Audio	-	6.8	6.8	12
Video	-	-	60.0	60.0

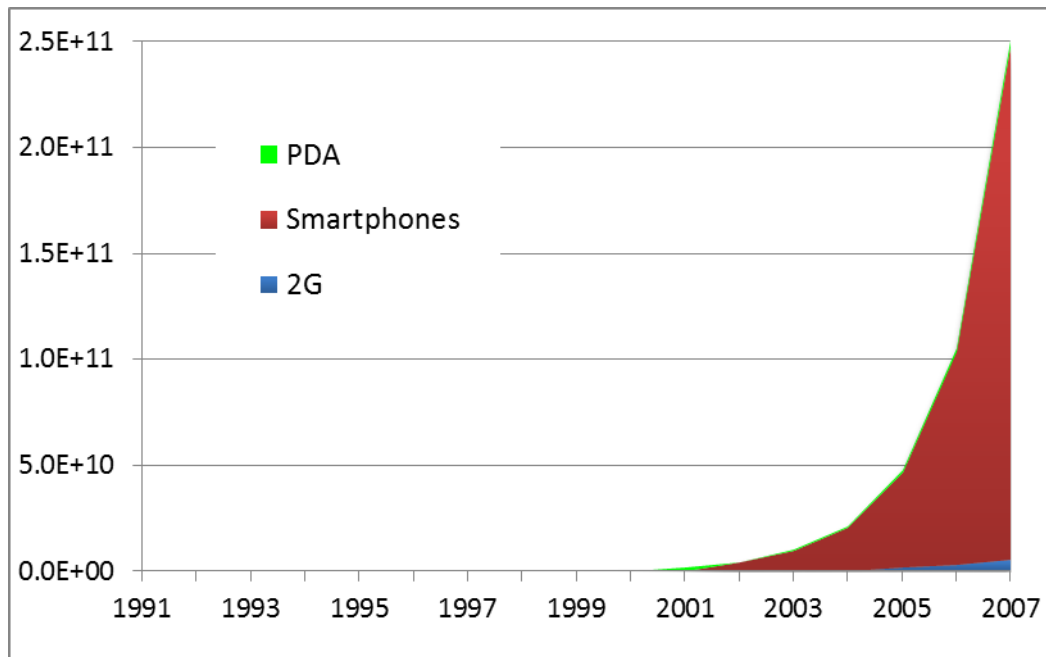
Source: Authors' own elaboration, based on B Compression.

## C.17 Mobile Telephones and PDA

Besides the use of memory cards, mobile phones have a memory space (Flash, mainly), used primarily for storing configuration codes, but also used for storing messages, sounds, and games. This type of internal memory has gained importance with PDA devices (personal digital assistant) and so-called Smartphones.

Fig. S C-22: Storage capacity of mobile telephones, in MB, without compression (capacity hardware).

<sup>27</sup>. "All" refers to: text, images, sound, video, and compressed files.



Source: Authors' own elaboration, based on various sources (see text).

### C.17.1 Mobile telephones: quantity

We have obtained the number of units of mobile phones using the figures indicated in (149). We apply the same distinction between users of 2G, 2.5G and 3G as identified in the section D.6.1 (Mobile telephony: Quantity). By definition, mobile phones of 2.5G and 3G can be considered smartphones. The number of PDAs and hand-held computers was obtained from (317-320) (Table S C-76). These devices have a shelf life of 3 years (311).

Table S C-76: Number of sold PDAs (millions)

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998
#	0.01	0.02	0.03	0.05	0.10	0.17	0.39	0.92	2.12

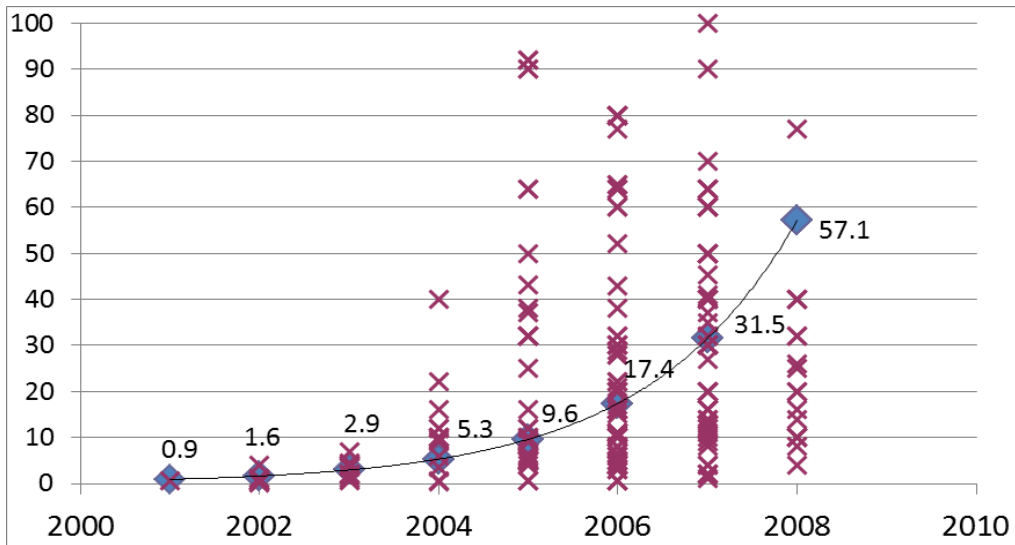
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
#	4.93	11.43	11.85	12.29	12.75	13.12	13.52	13.96	14.56

Source: (317-320).

### C.17.2 2G Mobile phones: performance

We have considered 234 models of 2G mobile phones from the four principal providers at the worldwide level: Nokia, Samsung, Motorola and Sony Ericsson (who dominate more than 75% of the global market) (321-323). Based on this data, we estimate an exponential trend between 2000 and 2007. We estimate the previous years (1992-1999) on basis of the smallest performance found among the data collected: the Motorola V70 from 2002, which has 0.15 [MB].

Fig. S C-23: Cellular phone storage performance in [MB] (n=234) (hardware capacity)

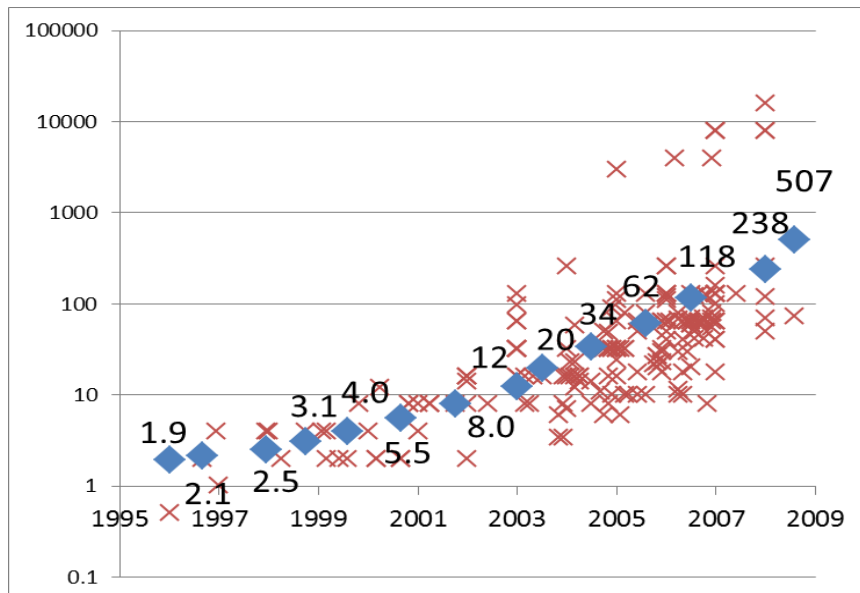


Sources: Authors' own estimation based on (321-323). Note: The figure does not show the 22 cellular phones that have a storage capacity higher than 100MB.

### C.17.3 Smartphones (2.5G y 3G) and PDA: performance

The results from the trend line are based on 197 models of PDAs and smartphones (324).

Fig. S C-24: Storage performance of smartphones/PDA en [MB] (n=197) (hardware capacity)



Sources: Authors' own elaboration based on (324). Note: A performance of 1 MB is estimated for the years 1990-1996.

### C.17.4 Content compression

It is assumed that the type of content stored depends on the ability of the device, and its area of application. Since there is no information to indicate what percentage the content would occupy, we can say that each is distributed uniformly (with the exception of smartphones, which store all types of content). Smartphones and servers (which handle mostly web content) distribute content in the same manner (Table S C-77). With regard to compression rates, we use the same factors that were used for portable media players in Table S C-75

Table S C-77: Types of content stored on cellular phones

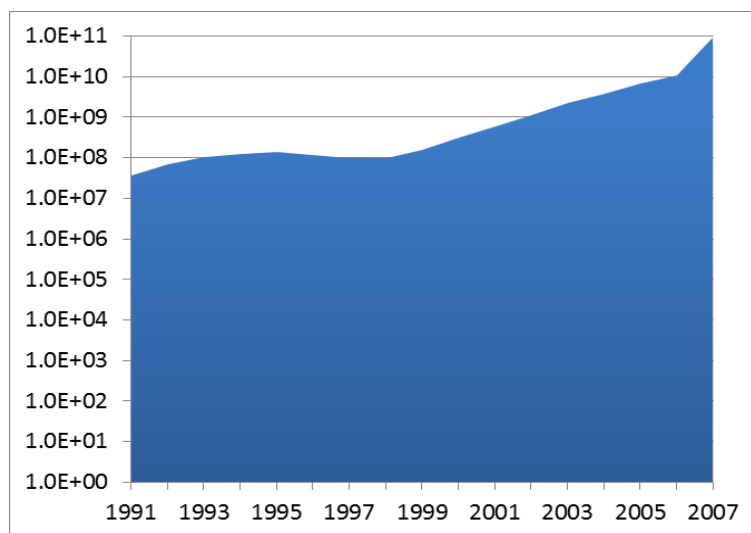
	1993	2000	2007
2G	Text	Text	Text + Photo
Smartphones/PDA	-	Text + Photo	All

Source: Authors' own elaboration

### C.18 Digital cameras and camcorders

Like mobile phones, digital cameras and camcorders use memory cards, but also employ Flash memory technology for their internal memories<sup>28</sup>.

Fig. S C-25: Storage capacity of digital camera internal memory in [MB], without compression (capacity hardware), semi-logarithmic plot.



Source: Authors' own elaboration, based on various sources (see text).

<sup>28</sup> The first digital cameras used hard disks for storage, but the emergence of memory cards and the improvements in image compression made it possible to have smaller internal memories at lower costs.

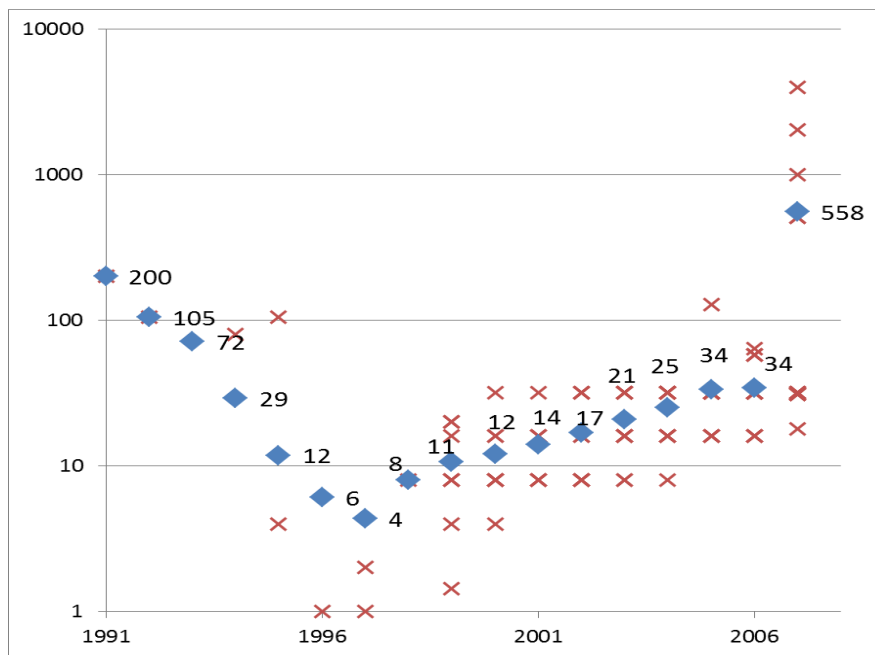
### C.18.1 Digital cameras and camcorders: quantity

We report our estimate on the quantity of digital cameras and camcorders in the E.8.2.3. Since a significant part of the camcorders does not count with any internal storage, we only consider half of the camcorders of each year to be relevant for storage.

### C.18.2 Digital cameras: performance

The average performance is estimated based on 112 models from the years 1991-2006 by the three largest manufacturers of digital cameras in the world: Canon, Kodak, and Sony (325-331). Storage capacity was extremely high during the first years, during which digital images were not yet compressed (the Kodak DCS100 of 1991 had more storage than the average PC hard-disk of those days). The subsequent fall (see Fig. S C-26) is based on the introduction of external memory during the second half of the 90s and the advancement of image compression algorithms.

Fig. S C-26: Storage performance of digital cameras (n=127) in [MB]



Source: Authors' own elaboration based on (325-331, 333)

### C.18.3 Content compression

While most digital cameras since the late 90s have included the necessary hardware to record and store video, for our studies we only consider the internal memory (whose storage capabilities are not great enough to store this type of content), where usually only high quality



JPEG images are stored. This implies a compression rate that varies between 12:1 and 16:1, assuming that 100% of the photographs have been taken in color<sup>29</sup>).

Table S C-78: Compression factors by content per year

	1993	2000	2007	Optimal
High quality JPEG	14.0	14.0	14.0	16.0

Source: Authors' own elaboration, based on B.3.3.

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<sup>29</sup> In agreement with what was reported in the previous chapter on Photography, in terms of the percentages of use of color and black and white film, the assumption is made that all photos have been taken in color. Although from 1991 to 1997, the use of black and white film represented between 5 and 9%; the downward trend in 2001 was carried forward to not exceed 3%, a negligible percentage.

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## D Communication

### D.1 General concepts

In the field of communication, a “transmission” is the act of sending information from one place to another (1), i.e., the process of sending, propagating and receiving an information signal (which may be analog or digital) over a point-to-point or point-to-multipoint, wired or wireless medium. Some technologies (such as the Internet and telephony) permit bi-directional transmissions; in other words, the receiver and transmitter may switch roles. Other technologies, such as broadcasting, are focused on the unidirectional diffusion of information. In our study, we have defined “upstream” as a process for sending information, while “downstream” refers to a process for receiving information (both regardless of who initiates the communication). We refer to the “downstream” and “upstream” capacity of communication, which refers to the flow of information, instead referring to “download” and “upload” capacity, which refers to bringing data from a remote source to local storage and storing it there (1), or “downlink” and “uplink”, which is mainly used for wireless and mobile communication. For example, in an analog broadcast channel, the “upstream” may be disregarded, whereas in a telephone channel, the size of the “downstream” and “upstream” channels are the same, so both parties could potentially speak (or sing together) at the same time, without any technological restriction whatsoever. An Internet connection will usually provide a larger “downstream” than “upstream”, since users tend to “download” more information than they send. The transmission of a letter sent by post is considered per mail (not per communication), while a telephone channel has to consider both sides of the communication.

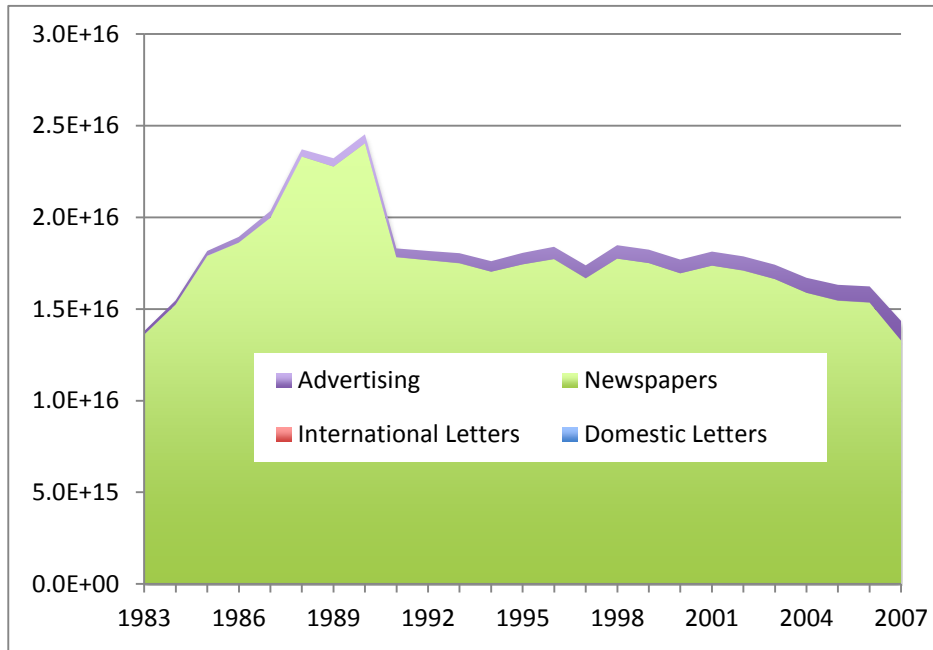
We present estimations on the quantities, performance and the respective installed capacity of four technological areas, in kilobytes per second (kbps): postal service, radio and television broadcasting (both analog and digital transmissions), telephony (fixed-line and mobile, also separated into analog and digital categories) and Internet access (wired, with dial-up, ISDN, DSL, FTTH, cable modem; and mobile (with 2G: GSM, CDMA, PDC, TDMA and e iDEN; 2.5G: GPRS, EDGE; 3G: WCDMA (UMTS), CDMA2000 1x, CDMA2000 1xEV-DO). We have also estimated the effective use of technology per year (=365.2422 days = 52.18 weeks).

### D.2 Postal Service

The following figure reports the total installed capacity in kilobits for each year.

**Figure S D-1: Transmission capacity of items sent by the postal service in [kb], without compression (hardware performance).**





Source: Authors' own elaboration, based on various sources (see text). Note: The sharp decline between the years 1990-1992 has its origins in the collapse of the Soviet Union. During this time, the mail system in this region was re-organized as each country became independent. This was a fall that could not be recovered from in terms of bits, as the simultaneous declining trend of the amount of newspapers brought down the average performance. See also Figure S D-2.

### D.2.1 Postal Service: Quantity

The amount of post sent per year by country is published by the *Universal Post Union* [UPU] (2010), who has kept statistics on the subject since the year 1980. The UPU publishes the total quantity of letter-post items by country, differentiating national traffic from international: "Letter-post items basically consist of letters, postcards, printed papers (newspapers, periodicals, advertising, etc.), small packets, literature for the blind and, as applicable in the domestic service, commercial papers, samples of merchandise, "Phonopost" items, postal packets, etc" (2).

The total of letter-post items is divided between domestic service (sent = dispatched) and international (dispatched and receipt), opting to use the quantity received for the latter (given that, interestingly, it turns out to be more complete). For international traffic we have supposed that the total consists of letters with text. For domestic traffic, we have assumed that the total of letter-post items is made up of letters, newspapers, and advertisements. We have also assumed that whatever post items are neither newspapers or advertisements are text letters. The quantity of newspapers sent is published by the UPU as well. The information reported on advertisements is less complete, and only includes data for the years 1999-2007. Estimations for the years before 1999 are based on the relation between the complete series for the United States (3, 4) and a sample of various other countries from many regions: during

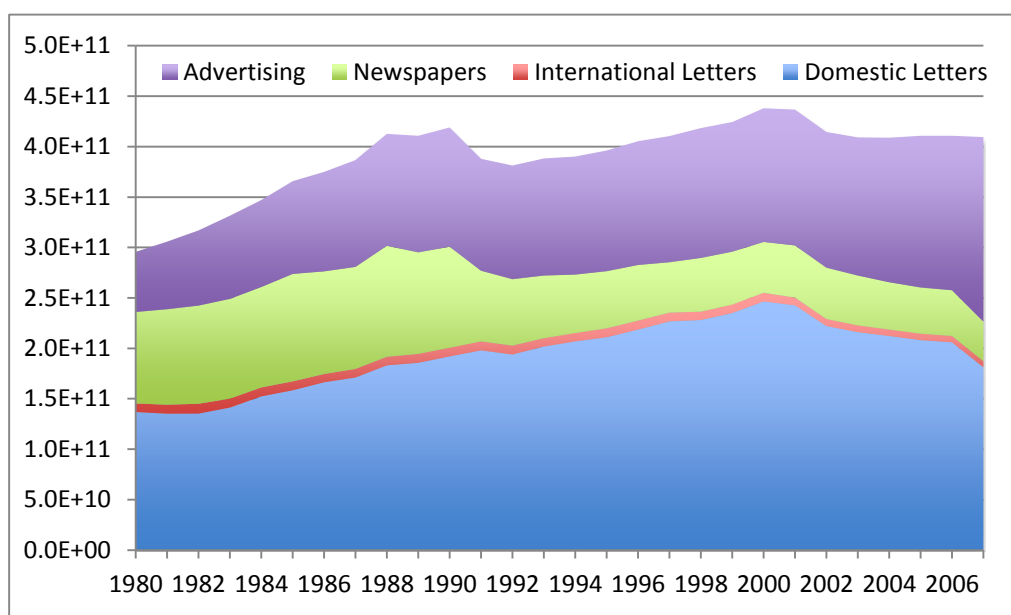
the period of 1999-2007 in the United States, 48% of all mail items were advertisements, while in the rest of the world, advertisements only made up for 37% of the total (averages of 9 years). We use this relation (year by year) to estimate the amount of advertising in the other countries for the years before 1999 (see Table S D-1).

**Table S D-1: Percentage of letter-post items that were advertising (worldwide).**

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
%	22	24	26	28	27	28	29	30	29	30	30	32	32	33
Year	1994	1995	1996	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	
%	32	33	33	33	33	33	33	35	36	38	40	40	48	

Source: Authors' own elaboration, based on (5)

**Figure S D-2: Total postal traffic (amount of shipments)**



Source: Authors' own elaboration, based on Universal Post Union (5). Note: The sharp decline between the years 1990-1992 has its origins in the collapse of the Soviet Union. During this time, the mail system in this region was re-organized. As the chart shows, it took almost a decade (between 1990 and 1998) for the quantity of worldwide shipments to return to the pre-collapse level.

The amount of postal shipments (as reported in Figure S D-2) can not be directly compared with other communication technologies, because postal mail is counted by the quantity of messages, not by the amount of established communication channels (such as for phones or the Internet). To make both somewhat comparable, we suppose that a user who sends a postal mail per working day represents "one unit of mail". We have divided the quantity of periodicals/advertisements/letters by 260.9 (5 working days per week \* 52.2 weeks/year) and have obtained what is called "units of working days of postal mail"

## D.2.2 Postal Letters: Performance

The United States tariff system supposes that the weight of a letter is 20 grams (6). Furthermore, the type of paper used is considered to be A4 (each with a weight of 3.87 grams)<sup>30</sup>, which would imply that a letter might contain up to 4 pages and an envelope. We assume that both sides of each sheet of paper have been written on. Since the vast majority of letters are not sent from homes (only about 10% each side in the United States (United States Postal Service [USPS], (7)), we may assume that they are written by machines (typewriters or computers) using the “Times New Roman font style with a text size of 12”, with 815 words on one side of the paper (8). This means that a letter would contain 6520 words (8 sides x 815 words), resulting in 35860 individual characters (considering an average of 5.5 characters per word (9)). According to the encoding used by most information programs (i.e. ASCII, American Standard Code for Information Interchange, pronounced [AS-kee], and Unicode UTF-8) 8 binary digits (one byte) are used to encode each character ( $2^8 = 256$  symbols) (10, 11). The result comes to a total of 286880 binary digits per letter. This performance is multiplied by the amount of letters sent per year. To calculate the upstream and downstream capacities, we have divided the total number of letters into two equal parts.

Although not necessary for our study, we have calculated the average speed of postal mail. For national mail, it takes on average between 3 and 5 days for a letter to arrive; while international mail takes between 8 and 10 (12-14). Considering the alternative of express mail, we opt for the lowest limit of the estimates found: 3 days for domestic mail and 8 days for international (see Table S D-2). The low bandwidth of postal mail explains its little contribution to the global technological capacity to communicate.

**Table S D-2: Bit transmission rates (bandwidth) for national and international postal mail**

	National Mail	International Mail
Letter sent by post (kilobits/second)	0.001107	0.000415

Source: Authors’ own elaboration, based on various sources (see text).

### D.2.3 Newspapers: Performance

To calculate the performance of newspapers, we have kept the same assumptions made for storage technology (see Appendix C, section 1.1). Using samples taken from the New York Times (from between 1975-2005), we assume that the performance of a newspaper depends on the year of its publication, the amount of images and text, and the quality of the images. Therefore, the values in Table S D-3 are achieved by multiplying 60 [pages/periodical] with the number of periodicals published per year. The average of 60 pages was obtained by comparing the number of periodicals sent with the statistics on produced (stored) newspapers (the number of produced periodicals should be higher, since they are also sold at newsstands<sup>31</sup>). We consider the total of periodicals as downstream capacity.

<sup>30</sup> In Table S C-4, Appendix C.

<sup>31</sup> The New York Times has an average of 85 pages per edition (see Table S C-2 in Appendix C, section 1.1.2), but this assumption would mean that more periodicals are sent than are produced. We suspect that the New York Times is an extraordinarily extensive newspaper, in comparison with many local newspapers, which are less page-intensive.

Table S D-3: Kilobits per printed page in periodicals (incl. images and text), without compression (hardware performance).

1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
1,616	1,621	1,625	1,629	1,633	1,638	1,642	1,904	2,163	2,419	2,672
1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
2,921	3,167	3,410	3,649	3,884	4,117	4,345	4,570	4,792	5,010	5,224
1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
5,434	5,448	5,461	5,475	5,488	5,502	5,516	5,529	5,543	5,556	5,570

Source: Authors' own elaboration, see Appendix C.

## D.2.4 Advertising: Performance

Many different types and sizes of mail are used for the purpose of advertising (15-17), which is also sometimes called “direct mail” (2). In agreement with (18), the formats of direct mail in the United States are as follows: 51% are letters in envelopes, 16% are post cards, 22% are self-mailers, with the remaining 11% being made up of other types, such as posters or free samples. For lack of better information, we assume that printed advertisements in envelopes (with the recipient’s address, such as advertisements for businesses and banks) make up for half of all direct mail; with the other half being composed of self-mailers (without addresses). For advertisements in envelopes (with address), we adopt the same estimations as were made for postal mail letters. While it is assumed that mail letters include about 4 pages, advertisements have only two, with writing on both sides (19). So we obtain a total of  $3260 \times 5.5 = 14930$  characters, coming to 143440 bits. As for self-mailers, they are nothing more than pieces of sturdy pre-folded paper, or else pamphlets or flyers which do not require any envelope (20). Their size is typically smaller than that of a sheet of newspaper (20-22), and the distribution of images to text depends on the content of the advertisement. We may suppose that they are designed in the same way as newspapers (two pages) but are half the size. Considering that a self-mailer consists of 4 pages of advertising, we multiply the figures from Table S D-3 by 2 [pages of newspaper], and then multiply that value with the amount of sent advertisements by year. We can consider the advertising total as downstream capacity.

## D.2.5 Compression of Content

For compression of content, we use the compression factors reported in Table S D-4. These correspond to the “optimal” factors achieved in 2007 (6.6 for text (PPMd), 16 for images in gray scale and 48 for high quality JPEG images in color), and the typical factors for the years 1986, 1993, 2000 and 2007 (for more information, see Appendix C).

Table S D-4: Compression factors

	1986	1993	2000	2007	“Optimal”
Text	2.2	2.9	4.6	4.7	6.6
Color image	1	7.0	14.0	14.0	16.0

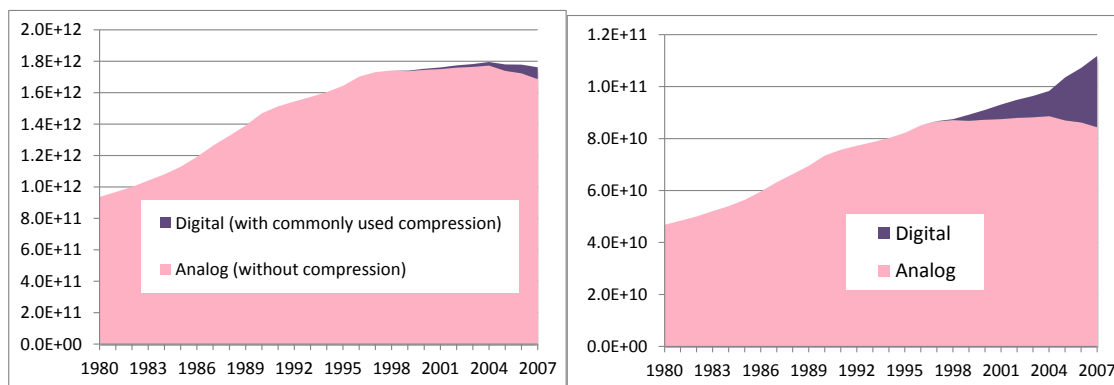
B&W image	1	4.7	4.7	4.7	6.0
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Source: Authors' own elaboration, based on B Compression.

### D.3 Radio

For the analog transmission of signals from radiostations, two forms of modulation are used: AM (Amplitude Modulation) and FM (Frequency Modulation). Of the two, FM provides a higher fidelity than AM, as it is able to minimize the noise effect. Since radio has the ability to reproduce information from a station at a given moment, it is assumed that only FM radio is transmitted, and with this we estimate the maximum installed transmission capacity. Figure S D-3(a) shows the capacity "hardware" (which reports the quantities of data "just as they are sent": digital being compressed and analog without compression) and Figure S D-3(b) normalized on optimal compression. We can see the trend of digital technologies which make it possible to send fewer and fewer "binary digits", while more "bits of information" are received. This clearly shows the importance of normalizing by rate of compression.

Figure S D-3: Transmission capacity of radio in [kbps]; (a): without compression (hardware performance); (b): normalized with optimal compression of 2007.



Source: Authors' own elaboration, based on various sources (see text).

#### D.3.1 Radio: Quantities

The total number of radio receivers for each country is registered in the database of the International Telecommunications Union [ITU] (23). For lack of information of digital radio, we make the assumption that every home that receives digital TV also receives digital radio. Specifically, we assume that for every digital television, whether it be terrestrial, cable, or satellite (see D.4.1.2), the house will have a digital radio. However, we apply this logic only for those countries that count with digital radio, from the year of its introduction (Table S D-5). This results in the estimation that in the year 2000, 2% of the world's radios received digital signals, and in 2007, 14%.

Table S D-5: Countries with DAB deployments (Digital Audio Broadcasting).

Country	Intro	Country	Intro	Country	Intro	Country	Intro
Austria	1999	Hungary	1997	Spain	2000	China	1996
Belgium	2000	Ireland	2005	Sweden	1995	India	1997
Croatia	1997	Israel	1996	Switzerland	1999	Singapore	1999
Czech Rep.	2006	Italy	1995	Netherlands	2004	South Korea	2005
Denmark	1999	Lithuania	2001	UK	1995	Taiwan	2000
Finland	1999	Norway	1999	South Africa	1999	Australia	1999
France	1997	Poland	2003	Canada	1999	Japan*	2005
Germany	1997	Portugal	1998	USA	1999	Malta	2006

Sources: (24-28))

### D.3.2 Radio: Performance

The estimate of the rate of bits per second in the transmission of an analog FM radio signal is made following Nyquist's theorem (29), which makes it possible to calculate the bit rate according to the following formula: rate of bits per second = sample rate \* number of bits per sample. Given that two channels are sent in an FM radio transmission (stereo sound), the result shown in the equation must be multiplied by two.

Table S D-6: Bit rate for the analog transmission of AM and FM radio signals.

Quality	Sample Rate [Hz = 1/s]	Sample Rate	Bit rate/channel [kbps]	Total Bit rate (stereo) [kbps]
Radio FM	22 050	16	352.8	705.6

Source: (30, 31).

Regarding digital radio, the audio signal is not only digitized, but also compressed with MPEG- Layer II with MUSICAM (Masking pattern adapted Universal Sub-band Integrated Coding and Multiplexing). This technology is applied to help reduce the rate of bits necessary for the transmission. The first implementation of these systems towards the end of the 90's in the United Kingdom and United States used a rate of 128 [kbps], providing medium to high quality audio (32). To improve quality, round the middle of the year 2000, stations in different countries increased the bit rate to 192 [kbps]. For a lack of more exact information, we suppose a linear transition between 128 [kbps] in 2000, up to 192 [kbps] en 2007. Radio is considered as downstream capacity.

### D.3.3 Compression of content

The content of radio is sound. The only difference between radio at 128 [kbps] and at 192 [kbps] is that the latter allows more redundance (less compression), therefore achieving a more robust transmission. The first achieves a compression factor of 11.025 and the second a

factor of 7.35. Using the most efficient compression available in 2007 (MPEG-4 HE-AAC), we get a factor of 20. Compressed at the optimal level, analog radio transmits 35.3 [kbps] and digital radio 70.6 [kbps], clearly showing the superior quality of the latter.

Table S D-7: Compression factors

	1986	1993	2000	2007	“Optimal”
Factor	1	1	11.025	7.35	20

Source: Authors’ own elaboration, based on B.4.3.

### D.3.4 Effective use

Estimates based on various sources are reported in Table S D-8.

Table S D-8: Effective use in hours per week.

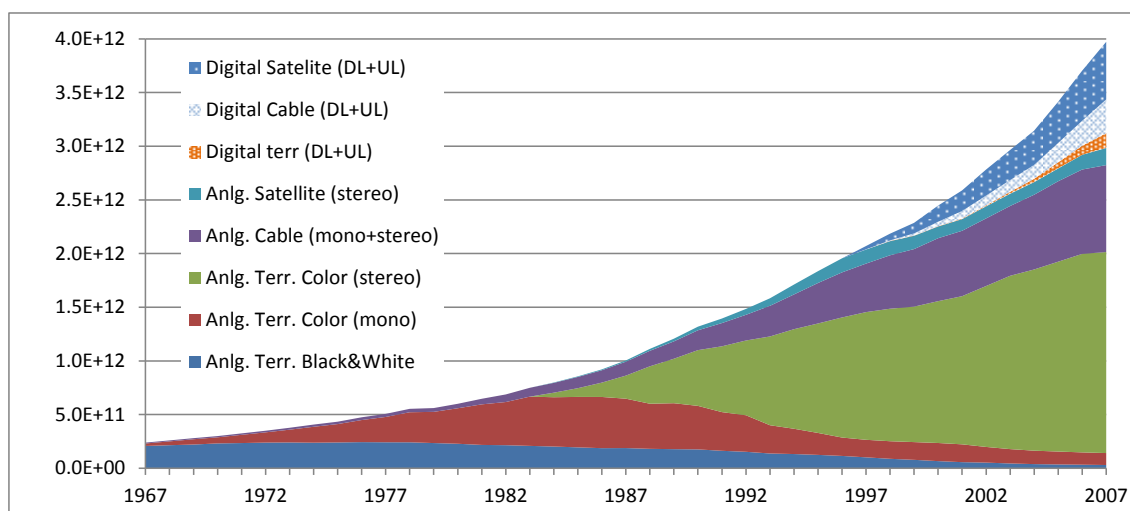
	1986	1993	2000	2007
OECD	16.8	13.9	13.2	13.2
Non OECD	28.7	23.8	22.5	18.2

Sources: Authors’ own elaboration based on (33-67). Note: the values shown for 1986 and 1993 for non-OECD countries were estimated based on the relation to OECD for the year 2000.

## D.4 Television

There are three methods of transmitting analog or digital television signals: terrestrial (or land-air), satellite or cable. The following figure reports the total installed capacity in [kbps] for each corresponding year.

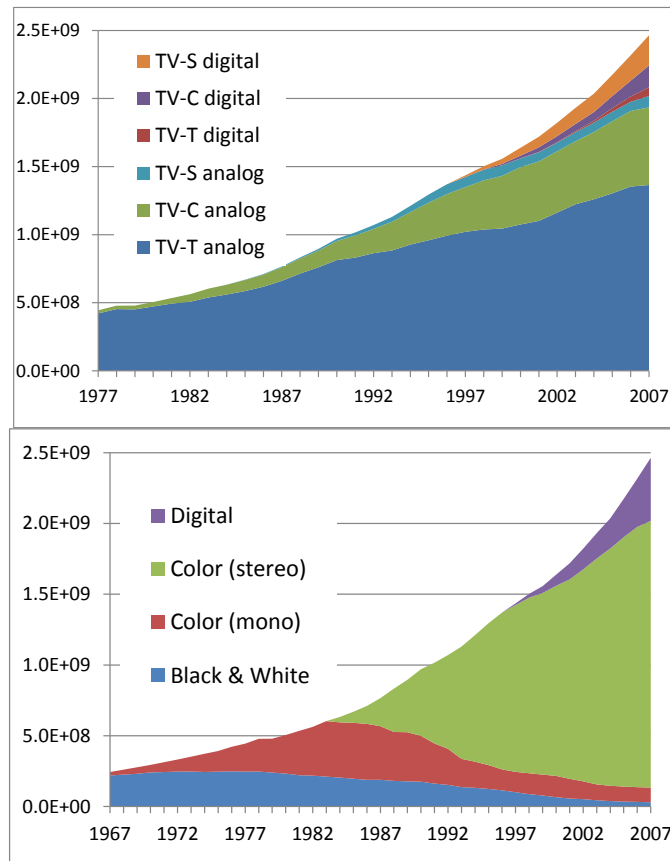
Figure S D-4: Transmission capacity of TV in [kbps], normalized with optimal entropic compression.



Source: Authors' own elaboration, based on various sources (see text).

### D.4.1 Television: Quantity

Figure S D-5: Quantity of TV receivers by technology



Source: Authors' own elaboration, based on ITU (23).

#### D.4.1.1 Analog Television: Quantity

The number of television receivers in each country for the period 1960 – 2007 is reported by ITU (23). Empty gaps are filled using linear estimates, considering the years of introduction of TV in each respective country. Monochromatic television is separated from color TV, considering the year of introduction of color TV presented in Table S D-9. Missing countries were estimated by taking a simple average of the five world regions.

Table S D-9: Years of introduction of television and color transmissions.

Country	Intro. TV	Intro. color	Country	Intro. TV	Intro. color	Country	Intro. TV	Intro. color
Albania	1960	1981		1963	1973	Nicaragua	1956	1973
Western Germany	1950	1967	Ghana	1965	1980	Nigeria	1959	1974
Eastern	1952	1969	Gibraltar	1962	1969	Norway	1960	1972



Netherlands Antilles	1960	1973	Greece	1966	1976	New Caledonia	1965	1971
Saudi Arabia	1965	1973	Greenland	1958	1970	New Zealand	1961	1973
Algeria	1956	1979	Guadalupe	1964	1972	Pakistan	1964	1976
Argentina	1978	1978	Guam	1956	1967	Panama	1959	1972
Australia	1956	1967	Guatemala	1956	1970	Papua New Guinea*	1986	1986
Austria	1955	1969	Equatorial Guinea	1968	1976	Paraguay	1965	1981
Bahrain	1973	1973	French Guyana	1967	1974	Peru	1958	1972
Bangladesh	1964	1980	Haiti	1959	1975	French Polynesia	1965	1971
Belgium	1953	1971	Holland	1951	1968	Poland	1954	1971
Bermuda	1958	1968	Honduras	1959	1973	Portugal	1957	1976
Bolivia	1963	1979	Hong Kong	1967	1970	Qatar	1970	1974
Brasil	1951	1972	Hungary	1954	1969	United Kingdom	1936	1967
Brunei*	1975	1975	India	1959	1979	Dominican Republic	1952	1969
Bulgaria	1959	1970	Indonesia	1962	1977	Reunion	1964	1972
Burundi	1984	1985	Iran	1956	1973	Romania	1957	1983
Bhutan*	1995	1995	Iraq	1966	1968	America Samoa	1964	1969
Cambodia	1962	1980	Ireland	1961	1971	Senegal	1965	1975
Canada	1947	1966	Iceland	1966	1973	Sierra Leone	1963	1978
Czechoslovakia	1954	1973	US Virgin Islands	1961	1968	Singapore	1963	1974
Chile	1958	1972	Israel	1966	1977	Syria	1960	1980
China	1958	1977	Italy	1952	1977	Sri Lanka	1979	1979
Chipre	1964	1976	Jamaica	1963	1975	South Africa*	1976	1976
Colombia	1954	1973	Japan	1953	1960	Sudan	1976	1976
Congo	1966	1975	Jordan	1968	1974	Sweden	1956	1970
North Korea	1963	1974	Kenya	1962	1978	Switzerland	1953	1968
South Korea	1961	1975	Kuwait	1961	1974	Suriname	1965	1977
Ivory Coast	1963	1970	Lebanon	1959	1975	Thailand	1955	1973
Costa Rica	1960	1973	Liberia	1964	1975	Taiwan	1956	1969
Croatia*	1992	1992	Libya	1968	1976	Trinidad and Tobago	1962	1969
Cuba	1949	197532	Lithuania	1957	1991	Tunisia	1966	1976
Denmark	1955	1969	Luxembourg	1955	1972	Turkey	1972	1981
Djibouti	1967	1974	Macao*	1981	1981	Ukraine	1951	1984
Ecuador	1959	1974	Madagascar	1967	1977	Uganda	1963	1975
Egypt	1960	1973	Malasia	1963	1972	Uruguay	1961	1980
El Salvador	1958	1973	Malawi*	1999	1999	USSR	1938	1968
United Arab Emirates	1969	1974	Malta	1962	1978	Venezuela	1965	1973
Spain	1959	1972	Morocco	1964	1973	Vietnam	1968	1978
United States	1941	1953	Martinique	1964	1969	North Yemen	1964	1979
Estonia	1955	1967	Mauritius	1965	1973	South Yemen	1975	1981
Ethiopia	1964	1979	Mexico	1950	1963	Yugoslavia**	1956	1971
Fiji*	1991	1991	Monaco		1973	Zaire	1963	1980
The Phillipines	1953	1974	Mongolia	1967	1975	Zambia	1961	1979
Finland	1954	1969	Nicaragua	1956	1973	Zimbabwe	1960	1984
France	1944	1967						

Average years of introduction of color TV by continent to estimate countries not included in the list above.

Africa	1977	Asia	1975	Oceania	1977
Latin America and the Caribbean	1973	Europe	1972	North America	1962

Source: (68, 69). Notes: (a) The countries marked with an asterisk (\*) received their first TV transmissions in color (never before having transmitted in black and white). (b) For countries

<sup>32</sup> In Cuba, the transmission of color signals began in 1958 and ended in 1959, only to return again in 1975.

such as Germany or Yemen, who have since united, we consider the earliest date of introduction for our estimations. (c) Since 1992, Yugoslavia corresponds to the nations of Serbia, Bosnia and Herzegovina, Macedonia, Montenegro and Slovenia.

Since there is no data available on the speed of technological replacement for color TV, we estimate a process of substitution registered for the case of the United States (70,71; see Table S D-10). This assumption has two problems: (a) together with Japan, the U.S. was the first country to adopt television in color. One would expect that followers (countries that began the transition later on) would have speeded up the replacement process, since the technology was already older and for that reason, less expensive; (b) most countries are poorer than the United States, which results in a reverse effect, which is to say, a slower diffusion. Instead of getting lost in adjustments and counter-adjustments, we will assume that the two effects cancel each other out, thus justifying the use of the United States' diffusion S-curve as an approximation for all countries.

**Table S D-10: Percentage of homes with color TVs in the United States (1964 - 1978).**

<b>1960</b>	<b>1961</b>	<b>1962</b>	<b>1963</b>	<b>1964*</b>	<b>1965</b>	<b>1966*</b>	<b>1967</b>
0.74	1.39	1.98	2.55	3.10	5.31	9.65	16.33
<b>1968*</b>	<b>1969</b>	<b>1970</b>	<b>1971*</b>	<b>1972*</b>	<b>1973*</b>	<b>1974*</b>	<b>1975</b>
24.16	32.00	35.23	45.32	52.56	60.06	67.29	68.47
<b>1976</b>	<b>1977</b>	<b>1978</b>	<b>1979</b>	<b>1980</b>	<b>1981</b>	<b>1982</b>	<b>1983</b>
73.56	77.11	78.05	80.94	82.89	87.61	88.72	90.45
<b>1984</b>	<b>1985</b>	<b>1986</b>	<b>1987</b>	<b>1988</b>	<b>1989</b>	<b>1990</b>	<b>1991</b>
91.76	93.25	94.62	95.51	96.67	97.83	97.85	98.91
<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997 – 2007</b>		
98.91	98.92	98.94	98.95	98.96	100.00		

Source: Authors' own elaboration, based on (70); \* (71).

With regard to technological advances in audio transmission, we consider that monochrome televisions always use monaural sound (72). It is assumed that in 1984, all countries belonging to the OECD (Organisation for Economic Co-Operation and Development) began transmitting in stereo, and that after 1984, all new televisions came equipped with stereo technology. For the rest of the world (non-OECD), an average gap of 15 years between the year of introduction of color TV and the introduction of stereo may be assumed, based on data from four developing countries (72-75). We may also suppose that all satellite television channels broadcast in stereo.

Starting out with the total number of TV subscriptions reported by ITU (23), we subtract the number of TVs subscriptions that receive cable, satellite or digital signals from the total number of color TV subscriptions, since we have supposed that (i) subscription to one of these services does not include reception to terrestrial analog TV; and (ii), all who subscribe to cable, satellite, or digital TV services have color televisions. To complete the gaps for the missing years based on the ITU (23), we look to several sources (76-104) and also assume that all countries belonging to the OECD already had cable television subscribers before 1960 (105-

107), with the exception of France, who only had a penetration of 2% in 1984 (108). For the remaining countries, we consider that cable television services began in 1990 (106). Linear interpolation is used between this year and the first year when statistics were had. As for satellite televisions, we consider that OECD countries began to have their first subscribers in 1990, given that companies such as Sky, PrimeStat and DirecTV appeared around this time (109, 110). We interpolate in a linear fashion.

Given that data from the ITU (23) reports subscribers of both cable and satellite, and because we want to estimate how much information is displayed (after effectively being communicated), we must multiply this figure by the number of receivers per household in order to obtain the total quantity of televisions receivers (Table S D-11). We estimate the shelf life of a television at 10 years (112).

**Table S D-11: Average number of TV receivers per home.**

Year	60-75	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
OECD Average	1.23	1.25	1.25	1.28	1.31	1.28	1.34	1.31	1.34	1.34	1.34	1.37	1.38	1,37	1,40
Average for the rest of the world	1.10	1.15	1.16	1.16	1.27	1.18	1.21	1.22	1.26	1.22	1.22	1.24	1.26	1,23	1,20
Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003 - 07	
OECD Average	1,44	1.45	1.43	1.44	1.49	1.52	1.51	1.53	1.55	1.51	1.53	1.64	1.69	1.72	
Average for the rest of the world	1,23	1.23	1.19	1.23	1.29	1.30	1.31	1.34	1.36	1.34	1.36	1.37	1.37	1.37	

Source: Authors' own elaboration, based on (23).

#### D.4.1.2 Digital TV: Quantity

Up until 2007, only 35 countries had digital TV networks deployed and up and running (see Table S D-12); of which 28 used DVB (113); 5, ATSC and only 1 DMB and ISDB technology.

**Table S D-12: Years of introduction for digital TV service.**

Country	Year	Country	Year	Country	Year
Albania	2003	Andorra	2005	Australia	2001
Austria	2005	Belgium	2002	Czech Republic	2005
Denmark	2006	Estonia	2006	Faroe Islands	2002
Finland	2001	France	2005	Germany	2002
Norway	2007	Italy	2003	Lithuania	2006
Luxembourg	2006	Malta	2005	Mauritius	2005
Namibia	2005	Holland	2003	Spain	2000
Saudia Arabia	2006	Sweden	1999	Switzerland	2001
Taiwan	2004	Slovenia	2007	Ukraine	2006
United kingdom	1998	Mexico [ATSC]	2004	South Korea [ATSC]	2001
United States [ATSC]	1998	Japan [ISDB]	2003	Canada [ATSC]	1998
Puerto Rico [ATSC]	1998	Hong Kong [DMB]	2006	Poland	2007

Brasil	2007	Croatia	2007
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Sources: (113-115, 160).

The data used is recorded by the OECD (116-118), among other sources (119-170), to show the number of households with digital and cable TV subscriptions in 1997, 1998, 1999, 2001, 2003 and 2005. Linear interpolation has been applied to estimate the missing statistics. It is supposed that non-OECD countries behave in the same way, but adjusted according to the year of introduction in the respective country from Table S D-12. This applies to the total number of receivers reported by the ITU (23).

**Table S D-13: Average percentage of households with digital TV subscriptions.**

	1997 Intro. year TV-d	98/ Year	99/ Year	00/ Year	01/ Year	02/ Year	03/ Year	04/ Year	05/ Year	06/ Year	07/ Year
		2	3	4	5	6	7	8	9	10	11
Terr. [%]	0.00	0.04	0.09	0.15	0.48	0.78	1.67	3.17	5.23	8.27	15.12
Cable [%]	0.04	0.26	0.66	1.56	2.46	2.62	2.75	4.64	4.96	7.93	10.87

Source: Authors' own elaboration, based on various sources (see text).

There is not a single source on basis of which to estimate the worldwide trend of digitization of satellite TV. There is data available for digital satellite TV for some of the OECD countries (96, 116-118), which we complete with various other sources (119, 132, 140, 156, 161, 166, 171). The remaining part of Europe is estimated with the simple average of the European countries, for which we have statistics (156). The distribution of digital/analog is also reported for Brazil, India, Russia and China. The simple average of these four major developing countries results in a division of almost 50% digital and 50% analog for 2007. This formula is used for the rest of the countries for which we have no better information. Based on the information that we have, it is estimated that in the year 2000, a third of satellite televisions were digital, and that in 1996 satellite television made its mass introduction on the market outside the United States (where it began in 1994). For countries without better data, we use linear interpolation.

## D.4.2 Television: Performance

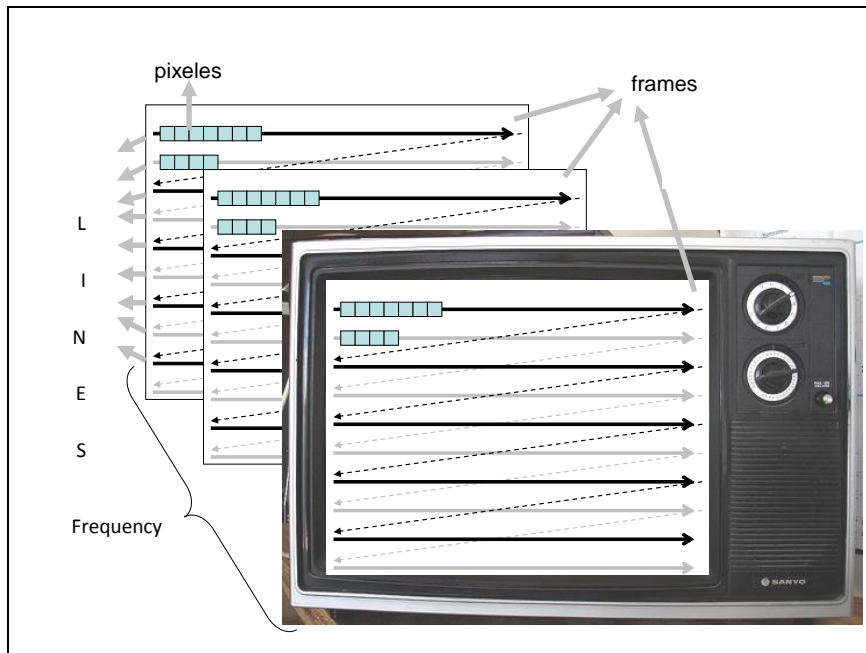
### D.4.2.1 Analog TV in Black and white: Performance

What follows should be considered an approximation of the performance of a typical TV, always taking into consideration that there were 14 different standards in use in the world, of which the number of brand lines varied from 405 (United Kingdom) to 819 (France) (172).

In order to obtain an estimation on the number of binary digits which are transmitted per second, we must follow the procedure of continuous signals, which consists of sampling and quantization. First of all, we assume that one sample corresponds to a pixel (picture element), that means the smallest sub-division of a TV image (173), which in the analog

practice is not a pixel, but corresponds to a tiny section with its shape and dimension defined in the phosphor-coated screen of the television (174). We have to consider: (i) the resolution of the TV image (total number of pixels in a frame) and (ii) the pixel rate per second in accordance with the frame refresh rate used, both following the specifications of each standard. With this last result, what remains is to assign to each pixel the number of bits needed for the representation of the corresponding brightness intensity.

Figure S D-6: Breakdown of the display on a television screen



Source: Authors' own elaboration.

In Table S D-14, we summarize all the variables necessary to make an estimate on the transmission rate for standard quality television. The amount of time that it takes to scan a complete line (line length (active) in Table S D-14) and to change a line (12 [us] in PAL/SECAM and 10.9 [us] in NTSC)<sup>33</sup> corresponds to the length of the line (total) in Table S D-14 and the inverse of this sum, the line frequency. On the other hand, once you have finished scanning the field lines, the cannon returns to the top of the screen. This “return” takes close to 8% of the total scan time (175), for which the total number of lines in a frame, almost 92%, are actually displayed on the screen (active lines per frame in Table S D-14). For its part, the duration of field is nothing more than the product between the line length (total) and the number of lines which each field has. The horizontal-vertical ratio (*ratio aspect*) of 4:3 was chosen by Thomas Edison when he created the first projectors and cameras. It is the standard for transmitting SDTV (174). This means that for every 4 parts that measure the base (ex. 1 [m]), there is a height of three of these parts (e.g. 0.75 [m]).

<sup>33</sup> 17% of the total line length is used in the synchronization pulses for NTSC, in the same way 19% of it is PAL/SECAM, so 83% and 81% are used to transmit videos.

Table S D-14: Black and white TV: CIF (Common Image Format) SDTV (Standard Definition) for PAL/SECAM and NTSC.

Item	Characteristics	NTSC	PAL/SECAM
1	Frame rate [fps]	30 (29.97)	25
2	Field frequency [Hz]	60 (59.94)	50
3	Type of scan	Interlaced (2:1)	Interlaced (2:1)
4	Lines per frame (total)	525	625
5	Lines per frame (active)	480	576
6	Horizontal resolution (active) [pixel] <sup>34</sup>	442	520
7	Line frequency [kHz]	15.75 (15.734)	15.625
8	Line length (total) [us]	63.5 (63.55)	64
9	Line length (active) [us]	52.6	52
10	Interval length blanking [us]	10.9	12
11	Field length [ms]	16.7	20
12	Horizontal/vertical screen	4:3	4:3
13	Broadband for videos [MHz]	4.2	5.0

Source: (176-178). Note: The specifications correspond to the standards of analog color televisions. This is justified in the following: The standards shown in the table are “evolutions” of the monochrome TV systems in use at the time of its formation; for example, NTSC (National Television System Committee) is based on and is compatible with the RS-170 used in North America of 525-lines, 60 fields per second and interlaced 2:1, the same way in which PAL (Phase Alternation Line) and SECAM (Sequentiel Couleurs á Memoire) come from the standard which was defined by the CCIR in Europe of 625-lines, 50 fields per second and interlaced 2:1 (172, 179).

The digitization of a TV image, which means to show the content of a signal frame by frame and line by line, requires that there be just as many lines per sample as there are pixels in each of them, in order to keep the quality of the image. For domestic applications, like the transmission of TV and DVD, black and white encoding with 8 bits is considered appropriate (176), i.e., they can represent up to 256 different shades of gray between black and white. That is how standard definition TV has the resolution shown in Table S D-15, which was

<sup>34</sup> The horizontal resolution is an approximation of the number of pixels per line that an analog TV would have if it were digital. This value is calculated as a broadband function which the standard in question has available for the transmission of a video signal (BW) and the line length (active), i.e., the difference between the total line length ( $T_h$ ) and the time it takes to change from one line to another (blanking,  $T_b$ ), according to the following formula:  $\text{Resolution}_{\text{horizontal}} [\text{pixels/line}] = 2 * \text{BW}_{\text{video}} * (T_h - T_b)$  (Couch, 1997). Concerning PAL and SECAM, which have different “sub-standards” according to the width of band available for video signals, we have decided on those with: PAL -B/G/H and SECAM-B/G, both with 5 [MHz]. It is important to note that for standard digital television, the horizontal resolution is in agreement with what is defined by BT.601 of ITU-R, which is to say, 720 pixels per line, which explains the better quality of the image.

calculated with the equation: byte rate per second [bits/s] = {[No. Pixels per line] \* [No. Active lines per frame] \* [Frames per second] \* [bits per pixel]}.

**Table S D-15: Resolution for standards of analog TV in black and white and rate transmitted.**

Standard	No. Active lines	No. Pixels per Line	Resolution [pixels/frame]	Refresh rate [frames/s]	Pixel rate [pixels/s]	Depth [bits/pixel]	Bit rate [kbits/s]
NTSC	480	442	212,160	30	6,364,800	8	50,918
PAL/SECAM	576	520	299,520	25	7,488,000	8	59,904

Source: Authors' own elaboration, based on various sources (see text).

The audio signal is transmitted separately from the video. All bandwidth is assigned to one TV channel (6 MHz for NTSC and 8 MHz for PAL/SECAM<sup>35</sup>), 50 kHz are used to transmit analogically with an FM modulation (176). For monochrome television, we assume that only a monaural sound is transmitted. The frequency response of the transmitted audio signal corresponds to 0.02 – 20 [kHz] (180), which implies that for its digitization, it is necessary to have a sampling frequency of at least 44 [kHz], in agreement with Nyquist's theorem, and the recommendations of Ibrahim (176). Assuming that each sample is assigned 8 bits, we get that the transmitted rate (uncompressed) would be equal to 352 [kbps], the same as the quality in analog radio (see Table S D-16). We look at the total of black and white analog TV and the downstream capacity.

**Table S D-16: Complete rate of binary digits for analog TV in black and white.**

Standard	Black and White TV signal	Binary digit rate [bps]	Binary digit rate [Mbps]
NTSC	Video	50 918 400	50.92
	Audio (mono)	352 000	0.35
	<b>Total</b>	<b>51 270 400</b>	<b>51.27</b>
PAL/SECAM	Video	59 904 000	59.90
	Audio (mono)	352 000	0.35
	<b>Total</b>	<b>60 256 000</b>	<b>60.26</b>

Source: Authors' own elaboration, based on various sources (see text).

#### **D.4.2.2 Analog color TV: Performance**

Analog color TV follows the specifications of the monochrome television shown in Table S D-14, but adds chrominance to the luminance, which is the video signals component which contains the color information (saturation and hue (173)). A color image is generally described with the RGB color model (Red-Green-Blue), which is a numerical representation of the possible mix of the primary colors into different intensities and tones to produce a specific color. The rate of "1's and 0's" generated by the chrominance components depends on the structure of the sample which is used, indicated by Y:C<sub>B</sub>:C<sub>R</sub>. There are various combinations of

<sup>35</sup> While PAL and SECAM standards define the use of 7 or 8 for the transmission of their signals, we have selected the latter because it is the most-used.

sub-samples (175). In this case, we have decided to use 4:2:0, as it is one of the most efficient and is used in video transmission applications<sup>36</sup> (177) (Table S D-17). Finally, just as for monochrome TV, each one of the pixels are represented by a code 8 binary digits in length, with which it is possible represent more than 16 million shades of different colors ( $2^8 * 2^8 * 2^8 = 2^{24}$ ).

**Table S D-17: Resolution of each color signal component and the total number of pixels per second.**

Standard	Component	No. Active lines	No. Pixels per line	Resolution [pixels/frame]	Refresh rate [frames/s]	Pixel rate [pixels/s]	Depth [bits/pixel]	Bit rate [bits/s]
NTSC	Y	480	442	212,160	30	6,364,800	8	
	C <sub>R</sub>	240	221	53,040		1,591,200		
	C <sub>B</sub>	240	221	53,040		1,591,200		
	<b>Total</b>					<b>9,547,200</b>		
PAL/SECAM	Y	576	520	299,520	25	7,488,000	8	
	C <sub>R</sub>	288	260	74,880		1,872,000		
	C <sub>B</sub>	288	260	74,880		1,872,000		
	<b>Total</b>					<b>11,232,000</b>		

Source: Authors' own elaboration, based on various sources (see text).

After color TV signals began to be broadcast, stereo sound was introduced. Using the same sampling rate (44 [kHz]) and the same number of binary digits per sample (8 bits) used in monochrome TV, we find that the transmission rate of stereo sound is equal to double the rate of mono sound 704 [kbps]<sup>(181)</sup> (Table S D-18).

**Table S D-18: Total rate of binary digits for the transmission of analog color TV signals**

Standard	Color TV Signal	binary [bps]	Standard	Color TV Signal	Rate of binary Digits [kbps]
NTSC	Video	76,377,600	PAL/ SECAM	Video	89,856
	Audio (mono)	352,000		Audio (mono)	352
	<b>Total (mono)</b>	<b>76,729,600</b>		<b>Total (mono)</b>	<b>90,208</b>
	Video	76,377,600		Video	89,856
	Audio (stereo)	704,000		Audio (stereo)	704
	<b>Total (stereo)</b>	<b>77,081,600</b>		<b>Total (stereo)</b>	<b>90,560</b>

Source: Authors' own elaboration, based on various sources (see text).

For lack of more specific information, we will assume the same rates for analog satellite and analog cable as for analog terrestrial color TV (making the difference between PAL/SECAM and NTSC), both mono and stereo, respectively (this assumption has also been adopted by Bohn & Short (182)). We take into consideration the total number of color analog TV as downstream performance.

<sup>36</sup> In the case of 4:2:0, the sampling of the components C<sub>R</sub> and C<sub>B</sub> applies to 4:2:0 in a line (only luminance and the component C<sub>R</sub> are sampled while C<sub>B</sub> is not) and in what follows, we apply 4:0:2, where the component C<sub>R</sub> is what is not sampled. Unlike with broadcast video, with stored video we normally opt for an image with more color intensity (therefore, in VHS and BetaMax, for example, a structure of 4:2:2 is maintained).



### D.4.2.3 Digital Television: Performance

For digital TV we look at the standard MPEG-2 encoding which is associated with standard definition TV broadcasting (SD) and used by all standards, i.e. (until 2007): ATSC (i.e. U.S.A and Canada), ISDB (i.e. Japan and Brazil) and DVB (i.e. Europe and the rest of the world). From a technological point of view, Digital TV can transmit multiple channels at standard quality, or one or two channels at high-definition and others at standard quality. This may be done utilizing the same bandwidth, which transmits only one analog signal, which turns out a maximum performance of between a 20-40 Mbps (183-190). Single channel transmission has a rate of around 3-7 Mbps (191-193). Up until 2007, the better part of receiving equipment was not prepared to deploy more than one channel simultaneously and the users were not known for taking advantage of this possibility. Given what we just mentioned, we can suppose that an average rate of 4 Mbps (Table S D-19) is used. Considering the aforementioned, this is a conservative guess.

Table S D-19: Transmission rate used to estimate the performance of digital satellite, cable and satellite television in [Mbps] (hardware performance).

	Video	Audio	Total
Bitrate [Mbps]	4.0	0.256	4.26

Source: Authors' own elaboration based on (191-194).

Digital television introduced two way communications. A return channel (upstream) is provided with which the service provider is able to know the preferences or demands of the viewer. On-demand video service is an example of one of these. Its performance is overshadowed by that of downstream (video transmission from the service provider to the TV) and is estimated from the rate of DVB-RCT, equal to 15 [kbps]. The upper end of the rate can vary—the lowest possible rate is 0.6 [kbps] (113). RCT is the solution created for DVB to offer a wireless interaction channel for interactive digital satellite.

### D.4.3 Content compression

Each factor is calculated considering that 124416 [kbps] is the standard bit rate of digital television without compression, i.e., the rate achieved after the digitization of the analog video signal in accordance with the ITU Rec. B.601 standard, used by MPEG-2 (without yet applying the compression scheme). We also consider that 1411.2 [kbps] is the corresponding bit rate for digital stereo sound without compression. In 2007, the optimal compression method was MPEG-4 for video as well, and MPEG-4 HE-AAC for audio, with the same rate used in the broadcasting of digital radio (64 [kbps], achieving excellent quality). This results in a compression factor of 31 for MPEG-2 and of 60 for MPEG-4, which is consistent with empirical experiments which show that MPEG-4 has been able to reduce the bit rate to 50% of that achieved by MPEG-2 (195). For upstream traffic, it is assumed that it can only transmit texts in ASCII format.

Table S D-20: TV compression factors.

	1986	1993	2000	2007	“Optimal”
Video NTSC/PAL	1	1	31.1	31.1	60.0
Audio	1	1	5.5	5.5	20
Text (upstream)	-	-	4.7	4.7	6.6

Source: Authors’ own elaboration, based on B Compression.

Table S D-21 contains the transmission rates resulting from the application of optimal compression. The results show us that digital TV transmits 1.4 times the amount of information of an analog stereo color TV channel (satellite, cable or land). It can be expected that this gap will continue to increase rapidly, while providers and consumers begin to use various channels simultaneously through one digital-TV transmission channel.

Table S D-21: Bit rate for analog TV using optimal compression in [Mbps].

	NTSC	PAL/SECAM/Satellite
Analog black and white	0.866	1.016
Color (mono) analog	1.291	1.515
Color (stereo) analog	1.308	1.533
Digital (DL&UL)	2.155	2.155

Source: Authors’ own elaboration, based on various sources (see text).

#### D.4.4 Effective use

For both OECD countries and those not affiliated with OECD, information was collected from various sources to estimate the average number of hours a person watches TV in a week. As some sources reported contradictory numbers, we have chosen the most conservative estimates.

Table S D-22: TV usage in hours per week.

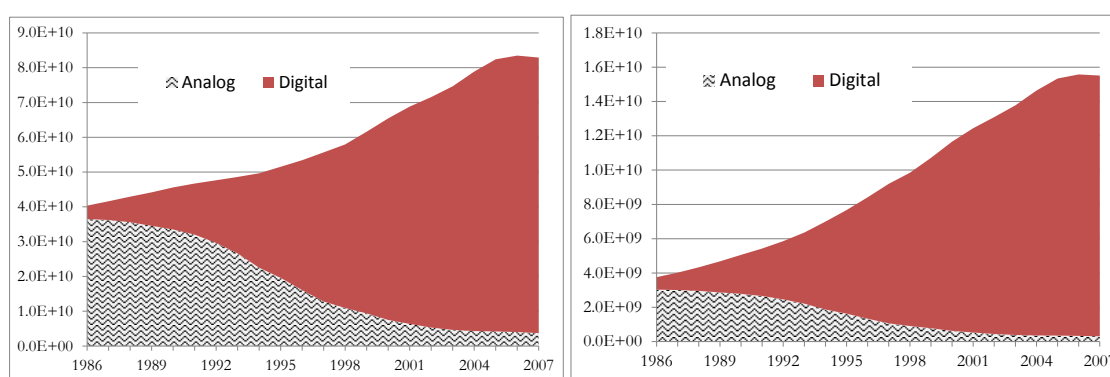
	1986	1993	2000	2007
OECD	20.1	20.5	21.1	21.8
Non-OECD	16.3	16.6	18.3	18.9

Sources: Authors’ own elaboration, based on (34, 35, 37-43, 46-49, 51, 53-55, 57, 59, 61, 63, 64, 66, 67, 83, 118, 119, 196-218).

## D.5 Fixed-line Telephone

The infrastructure of fixed-line telephone networks are used just as much for voice calls as for Internet dial-ups. Here we only look at the use of it for voice, while dial-up is recorded in the section about Internet, considering the complementary effective usage of both technologies (expressed in minutes per week per subscriber) for 1986, 1993, 2000 and 2007. The following graph shows the complete installed capacity [kbps] in each corresponding year.

Figure S D-7: Fixed-line capacity (voice): (a) without compression; (b) optimal compression; both in [kbps].



Source: Authors' own elaboration, based on various sources (see text).

### D.5.1 Fixed-line telephone: Quantity

In order to separate the number of analogue lines from digital ones we weigh the total of main lines actually in use, reported by the ITU data base (23), with the percentage of digital lines<sup>37</sup> (taken from the same source). The missing values from ITU (23) are estimated in a linear fashion. In 1986, 14% of the total number of land lines in use around the world were digital, and in 2007 some 97% (23). During a connection two lines are needed to transmit the data: one for the transmission of the voice of the subscriber who calls, and the other for the transmission of the voice of the receiver (219). Therefore, in contrary to what is often supposed, the respective rates (Table S D-23) should be weighed by a factor equal to two, accounting for the upstream and the downstream, both with the same bit rate.

### D.5.2 Fixed-line telephone: Performance

In the case of digital lines, the voice coding is done in accordance with the recommendation G.711 of the ITU-T. In the process of digitalization, samples are taken from the voice signal at 8000 times per second, i.e., a sampling frequency of 8 [kHz] and is then assigned 13 or 14 bits to each one of them, depending on the different standards used in the United States, Japan and Australia (13 bits) or in Europe and the rest of the world (14 bits) (220). These samples are normalized and sent to a non-linear quantizer<sup>38</sup> that produces a

<sup>37</sup> This percentage covers lines which are completely digital (ISDN) just as much as those which are only partly digital, i.e., those where the last phase is still analog.

<sup>38</sup> The methods which produce samples from 13 and 14 bits are called Law-A and Law- $\mu$ , respectively, each one of them has a function based on natural logarithm to transform the samples from 13 and 14 bits into one of 8 bits (1, 174).

sample of 8 bits in length, achieving a final transmission rate of 64 [kbps] (sampling rate \* No. of bits per sample).

To estimate the transmission rate in the analog network, we assume that the signal is digitized in the same fashion as the digital network (G.711), but that each sample is not compressed down to 8 bits, that means, 8 thousand samples taken per second are coded with 13 or 14 bits –depending on the country. The resulting rates are 104 and 112 [kbps]. Starting from this rate, an adjustment is made for analog signal quality based off the signal-to-noise ratio (SNR) (221). This takes into consideration that the analog signal is less complete, since it loses parts of its quality due to interference or crosstalk (222). The rule used is known as Rule 6 [dB] for PCM telephone (178, 223), which gives an estimate of the SNR of the signal received as a function of the number of bits used to encode the value of each sample (224). A good voice quality requires a SNR of at least 40 [dB] and if this number drops down below 27 [dB] the conversation is understandable, but with a quite disturbing noise (224, 225). An average quality of 34.84 [dB] means samples with an encoding of 7 bits ( $SNR_{dB} = 6.02 * n - 7.3$ ). Therefore, we can conclude that noise reduces the number of bits used for encoding the samples by one bit (from 13 to 12, and from 14 to 13 bits), for which we obtain effective rates of 96 and 104 [kbps].<sup>39</sup> For long distance calls, we assume the average of these rates (100 [kbps]).

**Table S D-23: Landline telephone performance (voice) analog.**

	Transmission rate Law-A (Europe and the rest of the world) [Kbps]	Transmission rate Law-μ (United States Japan, Australia) [Kbps]	International transmission rate [Kbps]
Analog (without compression)	104	96	100
Digital (with compression)	64	64	64

Source: Authors' own elaboration, based on (174).

### D.5.3 Content Compression

Considering the compression rate used in G.711 (112:64 = 1.75: 1, a compression at 0.57 for the Law-A; and 104:64 = 1.63, a compression at 0.62 of the original at Law-μ), a correction is made to the analog transmission rate, so that comparability between the two rates can be achieved. We get a reduction in the bit rate from 104 and 96 [kbps] to 59.4 and 59.1 [kbps], which shows the inferiority of analogue (with 64 [kbps]).

The estimate of the optimum compression factor is based on data presented by (226), which show the compression rate achieved for the algorithms looked at in el Speech Profile de MPEG-4 (CELP y HVXC) (MOS between 3.6-4.1). We have selected those which reflect the previously assumed quality (Table S D-24).

<sup>39</sup>  $[2^7/2^8] = [2^x/2^{13}] \Rightarrow x=12 \Rightarrow 8000*12 = 96 \text{ kbps}$ ;  $[2^7/2^8] = [2^x/2^{14}] \Rightarrow x=13 \Rightarrow 8000*13 = 104 \text{ kbps}$

Table S D-24: Compression factors and the respective transmission rates.

		Analog		Digital	
		"Optimal"	1986-2007	"Optimal"	
Compression factors	Ley-A	12.05	1.75	9.00	
Bit rate [kbps]		8.63	64	12.44	
Compression factors	Ley- $\mu$	12.05	1.63	9.00	
Bite rate [kbps]		7.97	64	11.56	

Source: Authors' own elaboration, based on B.4.1.1.

## D.5.4 Effective Use

Based on data reported by the ITU (227) regarding telephone traffic, a calculation is made of the average amount of minutes weekly weighed according to the number of telephone lines in use, utilized by the consumer (see Table S D-25), for those countries which belong to the OECD and for the rest of the world. The total corresponds to the sum of the national traffic (which includes local and long distance calls and international calls.)

Table S D-25: Fixed-line telephone traffic, in minutes per fixed-line per week.

		1986	1993	2000	2007
National traffic	OECD	113.59	115.10	145.58	91.36
	no-OECD	34.07	34.07	47.19	68.27
International traffic	OECD	1.03	1.65	2.95	4.90
	no-OECD	0.91	1.40	1.14	1.24

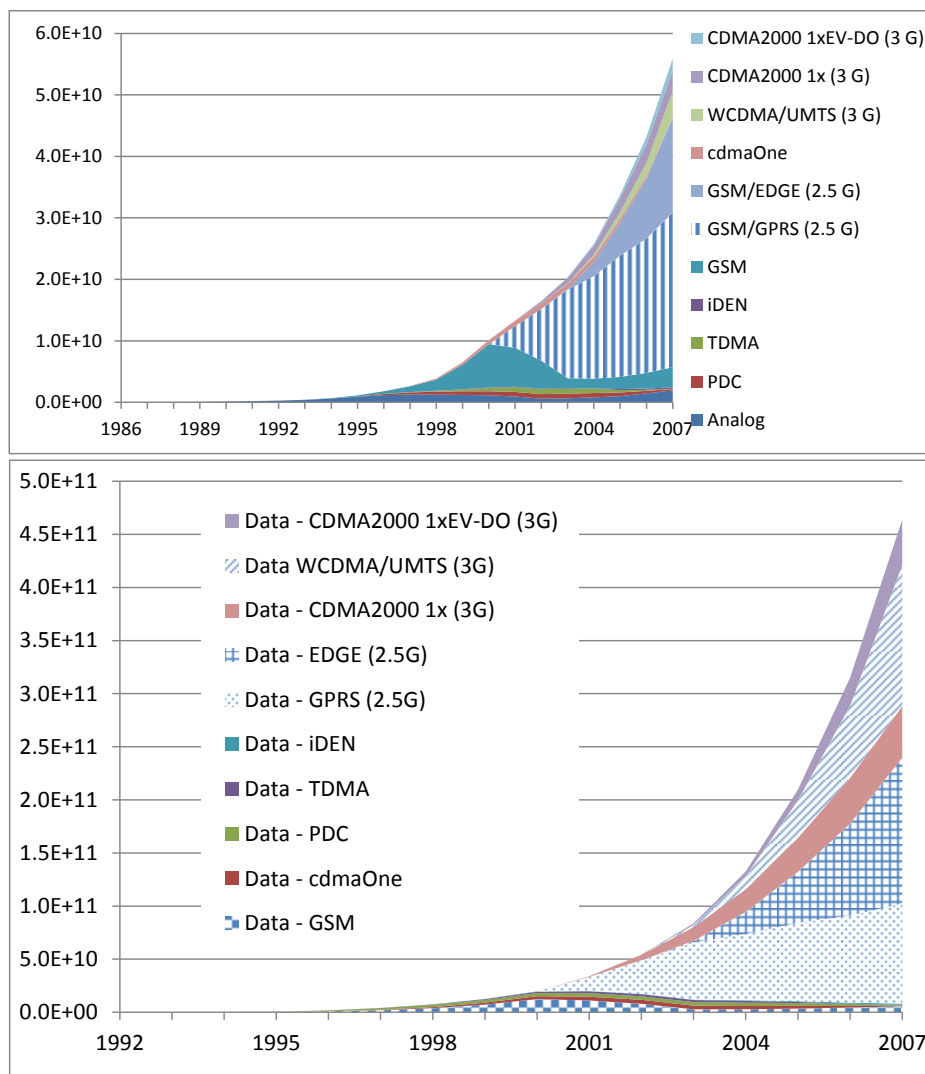
Source: Authors' own elaboration, based on (227).

For the separation between upstream and downstream, we may consider that upstream corresponds to the "speaking" part of the call, and downstream to the "hearing" part. Since there is no information available on how much time is spent speaking or hearing, we will assume that they are both distributed equally (50%-50%).

## D.6 Mobile Telephones

In this section, we present the capacity of the mobile telephone to transmit voice and data. The mobile technologies considered in this study correspond to those of the second generation (2G): TDMA (IS-54), PDC, iDEN, GSM and cdmaOne (IS-95); generation 2.5G: GPRS and EDGE; and those of the third generation (3G): WCDMA (UMTS), CDMA2000 1x and CDMA2000 1xEV-DO.

Figure S D-8: Total capacity (in kbps) of cellular technologies, (a) voice and (b) data service.



Source: Authors' own elaboration, based on various sources (see text).

### D.6.1 Mobile telephony: Quantity

The information on the total amount of mobile subscriptions is provided by the ITU (23, 227). The classification of families according to IMT-2000 (228) is provided by GSM World (229-233) and CDMA Development Group [CDG] (234-236). Because there is no information available at the country level (except for the PDC in Japan), we estimate of distribution according to regional percentages (Table S D-26 and Table S D-27). For TDMA, the assumption can be made that there are only subscribers in America (237); and iDEN subscribers are distributed in countries where it is deployed (238), in proportion to mobile telephone subscribers.

Table S D-26: Regional percentages of the GSM family of mobile technologies.

GSM 2G/2.5G Technologies [in millions]										
1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	

Africa	0.01	0.05	0.19	0.50	0.89	1.62	3.00	5.60	10.20	16.20
Middle East	0.00	0.03	0.10	0.26	0.73	1.43	2.40	4.40	10.30	17.20
Asia-Pacific	0.03	0.22	0.77	2.01	6.72	17.05	36.10	71.70	140.40	229.50
Europe*	0.16	1.10	3.92	10.20	24.16	49.66	93.70	170.10	283.80	346.30
Latin America	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.70	1.70	3.60
North America	0.00	0.01	0.02	0.05	0.25	1.36	3.10	5.90	9.60	13.50
Worldwide	0.20	1.40	5.00	13.02	32.75	71.12	138.50	258.40	456.00	626.30
	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>				
Africa + ME	77.90	105.10	146.00	219.50	305.56	358.80				
Latin America	9.50	29.00	66.70	137.60	207.52	303.60				
Asia-Pacific	314.00	394.60	494.40	631.20	824.47	1 131.60				
Europe*	383.00	445.50	536.30	645.80	740.73	745.20				
USA/Canada	24.90	37.80	52.60	75.20	88.16	220.80				
Worldwide	809.30	1 012.00	1 296.00	1 709.30	2 166.45	2 760.00				

GSM 3G Technologies (2001 – 2007) [in millions]							
	2001	2002	2003	2004	2005	2006	2007
Africa + ME	0.00	0.00	0.00	0.04	0.35	1.48	3.68
Latin America	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Asia-Pacific	0.03	0.15	1.99	9.47	24.39	46.34	82.80
Europe*	0.00	0.00	0.71	7.71	25.23	48.00	93.84
USA/Canada	0.00	0.00	0.00	0.00	0.05	1.07	3.68
Worldwide	0.03	0.15	2.70	17.23	50.03	96.89	184.00

Sources: (229-233, 239).

Table S D-27: Regional percentages of the CDMA family of technologies.

2G CDMA Technology (cdmaOne, 1997 – 2007)											
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Asia-Pacific	6.30	14.90	28.00	35.73	37.74	33.35	31.40	29.10	20.10	21.13	6.22
North America	1.50	6.80	16.50	38.70	48.42	50.93	39.63	28.50	19.80	14.18	2.69
Latin America	0.00	1.22	5.10	14.95	19.90	26.97	29.86	33.50	34.60	12.25	2.92
Europa+ME+Africa	0.00	0.09	0.50	1.06	1.65	2.33	2.30	2.30	2.30	0.90	0.79
Worldwide total	7.80	23.00	50.10	80.44	107.70	113.58	103.19	93.40	76.80	48.45	12.62

**CDMA 3G Technologies (CDMA2000 1x/1xEV-DO)[in millions]**

	CDMA2000 1x							CDMA2000 1xEV-DO					
	2001	2002	2003	2004	2005	2006	2007	2002	2003	2004	2005	2006	2007
Asia-Pacific	3.65	21.08	42.52	61.35	91.45	120.81	155.54	0.17	4.38	11.55	19.35	28.09	33.84
North America	0.00	11.57	35.57	63.10	83.25	84.71	79.79	0.00	0.00	0.50	4.45	24.49	45.10
Latin America	0.00	0.24	2.14	8.70	23.70	57.45	57.27	0.00	0.00	0.00	0.43	1.90	4.02
Europa+ME+Africa	0.00	0.07	0.80	1.57	2.70	7.01	10.78	0.00	0.00	0.04	0.20	0.59	1.05
Worldwide total	3.65	32.95	81.03	134.71	200.67	269.98	303.38	0.17	4.38	12.09	24.43	55.07	84.00

Sources: (234-236).

As available statistics do not separate between GSM, GRPS and EDGE (2G and 2.5G of the GSM family), we assume that since the first commercial deployments of GPRS and EDGE technologies (Table S D-28), all new equipment incorporate the new technology (considering that the useful lifetime of a mobile telephone is three years) (240).

**Table S D-28: First years of commercial deployment of GPRS and EDGE.**

Technology	Africa	Asia	Europa	Latin America	North America	Oceania
GPRS	2005	2000/1	2000/1	2002	2000/1	2000/1
EDGE	2004	2003	2003	-	2004	2005

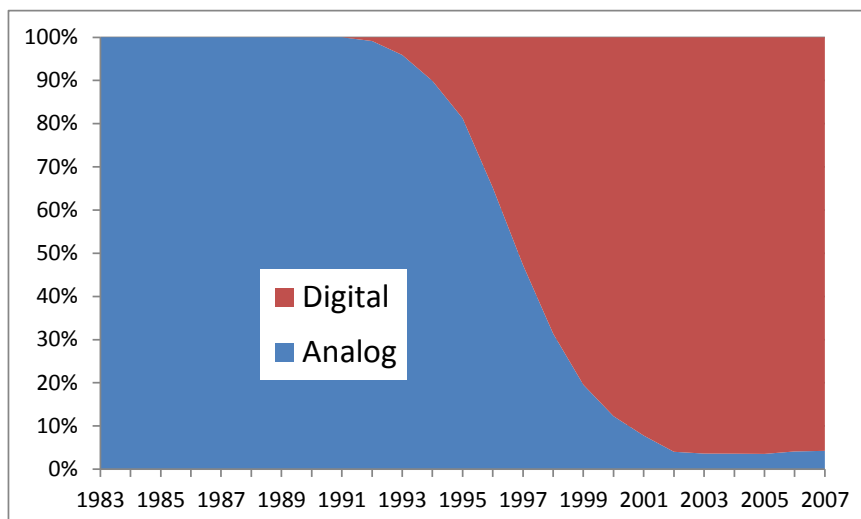
Sources: (241-249). The first commercial GPRS networks were deployed in 2000, but the phones did not have GPRS functionality until 2001. For this reason, we include GPRS starting in 2001 for those countries.

The quantity of analog mobile phone users corresponds to the difference between the total amount of subscribers to these digital technologies and the total reported by the ITU (23)<sup>40</sup> (Figure S D-9).

**Figure S D-9: Quantity of analog mobile phones in the world.**

<sup>40</sup> In cases where this difference resulted negative, we corrected to 0 (this was the case in some developed countries for the years between 2003 and 2007, for which it is known that analog transmission were gradually turned off).





Source: Authors' own elaboration, based on (23, 229-236, 247-249).

**Table S D-29: Summary of the distribution of different mobile technologies in the period 1980-2007 (percentages)<sup>41</sup>.**

	80-91	1992	1993	1995	1997	1999	2000	2002	2004	2006	2007
Analog	100.0	99.1	95.9	81.3	47.3	19.4	12.2	5.2	2.2	0.6	0.1
GSM/GPRS/EDGE	0.0	0.9	4.1	14.3	33.1	52.5	59.8	68.1	73.9	79.1	80.9
cdmaOne	0.0	0.0	0.0	0.0	3.6	10.2	10.9	9.6	5.3	1.8	0.4
PDC	0.0	0.0	0.0	3.6	12.5	9.1	6.9	4.8	3.1	1.2	0.5
TDMA	0.0	0.0	0.0	0.8	2.9	7.7	9.1	8.5	5.2	0.8	0.2
iDEN	0.0	0.0	0.0	0.0	0.7	1.0	1.1	1.0	1.0	1.0	0.9
1x	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	7.7	10.0	8.9
WCDMA (UMTS)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	3.6	5.6
1xEV-DO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	2.0	2.5

Source: Authors' own elaboration, based on various sources (see text).

## D.6.2 Mobile voice: Performance

Digital mobile technologies (2G onward) encode and compress voice signals (Table S D-30).

**Table S D-30: Details of voice encoders.**

Technology	Encoder	Complexity	Standard year	Period	Bit rate [kbps] with compression
GSM/GPRS/EDGE	GSM.FR	4.5 MIPS	1986	1992 – 1996	13

<sup>41</sup> The GSM table refers to the sum of subscribers of GSM, GPRS and EDGE, CDMA2000 1x to 1x and 1xEV-DO to CDMA2000 1xEV-DO.

GSM/GPRS/EDGE	GSM-EFR	18 MIPS	1997	1997 – 1998	12.2
GSM/GPRS/EDGE	GSM-AMR	20 MIPS	1999	1999 - 2007	4.75 – 12.2 (8.48)
WCDMA (UMTS)	AMR-WB G.722.2	38 WMOPS	2001	2001- 2007	6.6 – 23.85 (15.23)
cdmaOne	QCELP13	20-25 MIPS	1995	1997 – 2007	13.3
CDMA2000 1x	EVR-C	25 MIPS	1994	2001 – 2007	8.55
CDMA2000 1xEV-DO	VMR-WB	38 WMOPS	2002	2002 – 2007	6.6/8.85/12.65 (12.65)
iDEN	VSELP	20 MIPS	1989	1996 – 2002	4.2/4.4/8 (8)
iDEN	AMBE++	-	2003	2002 – 2007	4
TDMA	IS-54	25 MIPS	1989	1994 - 2007	8
PDC	PDC-FR	18.7 MOPS	1993	1994 – 1996	11.2
PDC	PDC-EFR	18 MIPS	1997	1997 - 2007	6.7

Source: (250-254). Note: GPRS and EDGE are only used for the transmission of information and use the GSM network for voice transmission.

It is assumed that: (i) the encoder is implemented in all the networks deployed from the year of standardization, (ii) for encoders that present a range of rates (such as GSM-AMR, AMR-WB), the rate is chosen using a simple average of the measurements; (iii) of the VSELP profiles available for transmission in iDEN, the most-used is 8 [kbps] (254); and (iv) in the case of VRM-WB (CDMA2000 1x EV-DO), the lowest rates are used (12.65 [kbps]) to ensure compatibility with those networks that do not use the same codification.

Regarding analog cellular technology, the assumption has been made that the transmission rate without compression is the same as that of land line telephony: 96 [kbps] for the United States, Japan and Australia; and 104 [kbps] for Europe and the rest of the world.

Cellular telephones, like landlines, use two frequencies per call (a duplex channel): one for the person who calls and the other for the person who is called. This suggests that the voice transmission rate must be multiplied by two.

### D.6.3 Mobile Voice: Compression of Content

Presented below are the resulting compression factors of various voice encoders used by different technologies.

Table S D-31: Compression rate achieved by voice encoders.

Technology	Sampling Frequency [kHz]	Bits per Sample	Bit rate (s/ compression) [kbps]	Bit rate (c/ compression) [kbps]	Compression Factor
GSM(GSM.FR 1992-1996)	8	13	104	13	8.0
GSM(GSM-EFR 1997-1998)	8	13	104	12.2	8.5
GSM/GPRS/EDGE(GSM-AMR 1999-2007)	8	16	128	8.48	15.1
WCDMA(UMTS) (3G)	16	16	256	15.23	16.8
cdmaOne	8	8	64	13.3	4.8
CDMA2000 1x	8	16	128	8.55	15.0
CDMA2000 1xEV-DO (3G)	16	16	256	12.65	20.2
iDEN	8	8	64	8.0	8.0
iDEN	8	13	64	4.0	16
TDMA	8	8	64	8	8.0
PDC	8	13	104	11.2	9.3
PDC	8	13	104	6.7	15.5

Source: Authors' own elaboration, based on (250-254). Note: as shown by the Table, GSM has evolved during 1996-99. We suppose that every new equipment counts with the most up to date standard, while others keep their standard during a lifetime of three years. This results in the fact that in 2000 some 17 % of GSM were GSM-EFR and 83 % GSM-AMR, which results in a transmission rate of 9.1 kbps and a compression factor of 14.

In order to harmonize the performance of digital telephony with analog in a given year (which transmit at 104 [kbps] and 96 [kbps]), we find an average compression factor by considering the factors utilized in digital technologies and their respective percentage of subscribers (Table S D-32). The optimal compression factor is based on the compression rates achieved by the algorithms considered in MPEG-4 Speech Profile (CELP-NB and HVXC for 2G and 2.5G technologies; AMR-WB and CELP-WB for 3G; see Appendix B for further detail) (226), choosing the one that reflects in the best way the quality characteristic of the mobile telephone (MOS between 2.91 and 3.16, 255). To double check the estimate, we may compare the resulting rates with those of fixed line telephones. For example, voice transmitted in GSM/GPRS/EDGE (with GSM-AMR) will result in an entropic rate of 8 [kbps] (128 [kbps] bit rate without compression /16 with optimal compression), which is similar to the entropic transmission rate of analog fixed-line telephony, and lesser in quality than digital fixed-line (which has around 12 [kbps]).

Table S D-32: Compression factors, weighted averages.

Year	1980-1992	1993	1994	1995	1996	1997	1998	1999	2000
Factor	8.0	8.0	8.1	8.3	8.4	9.9	9.3	13.1	13.0
Year	2001	2002	2003	2004	2005	2006	2007	“Optimal 2G/2.5G”	“Optimal 3G”
Factor	13.1	13.4	14.0	14.3	14.8	15.1	15.4	16.0	22.9

Source: Authors’ own elaboration, based on Appendix B. Note: 3G is compressed more than 2G, since 3G transmits voice in higher quality, and therefore also contains more redundancy that may be compressed.

#### D.6.4 Mobile Voice: Effective use

The ITU database (23, 227) reports mobile traffic data classified into the following categories: national mobile traffic (equal to the amount of traffic on one mobile network to another), and international and roaming traffic; call traffic from fixed networks to mobile, and from mobile networks to fixed. For roaming minutes, only digital technologies are considered, given that this concept was only introduced with 2G GSM technology.

Also included in Table S D-33 is traffic from fixed networks to mobile networks. For the separation between upstream and downstream, we make the same assumptions as were made in fixed-line telephony, dividing the final rates by two.

Table S D-33: Summary of traffic of mobile telephone networks, in minutes. Mobile subscriptions per week.

		1986	1993	2000	2007
National mobile traffic (incl. mobile-fixed and fixed-mobile)	OECD	6.83	17.35	27.88	33.60
	non-OECD	6.48	13.60	20.71	22.43
International mobile traffic	OECD	-	-	0.59	0.97
	non-OECD	-	-	0.12	0.13
Roaming	OECD	-	-	0.95	0.99
	non-OECD	-	-	0.75	0.87

Source: (23, 227).

#### D.6.5 Mobile data: Performance

The average rates achieved in mobile devices for commercial applications are shown in Table S D-34. This data represents a theoretical value which can be achieved in each piece of equipment, with which we can calculate the “potential capacity” for each user in [kbps]. However, if all the equipment were used at this capacity all at once, the network would collapse (an effect that we informally call “midnight on New Year’s Eve effect”). In other words, given the altering use of shared network infrastructure, the installed capacity in the

world is far less than that of the sum of all devices. We need a more realistic estimate on the actual traffic of mobile networks.

**Table S D-34: Different mobile technologies data transmission rate.**

Technology	Generation	Data transmission rate	
		Upstream [Kbps]	Downstream [Kbps]
GSM	2G	14	14
cdmaOne	2G	14	19
PDC	2G	28.8	28.8
TDMA	2G	9.6	9.6
iDEN	2G	19.2	19.2
GPRS	2.5G	14	28 a 64 (46)
EDGE	2.5G	42	100
WCDMA (UMTS) (3GSM)	3G	350	350
CDMA2000 1x	3G	70 a 90 (80)	60 a 100 (80)
CDMA2000 1xEV-DO	3G	70 a 90 (80)	300 a 700 (500)

Sources: (231, 234, 248, 256-258).

We estimate the actual use of data by mobile networks through the use of SMS (Short Message Service) and MMS (Multimedia Messaging Service). A SMS has up to 160 characters, of 7 bits for each one, so containing 1,120 bits in all, while an interoperability agreement between networks (MMS Conformance Document 1.2) regulates that MMS can have up to 300 kB per message (259).

## D.6.6 Mobile data: Actual use

Based on data by the ITU (227), an estimate is formed on the number of SMS and MMS sent per week. The first SMS was sent in December of 1992. For that reason we consider 1993 as year 0. We multiply the number of SMS by the subscribers of 2G, 2.5G and 3G, and the amount of MMS by the subscribers of 2.5G and 3G.

**Table S D-35: Number of SMS and MMS sent by subscribers in a week.**

		1993	2000	2007
SMS	OECD	0	3.92	13.59
	non-OECD	0	0.93	9.17
MMS	OECD	-	-	0.46
	non-OECD	-	-	0.08

Source: Authors' own elaboration, based on (227)

From (260, 261) we know that throughout 2003-2005, MMS traffic for 2.5G and 3G cell phones represented between 0.5% and 7% of all mobile data traffic. It is also known that during the last few years, the participation of MMS in all traffic has decreased, owing to the expansion of the use of the Web and streaming in mobile devices (261, 262). Therefore we

assume that the bottom of this range, specifically that of MMS, represents 1.2% of all data traffic in mobile devices. If we add the 98.8% of missing traffic (which consists of WAP, Web, Email, FTP, streaming), it results that the total traffic coincides with the total mobile traffic estimated by Cisco (263, 264) in their estimation on mobile IP traffic (which estimates 80,055 TB/month).

## D.6.7 Mobile data: Content compression

### D.6.7.1 SMS

2G technologies can only support SMS traffic (Short Message Service) of text, which is also enabled for 2.5G and 3G. Half of SMS are upstream and the other half is downstream.

**Table S D-36: 2G content compression factors.**

	2000	2007	“Optimal”
Text	4.6	4.7	6.6

Source: Authors’ own elaboration, based on B.2.3.

### D.6.7.2 2.5G and 3G content

Table S D-37 shows the distribution of the protocols and applications most utilized by 2.5G and 3G network users. For the estimation of effective use, we employ the downstream distribution and we count half of SMS, MMS and Email traffic as upstream. For the estimation of compressed hardware capacity, we use the distribution from Table S D-37 for downstream, and the proportions of SMS, MMS and Email for upstream (which results in that 17.1 % of upstream capacity is MMS, Email 82.5 %, and SMS 0.4 %).

**Table S D-37: Percentage of protocols/applications used by 2.5G and 3G mobile users.**

Application	2007
MMS	1.2 %
Email	5.8 %
WAP	10.0 %
Other	10.0 %
Streaming	15.0 %
Web	58.0 %
SMS	0.03 %

Sources: Authors’ own elaboration; based on (260-262).

We assume that the MMS (Multimedia Message Service) consists of a combination of text, photos, sound and video (Table S D-38). WAP Technology (Wireless Application Protocol) only supports texts and images, so for that reason we will assume that the distribution follows

the same relation which is seen in fixed-line Internet Web traffic, same for other applications (Web, e-mail, FTP among others) (see section D.7.6).

**Table S D-38: Content distribution (MMS), WAP and Streaming mobile.**

	MMS				WAP		Streaming	
	Text	Image	Sound	Video	Text	Image	Video	Sound
2007	5%	75%	10%	10%	52%	48%	95%	5.0%

Source: Authors' own elaboration, source Web traffic section D.7.6.

The following compression factors are used (following the rate used for computer servers), with the exception of streaming for mobile devices, which uses MPEG-4 (AACv2). This factor compresses audio a little more than for streaming used in Fixed-line Internet (to facilitate transmission over a wireless channel)

**Table S D-39: Different kinds of contents compression factors.**

	Text	Image	Audio (download)	Audio (streaming)	Video (download & streaming)	Compressed
2007	4.7	27.6	6.8	27.0	60.0	4.7
Optimal	6.6	48.0	12.0	32.0	60.0	6.6

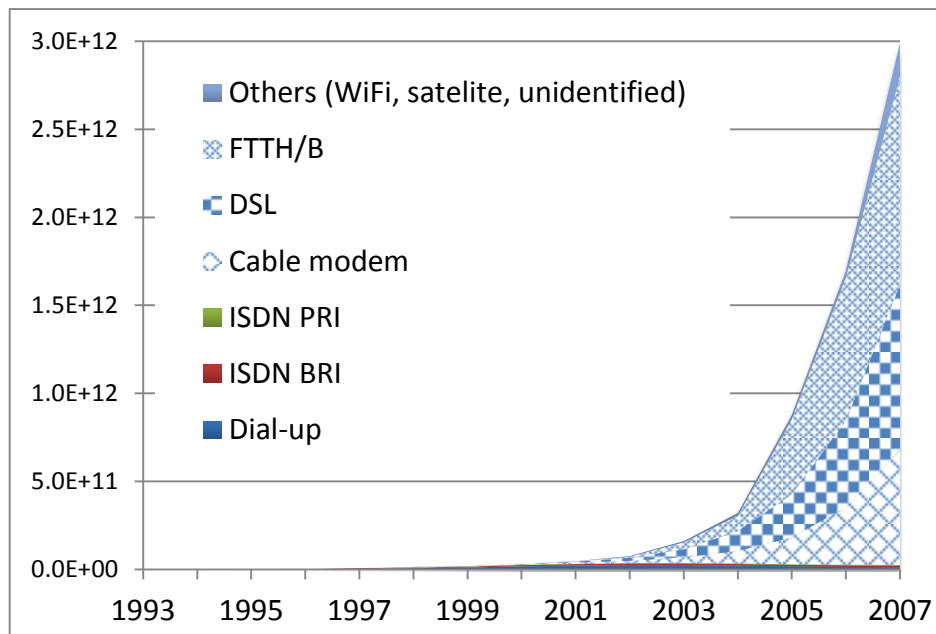
Source: Authors' own elaboration, based on Compression.

Applied to existing content, it turns out that in 2000, the compression factor (ratio between hardware capacity and optimally compressed capacity) is 1.43 (all content was SMS text: 6.6/4.6). In 2007, hardware upstream capacity was not very affected, given that most upstream is text, but for downstream 2007 has a compression factor of 1.3 (given that, for example, video content is already more compressed than text).

## D.7 Internet

In the following we look at upstream and downstream capacity in dial-up, ISDN, xDSL, FTTH/B (Fiber-To-The-Home/Building), cable modem and "others" (including wireless WiFi, microwaves or satellites, by electric cable (PLC), and non-identified). The following graph shows the complete installed capacity of [kbps] in each corresponding year.

Figure S D-10: Total capacity of data transmission throughout Internet Access technologies, in [kbps], including upstream and downstream, without normalization by compression (capacity hardware<sup>42</sup>).



Sources: Authors' own elaboration, based on various sources (see text).

### D.7.1 Internet: Quantity of dial-up, ISDN, xDSL, FTTH/B cable modem and others

Based on the number of subscribers to the different fixed-line Internet technologies (227) (not the users), we assume that the difference between the total of fixed-line internet subscribers and the sum of dial-up, ISDN, DSL, FTTH/B (Fiber-To-The Home/Building) and cable modem fall into the group "others" (wireless, satellite, power line, etc. and other technologies that are not identified by the available base of information).<sup>43</sup>

<sup>42</sup> One should take note that in this graph, there has been no normalization by compression. In other words, here we show the transmission "just as is occurs" in the transmission of data (in the sense of hardware use), while more recent compression algorithms can actually transmit more per unit of data.

<sup>43</sup> Between 2009 and 2010, the ITU changed its definition of fixed-line internet subscriptions (23, 227), creating two different categories: Fixed-line Internet and wireless internet. Unfortunately, there is still no data concerning the latter, and it looks as if countries still report wired and wireless technologies together in the category "wired internet". To settle our doubts, we have compared the new data from the ITU ("wired internet") with those from the OECD (96) (broadband + dial-up, for the 30 countries in the OECD in 2007), which explicitly include fixed wired and wireless Internet ("OECD broadband subscriber statistics count the broadband subscriptions which supply connectivity to a Wi-Fi hotspot in a home or office. The OECD also counts any leased lines or business DSL connections which furnish Internet access to commercial Wi-Fi hotspots in a cafés, etc."). Both sources turn out to be similar (with overestimates for some countries and underestimates for others), with a general difference of less than 1%. So in conclusion, we have found that the statistics from ITU (227) for fixed-line internet still include wired and wireless technology, and we have taken this basis as the estimate of the total subscribers (since it is the most complete source found in the world).



We use data provided by the OECD Outlooks (96, 116-118) to fill in missing data about dial-up technology; for DSL and cable modem we use data from the ITU (227). Furthermore, it completes the beginning of the time series of subscribers based on the commercial introduction of the Internet (which supposedly coincides with the connection of one particular country to the NSFNET (National Science Foundation Network), see Table S D-40), and based on the growth rates of Internet users, which are (interestingly) more complete than subscribers (227). In many cases, countries did not put any more effort into the reporting of the final days of dial-up. We get the information on the death of dial-up from the longest series of data available (Sweden 1995 – 2008), and we assume that all countries without corresponding data behave in the same way as the dial-up in Sweden. Concerning ISDN, the ITU reports the subscribers total to ISDN-BRI (Basic Rate Interface) and ISDN-PRI (Primary Rate Interface) (besides those subscribers to ISDN, which correspond to the sum of both, this value is used to make an estimation in the case of a certain year not being registered).

In the case of time series for subscribers to FTTH/B, the missing information was filled in using additional sources (265-277). Comparing these sources, each subscription from FTTH is counted (Fiber-To-The-Home) and FTTB (Fiber-To-The-Building) as only one single subscription (which we call FTTH/B) which assigns an average capacity<sup>44</sup>.

**Table S D-40: Years in which different countries connected to the NSFNET network (National Science Foundation Network) and the introduction of more advanced technologies.**

Year	Countries
1988	Canada, Denmark, France, Iceland, Norway, Sweden
1989	Australia, Germany, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, Puerto Rico y United Kingdom
1990	Argentina, Austria, Belgium, Brazil, Chile, Spain, Greece, India, Ireland, Korea and Switzerland
1991	Croatia, Hong Kong, Hungary, Poland, Portugal, Singapore, South Africa, Taiwan and Tunisia
1992	Antarctica, Cameroon, Cyprus, Ecuador, Slovenia, Estonia, Kuwait, Latvia, Luxembourg, Malaysia, Thailand and Venezuela
1993	Bulgaria, Costa Rica, Egypt, Fiji, Ghana, Guam, Indonesia, Kazakhstan, Kenya, Liechtenstein, Peru, Romania, Turkey, Ukraine United Arab Emirates and Virgin Islands (US)
1994	Algeria, Armenia, Bermuda, Burkina Faso, China, Colombia, Philippines, Jamaica, Jordan, Lebanon, Lithuania, Macao, Morocco, New Caledonia, Nicaragua, Niger, Panama, Senegal, Sri Lanka, Swaziland, Uruguay and Uzbekistan.
1995*	Ivory Coast, Ethiopia, Cook Islands, Cayman Islands, Gibraltar, Vatican Kiribati, Kyrgyzstan, Madagascar, Mauritius, Micronesia, Monaco, Mongolia, Nepal, Nigeria, Samoa (western), San Marino, Tanzania, Tonga, Uganda and Vanuatu.
1996*	Qatar, Central African Republic, Oman, Tuvalu, Fresh Polynesia, Syria, Aruba, Cambodia, French Guiana, Eritrea, Cape Verde, Burundi, Benin, Bosnia-Herzegovina, Andorra, Guadeloupe, Guernsey, Jersey, Laos, Maldives, Marshall Island, Mauritania, Northern Mariana Islands, Rwandan, Togo, Yemen and Zaire
1997*	Timor (east), Republic of Congo, Gambia, Guinea-Bissau, Hate, Iraq, Libya, Malawi, Martinique, Montserrat, Myanmar, Reunion, Seychelles, Sierra Leone, Somalia, Sudan, Tajikistan, Turkmenistan,

<sup>44</sup> This implies that some of the FTTB connections, that provide more than one subscription, are counted as “other” subscriptions, which have a lower performance (the group “other” is calculated as the difference between the total and all the rest of the access groups). In other words, it is possible that we underestimated the contribution of the FTTH/B to the total.

Georgia, Liberia, American Samoa, Niue, Equatorial New Guinea, Bhutan, Palau and the Republic of Congo
1998* Comoros, Nauru, Bangladesh and Palestine
Introduction of diverse technologies: ISDN: 1988; Dial up: 1990, HDSL: 1992, Cable modem: 1996; ADSL: 1998

Sources: (11, 278-283).

## D.7.2 Internet Dial-up: Performance

Dial-up uses the infrastructure of the telephone network with modems, a system which has evolved over time (Table S D-41).

Table S D-41: Dial-up transmission rate, in [kbps]

Year	< 1982	< 1984	< 1991	< 1994	< 1996	< 1998	< 2000	<= 2006
Downstream [Kbps]	0.3	1.2	9.6	14.4	28.8	33.6	56.0	56.0
Upstream [Kbps]	0.3	1.2	9.6	14.4	28.8	33.6	33.6	48.0

Source: Authors' own elaboration, based on (284-288).

## D.7.3 Internet ISDN: Performance

The ISDN (Integrated Services Digital Network) has two variants: ISDN BRI (Basic Rate Interface) for homes, and ISDN PRI (Primary Rate Interface) for businesses (289). The first of these offers symmetrical rates of 64 or 128 [Kbps], depending on how the operator configures the network. We suppose 128 [kbps]. As for ISDN PRI, we will suppose that it offered rates of 768 [Kbps] until 1997 (290, 291), and later on, rates of 1544 [kbps] in The United States, Canada and Japan; and 2048 [kbps] in the rest of the world, all being symmetrical.

## D.7.4 Internet xDSL, Cable Modem and others (wireless WiFi, satellite, power line, electric, unidentified, etc): Performance

Estimating the performance of DSL and Cable Modems is not as easy as dial-up and ISDN, since the capacity varies significantly between different markets. The same goes for those grouped as "others", which constitute the difference between the total of Internet subscriptions and the sum of subscriptions for the rest of the technologies<sup>45</sup>. Here we have access technologies like wireless (WiFi), those of microwaves or satellite, by electric cable (PLC), etc<sup>43</sup>.

For example, Table S D-42 shows the large speed variations available in some DSL technologies. There is no information on what kind of DSL was launched in what time period. It is even harder to find the true rates for DSL users, since DSL is the internet access technology which receives the highest amount of complaints from users about the unwillingness of

<sup>45</sup> In some countries, the difference: total subscription – [dial-up, ISDN, DSL, Cable modem, FTTH/B] has negative results. In these instances the negative number is converted into 0, assuming an incomplete record on the part of the ITU (227).

operators to provide the promised rates (292). The challenge is similar when measuring the access to Internet through cable modems. Theoretically, they achieve rates up to 40 [Mbps], with modulation 64QAM or 256QAM for data downloading, and up to 10 [Mbps] with QPSK for data upload (96, 288, 293-296), but this rate is not achieved in practice. Different from DSL, Internet access by cable or wireless are shared by a defined amount of subscribers that connect to the same cable (297). This makes it even more difficult to find the average speed offered by subscription.

Table S D-42: Description of DSL.

	Year of standard	Downstream (max)	Upstream (max)	Analog telephony	Distance max. [km]
IDSL	-	< 128 kbps	< 128 kbps	No	5
HDSL	1994	<1.5 Mbps	< 1.5 Mbps	No	3.6
ADSL	1998	< 8 Mbps	< 1 Mbps	Yes	3
G.dmt ADSL	1999	< 8 Mbps	< 1.5 Mbps	Yes	3
G.lite ADSL	2001	1.5 – 6 Mbps	128 – 384 kbps	Yes	3
ADSL2	2002	< 12 Mbps	< 1 Mbps	Yes	2
ADSL2+	2003	< 24 Mbps	< 2 Mbps	Yes	1.5
SDSL, G.shdsl	2004	< 2.3 Mbps	< 2.3 Mbps	No	5.5
VDSL	2006	< 52 Mbps	< 16 Mbps	Yes	0.1 – 2

Source: (96, 288, 298-300).

That being said, we have opted to use the average bandwidth of countries reported by NetIndex from Ookla (301). NetIndex compiles the results of two bandwidth velocity meters (Speedtest.net and Pingtest.net) and in this way estimates the average upstream and downstream speed for 164 countries since 01/01/2008 (a total of 8 million speed tests for for this date). A recent independent analysis by a groups of academics arrived at the conclusion that Ookla’s methodology gives a “realistic estimation” of the bandwidth speed for the most common uses of the web (302). Countries without information, or those where we suspect a bias in the measurement, are estimated using the average of the region to which the country belongs (see Table S D-43), or countries with simmlar socio-economic development. It is supposed that users of DSL and cable modem and wireless perform speed tests(because of DSL speed delivery problems or the sharing of speed with cable modem), while we suppose that users of dial-up, ISDN or fiber-optic do not make a significant number of such tests on these sites. We use the data from 01/01/2008 as an approximation on the average speeds of 2007 for each country (which entails a slight overestimation), and the simple average from daily tests from 2008 to estimate that year’s speeds.

It is well known that cable modem is generally faster than DSL. Revising several speed-tests which distinguish between the type of technology used, it is assumed that DSL is two times faster than cable modem (303, 304). With this, we may calculate the typical speed of DSL, cable modem and “others” in each country, taking the results from NetIndex as a

weighted average for each country: [% DSL users]\*[DSL performance] + [% CM users]\*[CM performance] =[NetIndex performance]. This formula has only one solution, considering that [% DSL users]+ [%CM users]= 100%; and supposing that [CM performance] = 2\*[DSL performance]. Additionally, given the lack of further information, we estimate that “others” (fixed Internet connections like wireless WiFi, satellite, power line, electric, non- identified, etc) achieve half the performance of DSL in 2007 for each country: [DSL performance] = [others performance]\*0.5. This respects country differences and aims at representing an average between un-identified narrowband and wireless broadband solutions.

During the ‘90s, the typical rates for downstream/upstream for DSL were 128/64 [Kbps] (305), and starting with the introduction of ADSL in 1998, rates of 256/64 [Kbps] were offered (265, 288, 306). As far as cable modems go, the rates in those first years varied between 1 and 3 [Mbps] for the downstream, and between 0.5 and 2.5 [Mbps] for the upstream, although many network operators limited the speed to 256/64 [Kbps] (307). Regarding “other” technologies, it is assumed that they had the same rates as dial-up up until 1997. Then, rates of 128 [kbps] downstream and 64 [kbps] upstream were utilized. By 2001, these “other” technologies had rates similar to those of the more common solutions of the time (i.e. ISDN BRI and DSL). This data is considered until 2001, and we consider the years 2002-2006 with a constant growth rate for each country. The results are reported in Table S D-43.

**Table S D-43: Simple average rates by region for DSL, Cable modem and others, DL/UL, in [kbps].**

DSL simple average of countries		1996-1997	1998-2001	2002	2003	2004	2005	2006	2007	2008
Africa	DL	128	256	286	322	367	422	489	589	771
	UL	64	64	76	91	111	137	169	210	321
Latin America and the Caribbean	DL	128	256	313	385	479	600	757	962	1,176
	UL	64	64	80	101	129	165	214	278	348
North America (USA/Canada)	DL	128	256	391	599	916	1,404	2,152	3,302	3,469
	UL	64	64	91	130	186	266	379	542	630
Asia	DL	128	256	321	416	559	781	1,135	1,716	1,980
	UL	64	64	85	117	166	243	370	584	668
Europe	DL	128	256	386	587	901	1,396	2,180	3,365	4,316
	UL	64	64	97	150	235	376	612	999	1,408
Pacific Ocean	DL	128	256	350	480	663	921	1,287	1,806	2,067
	UL	64	64	82	107	139	182	241	319	447

Cable modem simple average of countries		1997-2001	2002	2003	2004	2005	2006	2007	2008
Africa	DL	256	323	412	530	686	896	1,178	1,542
	UL	64	86	116	158	218	302	422	643
America Latina and the Caribbean	DL	256	351	486	677	952	1,348	1,925	2,352
	UL	64	90	128	183	263	381	556	695

North America (USA/Canada)	DL	256	439	754	1,296	2,228	3,835	6,604	6,939
	UL	64	102	164	263	421	676	1,083	1,259
Asia	DL	256	356	509	743	1,108	1,687	2,617	3,112
	UL	64	94	140	213	329	517	825	1,000
Europe	DL	256	432	736	1,265	2,190	3,819	6,583	8,454
	UL	64	108	184	318	559	998	1,788	2,581
Pacific Ocean	DL	256	392	605	938	1,463	2,292	3,612	4,134
	UL	64	92	134	197	290	429	638	895

Others/unidentified													
simple average of countries	86-90	1991-3	1994-5	1996-7	98-01	2002	2003	2004	2005	2006	2007	2008	
Africa	DL	9.6	14.4	28.8	33.6	56.0	73	95	125	166	220	294	387
	UL	9.6	14.4	28.8	33.6	33.6	38	46	56	68	83	105	161
Latin America and the Caribbean	DL	9.6	14.4	28.8	33.6	56.0	79	111	159	228	330	481	588
	UL	9.6	14.4	28.8	33.6	33.6	42	53	66	84	108	139	174
North America (USA/Canada)	DL	9.6	14.4	28.8	33.6	56.0	98	172	303	533	938	1,651	1,735
	UL	9.6	14.4	28.8	33.6	33.6	48	67	95	135	191	271	315
Asia	DL	9.6	14.4	28.8	33.6	56.0	80	117	175	267	414	654	778
	UL	9.6	14.4	28.8	33.6	33.6	44	58	78	106	147	206	251
Europe	DL	9.6	14.4	28.8	33.6	56.0	96	167	293	517	919	1,646	2,114
	UL	9.6	14.4	28.8	33.6	33.6	50	75	115	178	280	447	645
Pacific Ocean	DL	9.6	14.4	28.8	33.6	56.0	88	139	221	352	563	903	1,034
	UL	9.6	14.4	28.8	33.6	33.6	43	56	72	93	122	160	224

Source: Authors' own elaboration, based on NetIndex (301) and ITU (227). Note: Only countries that have the respective technologies are presented in the average.

## D.7.5 FTTH/B: Performance

FTTH/B (*Fiber To The Home/Building*) technologies use fiber optics to deliver access to the Internet, offering until 1 [Gbps] (K Opticom began to offer this residential service in Japan in mid-2008 (96)). Defining the actual performance of this technology is no easy task, given the wide range of existing bandwidth (mostly in OECD countries) and that many statistics do not distinguish between FTTH and FTTB. Reports suggest that in 2007 there exist two profiles: one for Japan and Korea, where it is known that by 2005 the majority of FTTH/B subscribers opted for connections of at least 50 [Mbps] (308, 309-311); and another for the remaining countries, which offered lower speeds.

The first deployments of FTTH began in Japan in 1997 (312), but subscriber statistics start in 2001, which we will consider as the starting with that year. It is known that the bandwidth offered was of 10 Mbps (308). We assume that bandwidth stayed this way until

2004<sup>46</sup> (271, 272, 313). The OECD Communications Outlooks (96, 118) enlists bandwidths offered by the main providers of FTTH services in 2006 and 2008. For example, in Korea, users could select from 10, 50, or 100 [Mbps]. (96) also reports that only 48% of the offered speed was actually observed by the users in FTTH/B connections. (314) reports that the average speeds offered to broadband subscribers in these Japan and Korea in 2006 were 61 and 45.6 [Mbps]<sup>47</sup>. Based on this, for the period from 2005 – 2007, we assume an actual transmission rate of 30 [Mbps] for Japan and Korea. Considering the sources cited, it is worth noting that this is a conservative assumption.

As for the remaining countries, (315) indicates that in 2009, all but 2 of the thirty OECD countries could obtain a FTTH connection of 20 [Mbps] and that in 12 of them it was possible to obtain services of at least 50 [Mbps]. The estimates are based on the data reported by OECD Outlooks (96, 116-118) and (111). In spite of the speeds offered, (96) reports that even in 2008, the actually observed downstream and upstream rates were of 14 [Mbps] and 2.2 [Mbps], respectively. This data is adopted for 2007.

**Table S D-44: Performance of FTTH/B in [kbps], UP = upstream; DN = downstream.**

	2001	2002	2003	2004	2005	2006	2007
Japan/Korea DN = UP	10,000	10,000	10,000	10,000	30,000	30,000	30,000
Other countries DN	2,000	4,000	6,000	8,000	10,000	12,000	14,000
Other countries UP	700	800	1,000	1,200	1,500	2,000	2,200

Source: Authors' own elaboration, based on various sources (see text).

## D.7.6 Compression of Content

The compression factors utilized are mostly the same as the ones used with hard disk drives. In the case of WWW traffic, we consider the same compression factors used for servers and for P2P and DDL traffic, those of PC (see Appendix C, Table S C-49). There exist two special cases: VoIP/Skype traffic and media streaming, which use the compression factors reported in Table S D-45.

**Table S D-45: Compression factors for different types of content**

<sup>46</sup> This assumption is based on the fact that in 2001 the e-Japan project was initiated, whose objective was to make Japan the most advanced country in terms of information technology resources in the 5 years that followed. For this reason, it is reported that in 2005, at least 30 million broadband subscribers had 10 [Mbps] and that 10 million FTTH subscribers had access to 100 [Mbps] (271, 272).

<sup>47</sup> According to Wikipedia (310), the average of FTTH in Japan in 2008 was 66 [Mbps] and 78 [Mbps] in Tokyo. Korea, on the other hand, with its eKOREA VISION 2006 initiative, set a goal of giving 5 million subscribers access to 100 [Mbps] in 2007 (313).

	Content	1986	1993	2000	2007	“Optimal”
Media Streaming	Video	1.0	1.0	27.0	60.0	60.0
	Audio	1.0	1.0	16.8	11.0	24.0
VoIP/Skype	Voice	1.0	1.0	7.9	8.3	8.3

Source: Authors’ own elaboration, based on B.4.3 and B.5.3.

The identification of the distribution of content traffic over the Internet is a complicated issue for, at least, three reasons: (i) The wide majority of studies about traffic only register the quantity of traffic, and do not analyze the type of content being sent; or they report the amount of minutes dedicated to different applications, and there is no way to translate minutes to the quantity of bits transmitted during said times; (ii) the distribution of the volumes of traffic per connected terminal is very assymmetric, which makes it difficult to speak of a “typical user” (it is estimated that about 10 % of hosts contribute to about 99 % of the total traffic) (316); and (iii) content distribution is also highly skewed at the worldwide level (it is dependent on the bandwidth connection and socio-demographic characteristics of the user). This being said, our approach is twofold: we first estimate the usage of different protocols over the Internet, which is a more reliable statistic: e-mail, FTP, WWW, *streaming*, instant messaging, NNTP, P2P, VoIP, DDL and tunnel/encryption (Table S D-46) (317)<sup>48</sup>; and then estimate the distribution of content for each protocol (text, images, videos, audio).

Table S D-46: Protocol/Applications considered in the study.

Protocol	Description
Email	The transmission of e-mail using protocols such as SMTP (Simple Mail Transfer Protocol) or POP (Post Office Protocol).
FTP	File transfers using the protocol of the same name (File Transfer Protocol), generally utilized by users who connect to a server.
www	Encapsulated traffic using the HTTP protocol (HyperText Transfer Protocol), which is the typical deployment of Internet web sites, which also include video and audio (like YouTube).
Media Streaming (incl. gaming)	Specialized traffic devoted to viewing multimedia files on line, through protocols such as RTP (Real-Time Protocol) or RTSP (Real Time Streaming Protocol), including gaming.
IM	Traffic from instant messaging application (such as Windows Live Messenger, Yahoo Messenger, among others).
NNTP	Transfers of information over the protocol named (Network News Transfer Protocol).
P2P	Traffic associated with Peer-to-Peer software, which allows users to share files using applications like Kazaa, Emule, eDonkey, BitTorrent, and others.
VoIP/Skype	Traffic from voice conversations over Skype or by VoIP (Voice

<sup>48</sup> Protocol is the name given to different standards which lay down methods for communicating or sending data over telecommunications networks.

	Over IP) protocols.
DDL	Just as the acronym implies (Direct Download Links), this is traffic that comes from download links, generally from Web-Hosting sites (like Rapidshare, for example).
Tunnel/Encryption	Traffic devoted to confidential information, such as private networks or VPN's (Virtual Private Networks), or related to security and network control or routing of traffic.
Unknown/Others	Traffic that cannot be classified in the above categories.

Source: Authors' own elaboration, based on various sources (see text).

For our purposes, we used "Internet Study 2007"<sup>49</sup> (317), "P2P Survey" (318) and Sandvine (319), which describe the composition of Internet traffic for different relevant geographic zones (Europe and the Middle East in Ipoque and North America, Latin America and Europe/Middle East/Africa in Sandvine), along with a specification of P2P (peer-to-peer<sup>50</sup>) content traffic. Sandvine (319) shows significant differences between downstream and upstream. While downstream is dominated by web traffic, upstream is dominated by P2P. P2P has grown decisively. Before the year 2000, P2P content was mostly pushed by music sharing (for example Audiogalaxy (1998); Napster (1999)), and then mostly by video sharing (eDonkey2000, BitTorrent, Gnutella and Freenet en 2000) (318). Something similar applies to streaming applications pre- and post-1997 (320). After studying these reports, we decided to establish two traffic profiles: one for OECD countries (developed countries), which is based on the content statistics of North America and Europe; and another for non-OECD countries (developing countries), based on the statistics from Latin America, Middle East and Africa (Table S D-47).

Most protocols carry different kinds of content. For instance, an e-mail or a web site may have just as many images as it has text. We use the information in Table S D-47 to form an estimate, which is based on several sources that consider a wide-ranging number of users scattered around the globe. Once we know the distribution for each of the four categories of content (text, image, audio and video) for each of the protocols and applications considered in this study, we may then determine the distribution of such content for both regions (Table S D-48).

<sup>49</sup>"The measurements took place during August and September 2007. Ipoque's PRX Traffic Managers installed in-line at the customers' Internet access and peering links generated the raw statistics data in real-time based on the traversing network traffic. Eighteen monitoring sites in five regions of the world contributed data to this study. Thirteen measurements sites were located at ISPs and five at universities. The regions are Australia, Eastern Europe, Germany, the Middle East and Southern Europe."

<sup>50</sup> P2P is an acronym for "peer to peer", a denomination given to applications that run not on server networks, but over connections that are established between different nodes or users of the system. This interaction between users is generally made over the Internet.



Table S D-47: Percentage distributions of Internet traffic classified by protocol and application for two traffic profiles, downstream and upstream.

<b>OECD (developed) DOWNSTREAM</b>	<b>1986- 1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Email	5.0	5.0	5.0	5.0	5.3	6.1	7.2	5.0	4.0	4.0	3.00	3.00	1.00	2.00	1.70	1.70	1.00	0.88	0.75
FTP	54.4	54.4	54.4	54.4	41.4	33.0	23.7	9.0	5.0	6.5	6.00	3.00	1.00	2.00	0.50	0.50	0.50	0.50	0.50
www	0.0	0.0	0.4	0.8	1.5	11.3	24.1	46.2	60.1	60.5	60.22	59.94	59.67	59.39	59.11	58.83	58.56	58.28	58.00
Media streaming (incl. gaming)	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.2	1.8	2.4	2.41	2.42	2.43	2.44	2.46	2.47	2.48	2.49	2.50
IM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.10	0.10	0.20	0.20	0.20	0.20	0.30	0.18	0.05
NNTP	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.10	2.00	3.00	4.00	4.50	5.00	5.00	4.88	4.75
P2P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.00	10.00	12.00	14.00	16.00	18.00	19.00	21.00	22.50
VoIP/Skype	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.20	0.30	0.40	0.50	0.60	1.00	1.00	1.38	1.75
DirectDownLink	-	-	-	-	-	-	4.3	4.3	4.3	4.3	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30
Tunnel/Encryption	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.30	1.00	1.50	2.00	2.00	3.00	3.00	3.50	4.00
Unknown/others	40.2	40.2	39.8	39.4	51.4	49.2	39.7	33.9	24.3	21.7	17.37	13.93	14.50	9.17	8.63	5.00	4.87	2.63	0.90

<b>Non-OECD (developing) DOWNSTREAM</b>	<b>1986- 1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Email	5.0	5.0	5.0	5.0	11.3	13.0	15.4	10.7	8.5	8.5	6.4	6.4	2.1	4.3	3.6	3.6	2.2	1.5	0.8
FTP	61.1	61.1	58.7	56.2	51.3	40.9	29.4	11.2	6.2	8.1	7.4	3.7	1.2	2.5	0.6	0.6	0.6	0.6	0.6
www	0.0	0.0	2.4	4.9	9.8	19.6	33.0	55.6	70.1	71.1	70.1	69.1	68.1	67.0	66.0	65.0	64.0	63.0	62.0
Media streaming (incl. gaming)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	0.1	0.1	0.3	0.5	0.6	0.7	0.8
IM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3
NNTP	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5	1.0	2.5	3.0	3.0	3.5	3.8	4.0
P2P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	10.0	11.6	13.1	14.7	16.3	17.9	19.4	21.0
VoIP/Skype	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.6
DirectDownLink	-	-	-	-	-	-	8.7	8.7	8.7	8.7	8.7	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Tunnel/Encryption	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	2.5	2.8	3.0
Unknown/others	32.0	32.0	32.0	32.0	25.7	24.6	11.6	11.9	4.6	1.5	1.1	2.3	8.0	2.3	3.6	2.7	2.0	1.5	1.0

<b>OECD (developed) UPSTREAM</b>	<b>1986- 1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Email	5.0	5.0	5.0	5.0	5.3	6.1	7.2	5.0	4.0	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.63	2.25
FTP	54.4	54.4	54.4	54.4	41.4	33.0	23.7	9.0	5.0	6.50	6.00	3.00	1.00	2.00	0.50	0.50	0.50	0.50	0.50
www	0.0	0.0	0.4	0.8	1.5	11.3	24.1	46.2	60.1	60.50	51.80	49.20	39.60	39.50	33.30	26.70	18.70	17.40	16.10
Media streaming (incl. gaming)	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.2	1.8	1.00	1.00	1.00	1.00	1.00	1.50	2.00	2.00	2.04	2.08
IM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.10	0.10	0.10	0.20	0.20	0.20	0.20	0.30	0.30	0.30
NNTP	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.25	0.40
P2P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	6.00	20.00	40.00	42.50	51.00	58.00	63.20	63.51	63.82
VoIP/Skype	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.20	0.30	0.40	0.50	0.60	0.60	0.70	2.60	4.50
DirectDownLink	-	-	-	-	-	-	4.3	4.3	4.3	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30	3.65	3.00
Tunnel/Encryption	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.30	1.00	2.00	2.00	3.00	3.00	4.00	4.00	5.00	6.00
Unknown/others	40.2	40.2	39.8	39.4	51.4	49.2	39.7	33.9	24.3	23.10	26.50	17.00	8.40	3.90	2.50	0.60	3.20	2.13	1.05

<b>Non-OECD (developing) UPSTREAM</b>	<b>1986- 1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Email	5.0	5.0	5.0	5.0	11.3	13.0	15.4	10.7	8.5	8.50	6.40	6.40	2.10	4.30	3.60	3.60	3.60	3.68	3.75
FTP	61.1	61.1	58.7	56.2	51.3	40.9	29.4	11.2	6.2	8.10	7.40	3.70	1.20	2.50	0.60	0.60	0.60	0.60	0.60
www	0.0	0.0	2.4	4.9	9.8	19.6	33.0	55.6	70.1	71.10	63.10	61.00	52.00	48.70	47.00	40.90	33.50	29.80	26.10
Media streaming (incl. gaming)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	0.10	0.10	0.30	0.40	0.50
IM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.10	0.10	0.10	0.10	0.20	0.20	0.20	0.20	0.20
NNTP	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.30	0.40
P2P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	4.20	14.10	28.30	30.10	36.10	41.00	44.70	51.43	58.16
VoIP/Skype	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.10	0.20	0.20	0.30	0.30	0.40	1.00	2.00	3.00
DirectDownLink	-	-	-	-	-	-	8.7	8.7	8.7	8.70	8.70	7.00	6.00	5.00	5.00	4.00	3.50	2.75	2.00
Tunnel/Encryption	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.70	1.70	2.00	3.00	4.00	4.00	5.00	5.00	5.00	5.00
Unknown/others	32.0	32.0	32.0	32.0	25.7	24.6	11.6	11.9	4.6	1.50	8.10	5.30	6.90	4.80	2.90	4.00	7.40	3.85	0.29

Source: Authors' own elaboration, based on (263, 264, 317, 318, 321-327). Note: between 1986 and 1989 we will assume that the distribution remained the same at the time, since the main change was the introduction of the web in 1989.

**Table S D-48: Distribution percentages of internet traffic content for different protocols and applications**

<b>Web [ bytes]</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	100	85.8	71.6	57.3	43.1	28.9	24.9	24.5	22.8	28.3	33.7	43.5	53.4	53.0	52.7	52.4	46.6	40.7	34.9
Image	0.0	0.0	14.2	28.3	42.5	56.7	56.8	55.2	47.6	47.3	47.1	40.2	33.4	30.4	27.5	26.0	28.1	30.2	32.3
Sound	0.0	0.0	0.0	0.0	2.2	4.3	3.0	3.2	3.9	4.0	4.2	3.6	3.1	2.8	2.5	2.2	2.2	2.2	2.2
Video	0.0	0.0	0.0	0.0	2.8	5.5	8.4	13.1	19.9	14.7	9.6	8.0	6.3	10.1	13.9	17.7	21.5	25.3	29.1
Unidentified compressed	0.0	14.2	14.3	14.3	9.4	4.6	6.8	4.0	5.8	5.6	5.5	4.7	3.9	3.6	3.4	1.7	1.7	1.6	1.6
<b>FTP [ bytes]</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	46.7	42.6	38.6	34.5	30.5	26.4	22.4	18.3	14.3	10.3	6.2	2.2	4.3	6.5	8.7	10.9	13.0	16.8	10.9
Image	8.0	7.3	6.7	6.0	5.3	4.6	4.0	3.3	2.6	1.9	1.3	0.6	1.2	1.8	2.4	3.0	3.6	0.6	1.9
Sound	0.0	0.0	0.0	0.0	10.9	21.9	32.8	43.8	54.7	65.6	76.6	87.5	75.0	62.5	48.6	30.0	11.3	8.3	10.4
Video	0.0	0.0	0.0	0.0	1.1	2.1	3.2	4.2	5.3	6.3	7.4	8.4	16.8	25.2	27.0	44.2	61.4	69.4	72.4
Unidentified compressed	45.3	50.1	54.8	59.5	52.2	45.0	37.7	30.4	23.1	15.9	8.6	1.3	2.7	4.0	13.3	12.0	10.6	4.9	4.3
<b>Email [ bytes]</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	100	97.7	95.5	93.2	90.9	88.7	86.4	84.1	81.9	79.6	77.3	75.1	72.8	70.5	68.3	66.0	63.7	61.5	59.2
Image	0.0	1.9	3.7	5.6	7.4	9.3	11.1	13.0	14.9	16.7	18.6	20.4	22.3	24.1	26.0	27.8	29.7	31.6	33.4
Sound	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Video	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Unidentified compressed	0.0	0.4	0.8	1.2	1.6	2.1	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.3	5.7	6.2	6.6	7.0	7.4
<b>Streaming Media</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Sound	0.0	0.0	0.0	0.0	0.0	0.0	100	100	100	90.6	81.1	71.7	62.2	52.8	43.3	33.9	24.4	15.0	5.6
Video	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.4	18.9	28.3	37.8	47.2	56.7	66.1	75.6	85.0	94.4
<b>P2P</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	4.3	6.5	8.7	10.9	13.0	16.8	10.9
Image	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.2	1.8	2.4	3.0	3.6	0.6	1.9
Sound	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	87.5	75.0	62.5	48.6	30.0	11.3	8.3	10.4
Video	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	16.8	25.2	27.0	44.2	61.4	69.4	72.4
Unidentified compressed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	2.7	4.0	13.3	12.0	10.6	4.9	4.3
<b>DDL</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	0.0	0.0	0.0	0.0	0.0	0.0	22.4	18.3	14.3	10.3	6.2	2.2	4.3	6.5	8.7	10.9	13.0	16.8	10.9
Image	0.0	0.0	0.0	0.0	0.0	0.0	4.0	3.3	2.6	1.9	1.3	0.6	1.2	1.8	2.4	3.0	3.6	0.6	1.9
Sound	0.0	0.0	0.0	0.0	0.0	0.0	32.8	43.8	54.7	65.6	76.6	87.5	75.0	62.5	48.6	30.0	11.3	8.3	10.4
Video	0.0	0.0	0.0	0.0	0.0	0.0	3.2	4.2	5.3	6.3	7.4	8.4	16.8	25.2	27.0	44.2	61.4	69.4	72.4
Unidentified compressed	0.0	0.0	0.0	0.0	0.0	0.0	37.7	30.4	23.1	15.9	8.6	1.3	2.7	4.0	13.3	12.0	10.6	4.9	4.3
<b>NNTP</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
<b>VoIP/Skype</b>	<b>1986-1989</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>

Voice/audio	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
<b>Tunnel/Encryp.</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
<b>Unknown</b>	<b>1986-89</b>	<b>1990</b>	<b>1991</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>
Text	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Source: Authors' own elaboration, based on: (328); FTP: (329); www: (330-339); Streaming: (340); P2P: (117, 318, 319, 341).

## D.7.7 Actual use

To estimate the actual use of internet one must make a separation between what we call “actual gross usage” (how much time people have reported “using” the Internet), and the “actual net usage” (how much time the user actually uses the available bandwidth to send/receive information).

ITU (227) provides the number of minutes per year in which the dial-up connections are used per country. We calculate the (subscription) weighted average. The data for 1986 is based on the year 1993, supposing that the amount of minutes per subscription did not change during those years (during this time the Internet was not yet commercial, but was mostly used in universities in countries in the OECD). Given that all subscriptions in 1986 had the same performance and were dial-up (with 9.6 [kbps] upstream and downstream), it turns out that for 1986 gross use equals net use.

For the years 1993, 2000 and 2007, gross and net use begins diverging. Additionally to the dial-up minutes reported by the ITU (227), we collect the gross usage reported by broadband users in hours per week (Table S D-49). However, we know that even though users report “being” on the Internet for that much time, they are not actually using their available bandwidth every second. In fact, just as with cell phones, if all devices should use this capacity at the same time, the network would collapse (an effect that we refer to as the “midnight on New Year’s Eve effect”). Normally, a user will download an email, and then dedicate in a few minutes to reading, or one streams a video, and even though the full video is already accumulated in the buffer, time passes while the entire video is watched. The question is: how much of this “gross use” accounts for the “net use” of the effective net communication of the user?

**Table S D-49: Gross use: Average number of hours per week that a subscriber uses the Internet.**

Gross	Broadband				Dial-up			
	1986	1993	2000	2007	1986	1993	2000	2007
OECD	-	5.2	6.9	12.1	1.0	1.0	2.3	1.7
non-OECD	-	4.0	5.3	9.3	-	0.7	1.5	0.5

Source: Authors own elaboration based on (37-40, 42, 45-48, 51, 53, 59, 66, 67, 227, 342-350).

To form a clearer idea, we look to statistics which estimate the capacity of internet based the relevant backbone networks. One of the most consistent and persistent sources is the The Minnesota Internet Traffic Studies (MINTS), led by Odlyzko (351). These reports estimate a worldwide traffic of between 3000-5000 PB/a month for 2007, but do not include non-Internet IP traffic like “corporate IP WAN traffic, IP transport of TV/VoD”. Clearly we include this class of traffic, given that is competes with broadband (i.e. during 2007) and is also counted as information received by the user. Another estimate provided by Cisco Systems (263, 264) estimates 4,675 TB/a month for IP traffic, plus 1,966 for non-IP traffic, giving a total of 6,641 TB/a month for 2007. Using this data, we would have to divide our gross use of broadband in 2007 by a factor of 10.3. This means that of the 104 minutes a person from the

OECD uses the Internet on average per day, only during 10.4 minutes the user effectively takes advantage of the entire bandwidth available. The same estimate is made for the years 2000 and 1993, based on the data from Odlyzko (351), which results in the fact that in 2000 the gross broadband use must be divided by a factor of 2.1 and in 1993 by 3.3 (it should be remembered that there is no need to adjust the actual use of dial-up, given that it is measured in minutes of actual traffic). Table S D-50 shows the result. It is interesting to note that the net use increased up to 2000 (in which time there was a high demand for band width) and that later the demand began to fall (when the supply of bandwidth increased with so-called “broadband”).

**Table S D-50: Net use: Average number of hours per week in which a subscriber effectively uses the available bandwidth.**

NET	Broadband				Dial-up (gross=net)			
	1986	1993	2000	2007	1986	1993	2000	2007
OECD	-	1.6	3.3	1.2	1.0	1.0	2.3	1.7
non-OECD	-	1.2	2.6	0.9	-	0.7	1.5	0.5

Source: Authors’ own elaboration based on (37-40, 42, 45-48, 51, 53, 59, 66, 67, 227, 264, 264, 342-351).

## D.8 Personal Navigation Device (GPS)

Personal navigation devices are linked to the GPS system (Global Positioning System), which is a global navigation system provided by satellite (GNSS) that allows one to find the position of an object, person, vehicle or ship anywhere in the world. GPS works through a network of 32 satellites (28 operational and 4 used as back up).

### D.8.1 Personal Navigation Device: Quantity

The amount of different GPS devices is presented in Table S D-51. A three-year shelf life is assumed for devices that are integrated in mobile telephones, like for the phones themselves. We expect a useful lifetime of 5 years for standalone GPS units.

**Table S D-51: Shipments of different types of GPS (In millions of devices).**

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
PND	-	-	-	-	-	-	-	-	-	1.5	5.0	15.0	25.0
Professional	0.4	0.9	1.3	1.7	2.1	3.0	4.5	7.2	7.8	9.5	11.0	13.0	14.0
Automated dashboard	0.4	0.9	1.3	1.7	2.1	3.0	5.5	6.5	7.5	9.1	10.0	22.0	30.0

Low cost low power	0.0	0.0	0.0	0.1	0.1	0.1	0.2	1.5	3.5	8.9	19.0	35.0	53.0
Mobile phone	0.0	0.0	0.0	0.1	0.1	0.1	0.3	2.0	3.0	4.0	30.0	80.0	164.0
SUM	0.9	1.8	2.7	3.5	4.4	6.2	10.5	17.2	21.8	33.0	75.0	165.0	286.0

Source: (352). Note: The years before 2000 are estimated in a linear fashion, considering that the GPS system was launched in December 1993.

### D.8.2 Personal Navigation Device: Performance

Originally, each device was limited to monitoring five or six satellites, but over time, this number grew progressively. In 2007, receivers typically monitored between 12 and 20 satellites. Each GPS satellite continually transmits a navigation message at the rate of 50 bits per second (353). We assume that up to the year 2000, each device had a performance of five satellites ( $5 \times 50 \text{ bits/s} = 250 \text{ bits/s}$ ), and in 2007 about twenty ( $20 \times 50 \text{ bits/s} = 1.0 \text{ [kbps]}$ ), with a linear approximation for the years in between.

### D.8.3 Personal Navigation Device: Compression of content

Forward Error Correction (FEC) is used with a  $\frac{1}{2}$  convolution code rate, resulting in a message of 25 bits/s, while the respective signal is of 50 bits/s (354). It is assumed that these 25 bits are at the optimal level of compression.

### D.8.4 Actual use

Personal navigation devices are mainly used in the United States and Europe, representing 87.5% of the world market in 2007 (355). In the United States, an average person spends around 43 minutes a day using some form of transport (356, 357) report that half of GPS users use the devices on a regular basis. So, for lack of better statistics, we assume that half of GPS device owners use their device for 43 minutes per day.

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## E Computation

### E.1 General concepts

#### E.1.1 MIPS as an indicator of hardware performance

Measuring the computational power of digital devices is not an easy task, chiefly because their characteristics are multidimensional (1-3). The final choice of our unit of measurement was determined principally by the availability of relevant and consistent statistics, more than their robustness.

##### E.1.1.1 The selection of Dhrystone MIPS 1.1

Despite the disadvantages that this metric possesses, which makes it seem like one of the weakest (3), we utilized VAX MIPS as a unit of measurement. This permitted us to use the extensive databases reported by (1, 2, 4, 5). Nordhaus's statistics generate a “timeline” of performance from 1850 to 2006 – starting with manual calculation with an abacus– based on work by McCallum and the analytical methods of Knight and Moravec. McCallum and Nordhaus normalize performance values to the DEC VAX 11/780 machine (1 MIPS with the Dhrystone 1.1 benchmark) (6). We opted to continue the same line of work. This implies that the performance of other devices must be in the same units and, in case they are in other units, we must use a transformation to VAX MIPS. If the performance were obtained using the Dhrystone MIPS 2.1 benchmark, we multiply the value with 0.943, which makes it comparable with the Dhrystone 1.1<sup>51</sup>.

##### E.1.1.2 From SPEC to Dhrystone MIPS 1.1

With the end of standardizing one unit of measurement, various computational system manufacturers joined in the *Standard Performance Evaluation Cooperative* (SPEC) (SPEC89, SPEC92, SPEC95, SPEC2000, and SPEC2006) (7). When reported in SPEC, we utilize the benchmark SPEC CPU2000 (i.e. CINT2000 “base”), because it has performance measures for computer systems between 2000–2006.<sup>52</sup>

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<sup>51</sup>This is obtained from the ratio of DIPS achieved by the VAX 11/780 with both benchmarks, that is: [MIPS Dhrystone 1.1] / [MIPS Dhrystone 2.1] = [1657 DIPS] / [1758 DIPS] = 0.943

<sup>52</sup> This utilizes, as a reference machine, a Sun Ultra 5-10 with a 300 [Mhz] SPARC processor and 256 MB of memory (RAM), whose benchmark execution time is assigned a score of 100 and, based on this, we assign the value of the measurement of other machines.

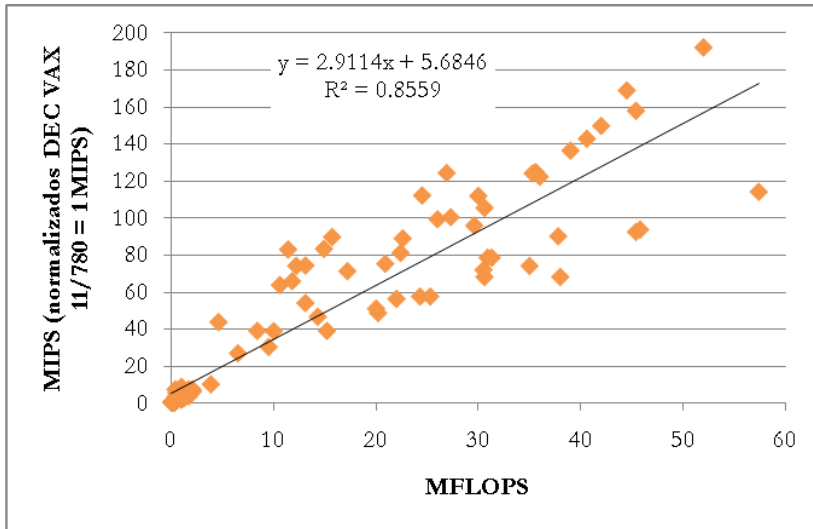
The conversion to VAX MIPS is given by a series of relationships between distinct benchmarks found in the literature. In the first place (8), determined that the ratio between SPECint2000 and SPECint92 is equal to 4.5; later, given that SPECint92 and SPECint89 use the same machine as a frame of reference (also the VAX 11/780), (9) defines that the results of both tests are comparable. Therefore it can be said that the ratio between SPECint2000 and SPECint89 is equal to 4.5. On the other hand, (10) found that the results of SPECint89 and Dhrystone 2.1 are related by a factor equal to 1.5. Thus, given the relationship between Dhrystone 2.1 and Dhrystone 101 previously mentioned, the relationship between SPECint2000 and Dhrystone 1.1 is arrived at in the following manner: [1 Dhrystone MIPS 1.1] = 4.5 x [SPEC2000 / 1.4143].

### ***E.1.1.3 From FLOPS to Dhrystone MIPS 1.1***

Supercomputer performance is measured in MFLOPS (Millions of Floating Points Operations Per Second), that is to say, the number of floating point operations that the program executes – which can be derived from the size of the matrix representing the system of equations that the device must resolve in order to measure its performance (11). Lamentably, there is no straightforward formula for the conversion between FLOPS and MIPS. The two types of metrics measure complementary computations. However, for our investigation, we strive for having one single metric.

McCallum (12) supposes that each floating-point operation requires that the processor executes (approximately) 6.5 instructions (1 MFLOPS = 6.5 MIPS). This conversion rate is based on a single datum, that of the VAX 11/780 from 1977, that achieves 0.14 MFLOPS and 0.91 MIPS. Following this logic and extending to the 97 machines from 1981-1995 for which Giladi (13) reports MFLOPS and MIPS, we observe that over the years the relationship between MFLOPS and MIPS is close to 1:3 (as shown in Figure S E-1). This implies a constant conversion rate of 3 MIPS for each MFLOPS, even for the post-1995 period. In short: 1 MFLOPS = 3 MIPS).

**Figure S E-1: Relationship between MFLOS and MIPS, 1981-1995 (n=97).**



Source: Authors' own elaboration, based on (13).

## E.1.2 Speculations on the contributions of faster algorithms<sup>53</sup>

Theoretically, the world's computational capacity depends on three factors:

- infrastructure: the amount of computational devices;
- hardware: the hardware capacity of computational devices (measured in MIPS or any other hardware indicator);
- software: the speed of the applied algorithms.

Conceptually, the logic is similar to what we argue for information storage and communication, which depends on the installed infrastructure, its performance (or bandwidth), and on the level of compression of the respective content. The compression of content allows effectively storing and communicating more information with the same amount of hardware. As we have seen, compression algorithms came a long way during the past two decades and it does make a difference. As evidenced by the notes on (B Compression), the specification of the contributions of compression gave us a lot of headache, but we finally came up with what we consider to be reasonable approximations. Translating this logic to the case of computation, we also know that more efficient algorithms allow the realization of more computations with the same amount of hardware. For example, an algorithms that runs in polynomial time, such as a discrete Fourier transformation used for the compression of lossy images and sound compression (which runs in  $O(N^2)$ ) is much slower than a fast Fourier transformation, which runs in  $O(N \log N)$  (for more on algorithms and O-notation, see 14). Running both on the same amount of hardware makes a significant difference. If we would have a measure on these advancements, we could (similar to what we did with storage and communication) argue that computer hardware has contributed X % to technological progress in computation, while better software has contributed Y %

<sup>53</sup> We would like to thank Len Adleman, from the University of Southern California, for his inspiring words and ideas for this section.

during recent decades. Nevertheless, we did not execute this same exercise for the case of computation. Why not? The reasons are both theoretical and practical in nature.

Our main theoretical doubt is that the theoretical basis for performance measurements for computers is much less solid than the theoretical basis for information storage and communication. For the latter, Shannon (15) gave us an ultimate measure with the bit, which is defined as a received symbol that reduces a given probability space in half (i.e. using entropic coding, which approximates the entropy of the message). This definition is independent from the specific task or content and measures the reduction of uncertainty in a strict probabilistic sense. One bit reduces uncertainty by half. In contrary, there is not only one thing that is achieved by “one computation”. What is the final ultimate goal of computation? If we would have two computations, both in their fastest available algorithmic speed (normalized on what is defined to be the “fastest in 2007”), but focusing on two different tasks, would those two be comparable? We are not aware of a theoretical framework that would allow us to unambiguously reconcile these questions.

Even if we would go ahead and add some kind of normalization on “what is considered to be the fastest possible computation for a specific task in 2007”, we would be confronted with several practical hurdles. We would need:

- (a) statistics on the performance and running speed of a particular class of algorithms dedicated at a specific kind of task at a given point in time;
- (b) statistics on the most commonly used algorithms on different kinds of equipment;
- (c) statistics on how frequently which kind of task is executed on which kind of computer.

With the sufficient resources, we are confident that one could come up with an estimate for (a), i.e. running time in O-notation. We know that algorithms have improved significantly over the past couple of decades, even though it seems like the largest leap have been made before the period of our study. The Journal Computing in Science and Engineering was brave enough to enlist what they consider to be the top ten algorithms of the twentieth century (16). From those selected, one gets the impression that the hay days of the greatest discoveries in algorithms were much more during the middle of the 20<sup>th</sup> century, than toward its end.<sup>54</sup> This does not mean that since then algorithms did not improve, but they improved less, mainly by improvements in leading constants. While not too exciting theoretically, the importance of constants is not to be underestimated for our practical purposes, since an algorithm that runs twice as fast, is equal to roughly 1.5 years of progress in computational hardware (which doubles every +/- 18 months). It is very likely that one will find important advancements, especially with regard to gaming-algorithms and approximation algorithms.

Regarding statistics on (b) and (c), it would maybe be possible to justify some estimate on which kinds of computer use are capable of which kind of algorithms, but it would be highly speculative to

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<sup>54</sup> The top ten of the Journal Computing in Science and Engineering include: the Dantzig simplex method for linear programming (1947); Krylov subspace iteration (1952); The Metropolis Algorithm (1953); The Fortran I compiler (1957); The QR algorithm (1958); the decompositional approach to matrix computation (1961); a perspective on Quicksort (1962); the Fast Fourier transform (1965); Integer relation detection (1977); the fast multipole algorithm (1987). Furthermore, not in this list, we might speculate that many computations are nowadays spent on public-key cryptography, like RSA (1978).

estimate the proportions of time dedicated to the actual execution of each of them. Let us do some speculation. From our estimates we know that some part of the world's computational power is dedicated to assisting communication and storage devices in the encoding and decoding of digital information. We could track the speed improvements of the leading compression algorithms to estimate technological progress for these tasks. Besides, we know that videogame consoles heavily focus on image transformation, and mainframes and supercomputers execute some kind of simulation or optimization tasks. Servers will probably be dedicated to some kind of routing or sorting (for example through search engines). This would leave us with some broad groups (compression algorithms, image and sound transformation, simulation, optimization, sorting, etc). However, while personal computers are general-purpose computers capable of executing quite sophisticated algorithms, they are usually used for very uneventful tasks, such as typing or the reproduction of some media. How many seconds is the typical personal computer used for which kind of computational task? How long does a program "sort" numbers and how long does it reproduce media? What are the most typical algorithms involved in word processing and how frequent is each one used? We would need to have some approximation of this in order to be able to weight the technological progress made by the advancements of algorithms.

Summing up, in order to estimate the contributions of faster algorithms to the world's capacity to compute information one faces both theoretical and practical challenges. Based on a disputable theoretical framework, one would require the necessary resources to create statistics on the actual usage of algorithms (which we do not have at this point). While it would be very interesting and exciting to compare hardware and software contributions to the global computational capacity, we consider it to be highly speculative. We decided not to pursue this task at this point and instead leave the reader with these speculations, which might inspire future work in this area. This being said, our numbers of computational capacity (in MIPS), merely present the contributions of changes in computational infrastructure and changes in computational hardware performance.

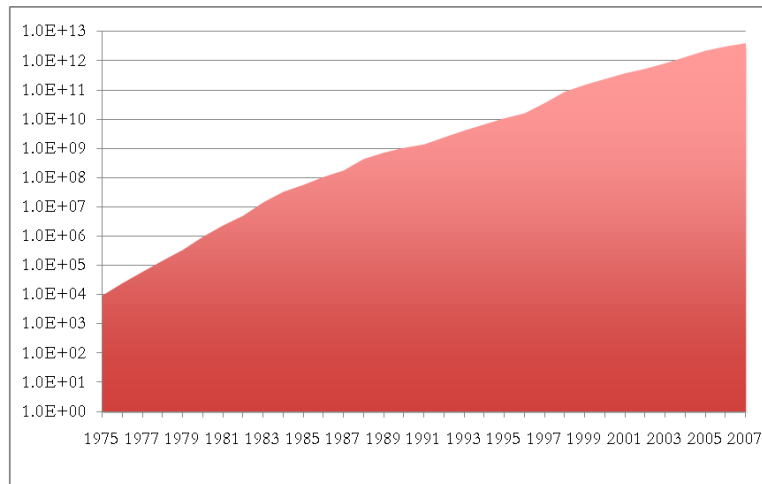
### **E.1.3 General-purpose and application-specific computer**

Sections E.2 until E.7 cover what we define "general-purpose computer" (for which we also include estates for effective gross usage), and Sections E.8, E.9 and E.10 refer to application-specific computer. The case of electronic calculators (E.6) is somewhat ambiguous, as it could justifiably be classified as both. In this presentation we include it into the group of general-purpose computers in order to give this group a solid base rate.

## **E.2 Personal computers (PC)**

In this section, we will consider personal computers (PCs, laptops, mini-computers and low-end workstations). We will use the acronym "PC" for this group, independent of the producer (HP, Dell, Apple, etc) and its portability (workstation or notebook/laptop).

Figure S E-2: Computational capacity of personal computers (MIPS, semi-logarithmic presentation).



Source: Authors' own elaboration, based on various sources (see text).

## E.2.1 Personal computers: capacity

The total number of personal computers is extracted principally through the International Telecommunications Union [ITU] database (17).<sup>55</sup> The intervening years were estimated using a constant growth rate.

Table S E-1: Number of personal computers installed 1985 - 2007.

Year	1985	1986	1987	1988	1989	1990
MIPS	33,000,000	41,191,836	51,701,550	74,910,346	87,744,045	102,517,280
Year	1991	1992	1993	1994	1995	1996
MIPS	115,919,664	133,852,707	151,930,586	177,082,348	209,691,057	245,347,583
Year	1997	1998	1999	2000	2001	2002
MIPS	288,469,875	336,707,817	394,111,836	465,460,671	527,835,914	590,429,449
Year	2003	2004	2005	2006	2007+	
MIPS	666,409,514	754,780,982	848,302,252	945,729,882	1,034,024,833	

Source: Authors' own elaboration, based on (17).

It is important to note that the ITU reports the quantity of PCs per country, that is to say, it contains all computers accumulated, from those that are sold in a particular year, as well as those that have been sold in previous years. In order to allocate the respective performance of those computers, we need to disaggregate the total. For this, we orient ourselves at the useful lifetime of hard disks (see C.8.1), which is equal to 10 years for 1976-1986, 7 years from 1987-1989, and 5 years from 1990-2007 (various sources point to an actual lifespan of between 3 and 7 years; 18-22). Each computer is

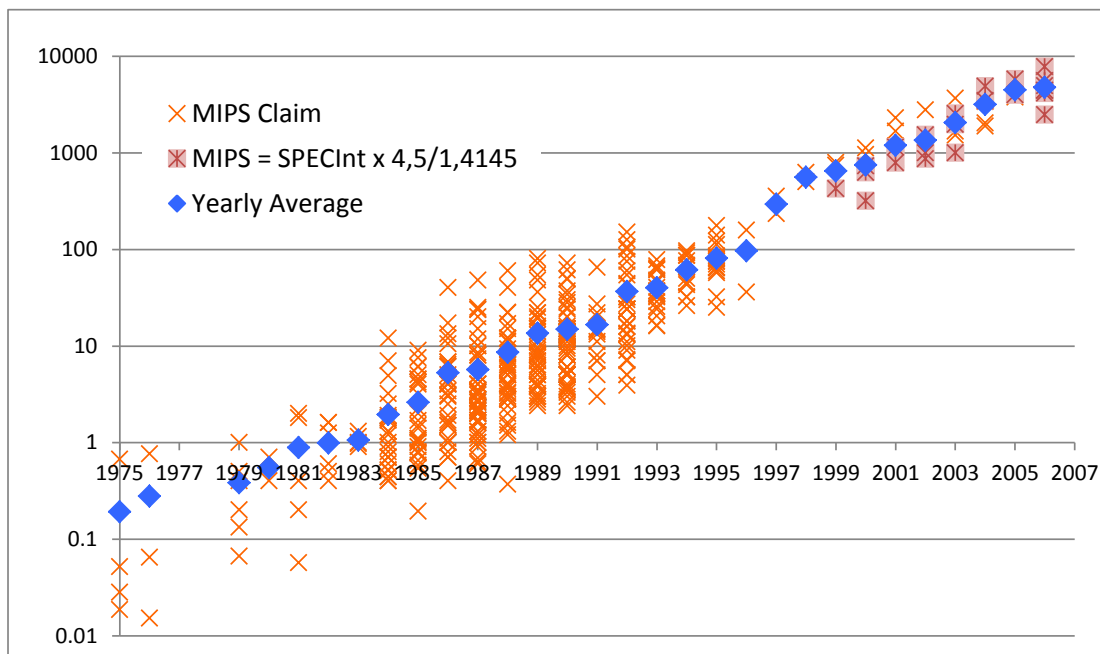
<sup>55</sup> To complete the series –especially 1975 and 1985 – we utilized reported data referring to the number of computers installed in the United States and the world through (283).

multiplied by their corresponding capacity based on year of production and remains constant during the specified number of years. In the year after the last year of useful life, the computing performance is upgraded to the newest technology, which is equivalent to saying that all machines which have completed their useful life are replaced by new computers.

### E.2.2 Personal computers: performance

The principal sources from which we extract the processing levels are (1, 4, 5, 12, 23-25). From these, we aggregate the performance of 499 computers distributed from the period of 1975-2006 (of which 133 are PCs, 282 mini-computers, and 84 low end-work stations). The performance of various equipment from 1999-2006 are measured in SPEC and we applied the conversion  $MIPS = SPECInt * (4.5/1.4145)$ , with a linear extension of the computing power for 2007 (which is in accord with the general tendency detected in Figure S E-3).

Figure S E-3: Personal computer performance 1954 - 2006 (n=5162), en MIPS.



Sources: Authors' own elaboration, based on (1, 4, 5, 12, 23-25).

Table S E-2 summarizes the average performance of PCs for the period 1975-2007.

Table S E-2: Personal computer performance 1975 - 2007 [in MIPS].

Year	1975	1976	1977	1978	1979	1980	1981
MIPS	0.19	0.28	0.31	0.35	0.38	0.55	0.89
Year	1982	1983	1984	1985	1986	1987	1988



MIPS	0.99	1.06	1.95	2.62	5.28	6.32	8.59
Year	1989	1990	1991	1992	1993	1994	1995
MIPS	13.6	14.9	16.6	36.7	40.2	61.4	81.3
Year	1996	1997	1998	1999	2000	2001	2002
MIPS	97	294	561	651	749	1,197	1,351
Year	2003	2004	2005	2006	2007+		
MIPS	2,056	3,177	4,495	4,756	5,017		

Source: Authors' own elaboration, based on various sources, i.e. (1, 4, 5, 12, 23-25). +: Linear estimation.

### E.2.3 Personal computers: effective use

We usually report the number of maximally possible computations (supposing that all machines run 24 hours a day). However, to put things into perspective, we also make estimations on effective gross usage. We use global Internet usage statistics to approximate PC use. The reported data represent the "gross" use value; that is to say, we approximate how many hours a week the user is interacting with the computer, not how much time the computer is running at maximum capacity.

Table S E-3: Average gross use of computers/Internet

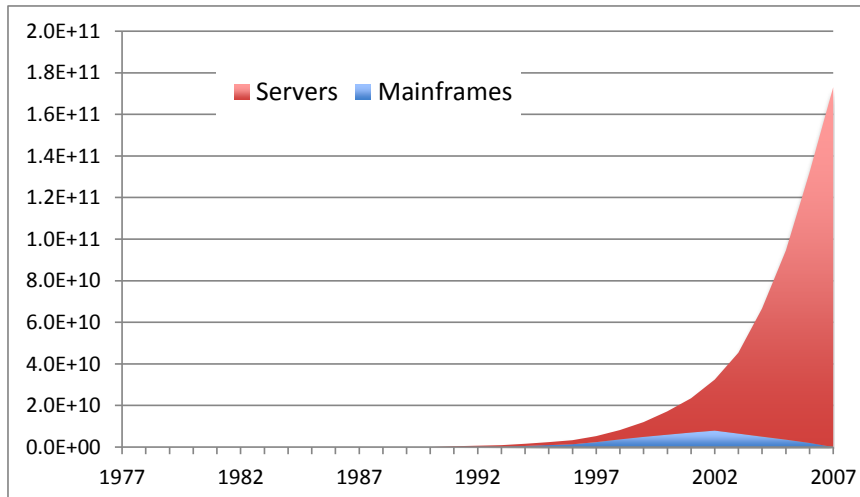
		1986	1993	2000	2007
Hours per week	OECD	1.0	5.2	6.9	12.1
	Non-OECD	0.7	4.0	5.3	9.3
Weighting for number of computers	OECD	100%	87%	80%	67%
	Non-OECD	0%	13%	20%	33%
Average	Global	1	5	6.6	11.2

Source: Authors' own elaboration based on (26-49)

## E.3 Professional computers

In this section, we consider professional computers (mainframes, servers, and mid-/high-end workstations).

Figure S E-4: Computational capacity of professional computers (MIPS).



Source: Authors' own elaboration, based on various sources (see text).

### E.3.1 Professional computers: quantity

Due to the lack of a better historical record, we estimate the number of mainframes based on the number of hard disks that were sent to mainframe and server manufacturers reported by Porter (50-61). Mainframes are not recorded after 2002, because of their rapidly decreasing numbers and their subsequent integration into the statistics on “mid-range and high-end enterprise servers”. With the last officially recognized mainframes shipped in 2002, their installed number reaches zero in 2007 (after a five years lifespan). For this calculation we assume that each mainframe contains only one hard disk (though this disk may be very large).

Table S E-4: Quantity of hard disks shipped for mainframes in thousands (= quantity of mainframes).

Year	# equipment	Year	# equipment	Year	# equipment
1978	57	1988+	441	1998	2,339
1979	72	1989	446	1999+	1,875
1980	92	1990	610	2000	1,280
1981	106	1991+	676	2001+	1,091
1982	165	1992+	823	2002	960
1983+	275	1993	868	2003+	-
1984+	385	1994+	1,106	2004+	-
1985	345	1995+	1,331	2005+	-
1986	327	1996	1,463	2006+	-
1987	389	1997+	1,962	2007+	-

Source: Unmarked: Estimation based on (50-61), +: Linear Estimation.

The quantity of servers from 1996-2007 is based on data for volume servers, mid-range enterprise servers, and high-end servers from the International data Corporation (IDC) (62). For the years pre-1996, we use the number of hard disks in servers, just as for mainframes. However, according to the technical specification reports on hard disk arrays presented by Porter (50-61), the number of drives per array is extremely variable. Therefore, we calculated the quantity of disks per server for 1996 (which turns out to be 5), and estimated a constant growth rate for the number of disk per sever for the period since 1980 (for which we assume 1 disk per server) (see Table S E-5).

**Table S E-5: Quantity of servers shipped in thousands.**

Year	# equipment	Year	# equipment	Year	# equipment
1981	195	1990	1,770	1999+	3,589
1982	138	1991	1,607	2000+	4,222
1983	291	1992	1,637	2001+	4,197
1984	545	1993	1,405	2002+	4,397
1985	723	1994	1,619	2003+	5,237
1986	823	1995	1,762	2004+	6,276
1987	881	1996+	1,751	2005+	7,017
1988	934	1997+	2,256	2006+	7,473
1989	897	1998+	2,862	2007+	7,974

Source: Unmarked: Estimation based on (50-61), +: (62).

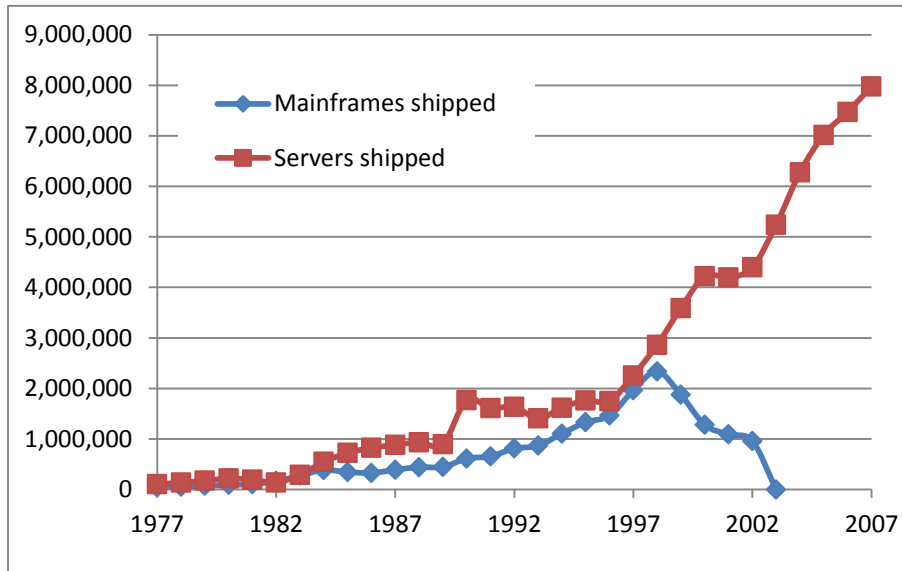
**Table S E-6: Quantity of hard disks per server.**

Year	Disks per server	Year	Disks per server	Year	Disks per server
1980+	1.00	1989+	2.47	1998	5.74
1981+	1.11	1990+	2.73	1999	4.52
1982+	1.22	1991+	3.02	2000	3.84
1983+	1.35	1992+	3.34	2001	5.24
1984+	1.50	1993+	3.70	2002	6.75
1985+	1.65	1994+	4.09	2003	5.44
1986+	1.83	1995+	4.52	2004	5.00
1987+	2.02	1996	5.00	2005	5.07
1988+	2.24	1997	5.69	2006	5.57
				2007	5.73

Sources: + on (50-61), others: (62).

The results for both mainframes and servers can be appraised in Figure S E-5. What is clear is that, in recent years, servers have replaced mainframes.

**Figure S E-5: Quantity of servers and mainframes shipped.**



Source: Authors' own elaboration, based on Disk Trend and IDC.

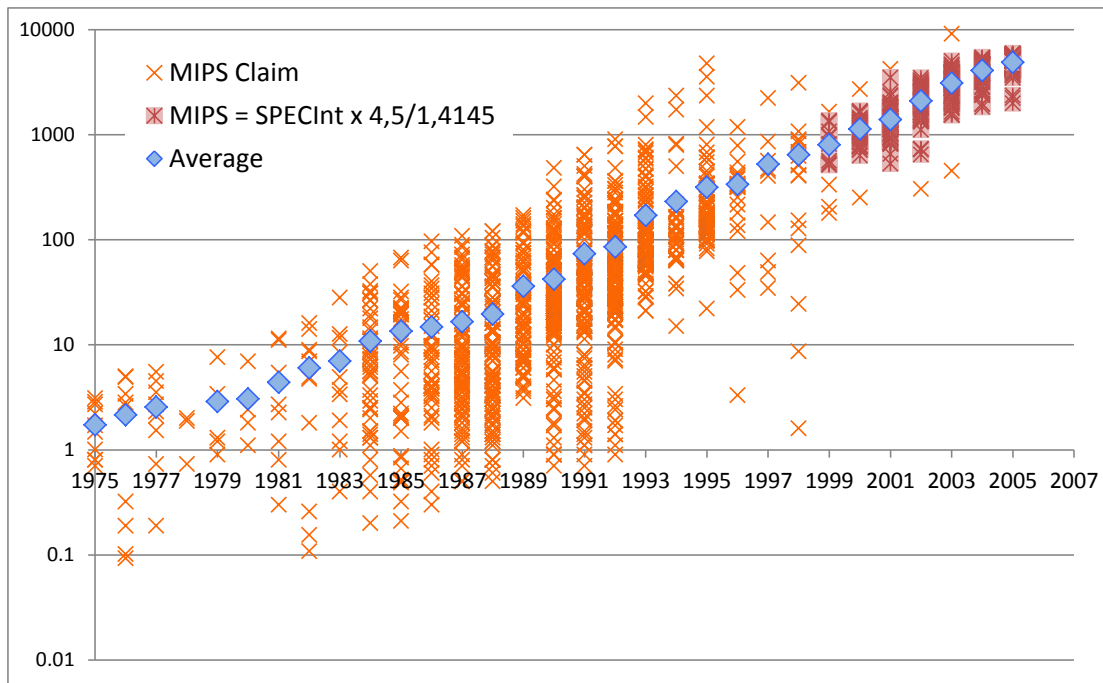
With respect to the useful lifetime of mainframes and servers, we follow the same assumptions made for PCs and HDDs. That is to say, 10 years lifespan for the period 1980-1986, 7 years for 1987-1989 and 5 years for 1990-2007. The last assumption is reconfirmed by the relationship between the numbers of shipped and installed servers reported for the period 1997-2006 by IDC (62).

### E.3.2 Professional computers: performance

The same sources as for PCs are utilized (1, 4, 12, 23-25). Combined we were able to obtain the performance for 2433 computers for the period 1975-2007<sup>56</sup>, of which 582 are mainframes, 1454 servers, and 396 mid-/high-level workstations. Various machines from 1999-2007 give their measurement of performance in SPEC, for which we utilized the conversion formula  $MIPS = SPECInt * (4.5/1.4145)$  (see Figure S E-6).

Figure S E-6: Professional computer performance 1975 - 2007, MIPS (n=2433).

<sup>56</sup> The fact that the number in the sample of mainframes and servers is so much larger than for personal computers most likely comes from the simple fact that the industry tends to measure the performance of mainframes and servers much more frequently than for personal computers, as this indicator has more relevance for the advanced use of computers.



Sources: Authors' own elaboration, based on (1, 4, 12, 23-25).

In Table S E-7 we represent the performance summary of professional computers.

**Table S E-7: Professional computer performance 1975 - 2007 (MIPS).**

Year	1975	1976	1977	1978	1979	1980	1981
MIPS	1.73	2.15	2.56	2.72	2.88	3.05	4.39
Year	1982	1983	1984	1985	1986	1987	1988
MIPS	6.0	7.0	10.9	13.5	14.8	16.6	19.6
Year	1989	1990	1991	1992	1993	1994	1995
MIPS	36	42	74	86	170	231	316
Year	1996	1997	1998	1999	2000	2001	2002
MIPS	336	524	643	802	1,130	1,391	2,096
Year	2003	2004	2005	2006	2007		
MIPS	3,091	4,086	4,865	6,029	6,532		

Sources: Authors' own elaboration, based on (1, 4, 12, 23-25).

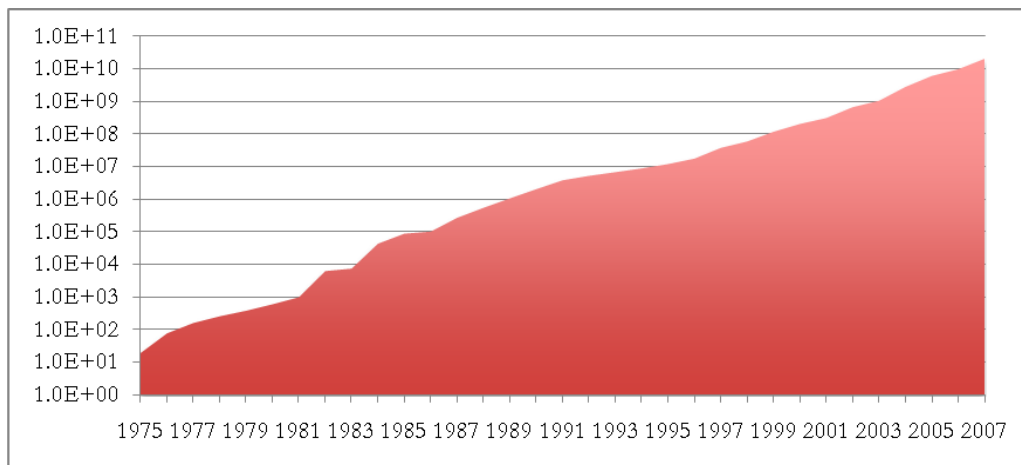
### E.3.3 Professional computers: effective use

Due to a lack of more detailed information, we assume that mainframe computers run 8 hours during the work week (5 days a week), and that servers run 8 hours a day, 7 days a week.

## E.4 Supercomputers

The term supercomputer refers to computational systems, which provide the best achievable performance in solving challenging computational problems (63, 64). In general, supercomputers are classified into three categories: parallel, vector, and cluster. The first type utilizes multiple CPUs for resolving problems and is therefore able to perform more than one instruction simultaneously. The second type's functionality is based on a *pipeline* architecture, which connects a set of data processing elements serially. For their part, clusters are a group of computers connected to a local area network to function as a single computer. This type of supercomputer is more cost-effective than a single supercomputer of another type of comparable speed and capacity (65). The first clusters were introduced in 1996 and, by 2007 they represent 79% of the 500 fastest supercomputers in the world.<sup>57</sup>

Figure S E-7: Total computational capacity of supercomputers (MIPS, semi-logarithmic presentation).



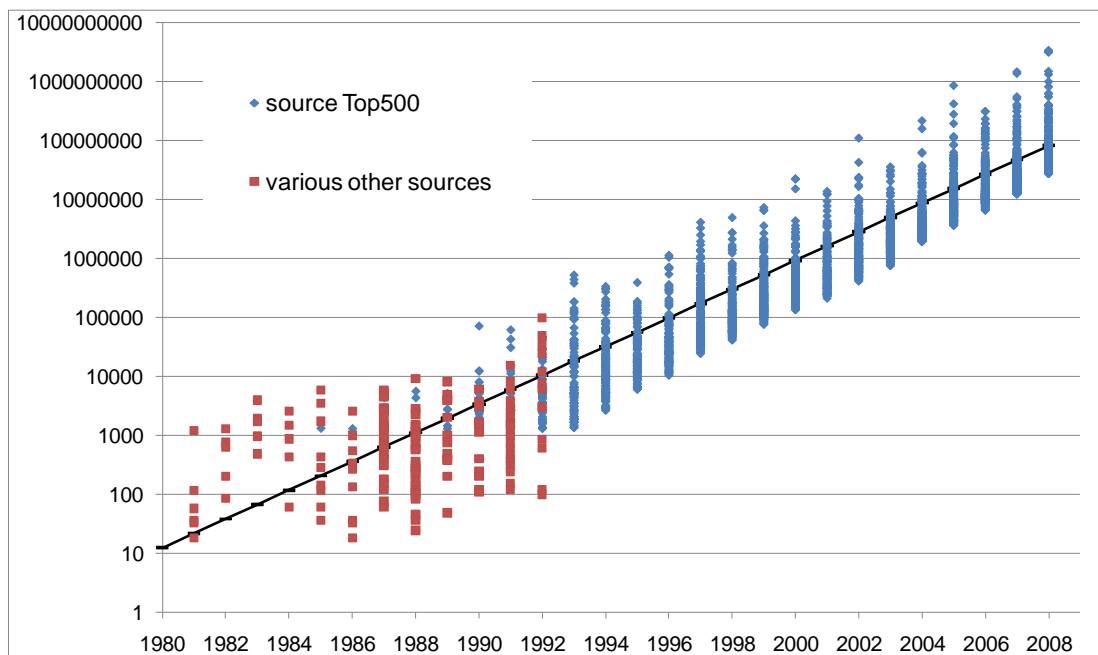
Source: Authors' own elaboration, based on various sources (see text).

### E.4.1 Supercomputers: performance

Top500 (67), Longbottom (4), McCallum (1) and Nordhaus (2) and report the performance of almost four thousand supercomputers in MFLOPS. After the conversion to MIPS (utilizing the conversion of 3 MIPS for each MFLOPS), we applied an exponential trend line to locate the "representative computing power" for each year (Table S E-8).

Figure S E-8: Supercomputer Performance 1980 - 2008 (n=3805).

<sup>57</sup> For example, Sun's TSUBAME Grid Cluster, which was the ninth fastest computer in the world in 2006, consists of 648 Sun Fire™ X4600 servers with a total of 11,088 AMD Opteron™ processor cores (66).



Sources: (1, 2, 4, 67-77).

**Table S E-8: Average supercomputer performance from 1975 to 2007, (MIPS).**

Year	1975	1976+	1977+	1978+	1979+	1980	1981
MIPS	1.73	3.8	5.9	8.1	10.2	12.3	21.5
Year	1982	1983	1984	1985	1986	1987	1988
MIPS	38	66	116	203	355	622	1,090
Year	1989	1990	1991	1992	1993	1994	1995
MIPS	1,910	3,347	5,865	10,276	18,007	31,553	55,288
Year	1996	1997	1998	1999	2000	2001	2002
MIPS	96,878	169,755	297,453	521,211	913,291	1,600,314	2,804,148
Year	2003	2004	2005	2006	2007		
MIPS	4,913,564	8,609,787	15,086,489	26,435,283	46,321,193		

Sources: Authors' own elaboration, based on (1, 2, 4, 67-77).

To estimate the capacity in the period before 1991, the total number of new computers is multiplied by their respective capacity shown in the previous table. In contrast, from 1992 onwards, due to the fact that the computing power of each supercomputer was included in the TOP500 list, a simple sum of these values (converted to MIPS from MFLOPS) gives us the total capacity, which is even more precise.

#### E.4.2 Supercomputers: quantity

For the years 1976-1988, we base the estimation on an inventory done in 1988 (78, 79). For the period 1992-2007, we extract the number of new supercomputers listed in the TOP500 (67) for each year. This list does not include the total number of machines installed worldwide – only the 500 fastest. After consulting with TOP500 about their estimate of the total number of supercomputers (electronic correspondence 2008), we assume that for each supercomputer included, there exists another that is not. These remainders are multiplied by the computing power (performance) of the least powerful supercomputer considered for the TOP500. We consider an accumulation effect of 14 years, supposing that supercomputers are reutilized for other functions after their principal use (it turns out that the performance of a supercomputer is about equal the performance of a PC 14 years later, e.g. 1987/8 - 2000/1) (Table S E-9).

**Table S E-9: Estimated total number of supercomputers worldwide 1975 - 2007.**

<b>Year</b>	<b>1975</b>	<b>1976</b>	<b>1977</b>	<b>1978</b>	<b>1979</b>	<b>1980</b>	<b>1981</b>
MIPS	11	26	40	52	64	82	100
<b>Year</b>	<b>1982</b>	<b>1983</b>	<b>1984</b>	<b>1985</b>	<b>1986</b>	<b>1987</b>	<b>1988</b>
MIPS	241	259	573	796	836	1,109	1,368
<b>Year</b>	<b>1989+</b>	<b>1990+</b>	<b>1991+</b>	<b>1992</b>	<b>1993</b>	<b>1994</b>	<b>1995</b>
MIPS	1,634	1,915	2,215	2,535	2,807	3,043	3,325
<b>Year</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>
MIPS	3,436	3,832	3,788	3,957	4,299	4,308	4,411
<b>Year</b>	<b>2003</b>	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>		
MIPS	4,463	4,724	4,848	4,864	5,188		

Source: Authors' own elaboration based on (67, 78, 79; +: Linear Estimation).

### E.4.3 Supercomputers: effective use

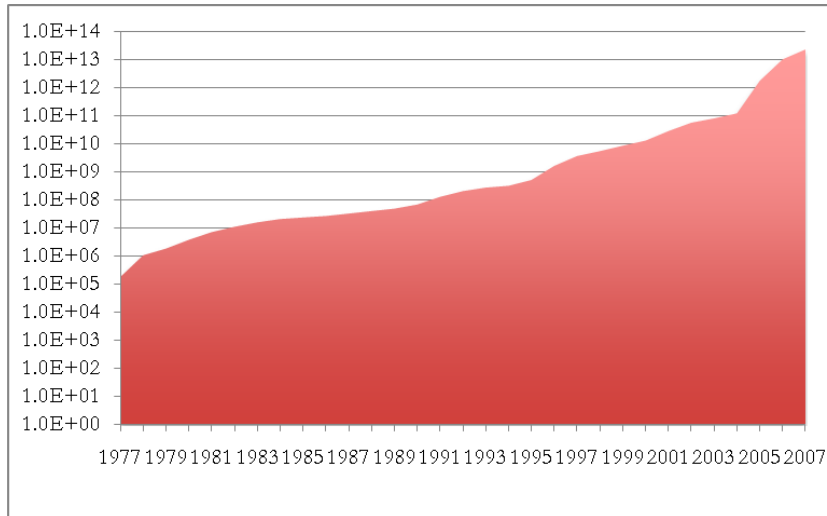
Due to a lack of more detailed information, we suppose that a supercomputer runs 24 hours a day, 365.2422 days a year.

## E.5 Game consoles

We consider the 29 most popular models of video-game consoles. Each of these models has sold more than a million units (see Table S E-11).

**Figure S E-9: Computational capacity of video-game consoles (MIPS, semi-logarithmic presentation).**





Source: Authors' own elaboration, based on various sources (see text).

### E.5.1 Game consoles: performance

Table S E-10 contains the computing power for each console utilized in the estimation.

Table S E-10: Computing power of video-game consoles.

Console	MIPS	Console	MIPS	Console	MIPS
Wii	<i>2,800</i>	Dreamcast	360	TurboExpress	<i>1.5</i>
PlayStation 3	81,920	Neo Geo Pocket	<i>17</i>	GB & GB Color	<i>1.5</i>
Xbox 360	19,200	Nintendo 64	125	Sega Genesis	<i>1.0</i>
Nintendo DS	<i>114</i>	Nomad	<i>26.6</i>	TurboGrafx-16	<i>1.5</i>
PSP	<i>114</i>	PlayStation	30	Master System	<i>0.7</i>
N-Gage	<i>18</i>	Saturn	50	NES	<i>0.7</i>
GBA	<i>18</i>	Panasonic 3DO	10.6	ColecoVision	<i>0.7</i>
Xbox	1,980	Sega-CD	<i>1.5</i>	Intellivision	<i>0.7</i>
GameCube	1,125	SNES	4.8	Atari 2600	<i>0.7</i>
PlayStation 2	450	Game Gear	<i>1.5</i>		

Sources: Authors' own elaboration, based on (80-86). Italics: estimate based on similar console.

### E.5.2 Game consoles: quantity

We counted the number of consoles sold per year of 17 models (PlayStation, PlayStation 2, PlayStation 3, PSP, Nintendo Wii, Nintendo DS, GameCube, Nintendo 64, SNES, NES, GameBoy, GameBoy Advance, Xbox, Xbox 360, Sega Dreamcast, Sega Genesis y Sega Master System) (87-94); for the rest was estimated on basis of trend of the total sales from 1977 to 2007. The distribution of products sold per

year in this group was estimated to behave like other consoles from the same period of production, both in their functionality and applications (Table S E-11).

**Table S E-11: Total sales of different videogame consoles (in millions until the end of 2007).**

Console Model	Units sold	Console Model	Units sold	Console Model	Units sold
Wii	50.4	Dreamcast	10.6	TurboExpress	1.5
PlayStation 3	12.6	Neo Geo Pocket	2.0	GB & GB Color	118.5
Xbox 360	17.7	Nintendo 64	32.9	Sega Genesis	30.9
Nintendo DS	122.4	Nomad	1.0	TurboGrafx-16	10.0
PSP	40.5	PlayStation	102.5	Master System	13.4
N-Gage	3.0	Saturn	17.0	NES	61.9
GBA	81.1	Panasonic 3DO	2.0	ColecoVision	6.0
Xbox	24.2	Sega-CD	6.0	Intellivision	3.0
GameCube	21.7	SNES	49.6	Atari 2600	30.0
PlayStation 2	129.9	Game Gear	11.0		

Source: (87-111).

Finally, we have opted to consider a useful lifespan of 5 years, equal to that of a computer, which is in accord with product cycles (generations) that main product manufacturers, for example: Playstation1 (1995); Playstation2 (2000); Playstation3 (2006) (112).

### E.5.3 Game consoles: effective use

Similar to PCs, the effective use data on videogame consoles refers to “gross” use, that is to say, the approximate number of hours per week the user is interacting with the console, not how long the computer runs at maximum capacity.

**Table S E-12: Simple average use of videogame consoles, hours per week.**

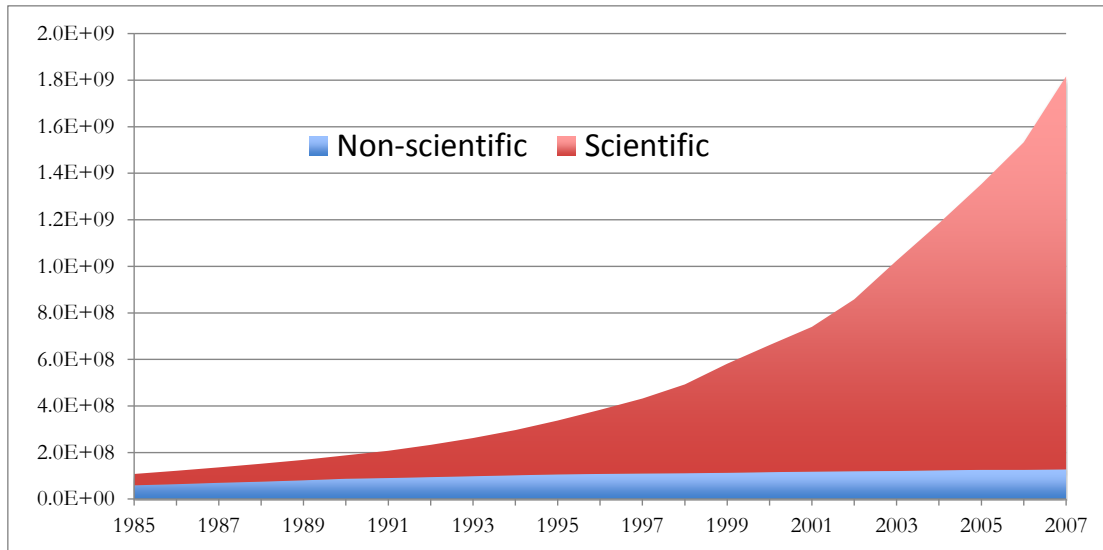
Year	1986	1993	2000	2007
Average hours/week	0.4	2.6	6.1	11.5

Source: Authors’ own elaboration based on (113-124).

## E.6 Electronic calculators

In this section we distinguish between two types of calculators: non-scientific electronic and scientific electronic.

**Figure S E-10: Computational capacity of calculators (MIPS).**



Source: Authors' own elaboration, based on various sources (see text).

### E.6.1 Calculators: Quantity

Due to the lack of statistics on total worldwide calculator use in different years, we turned to statistical information on the number of households and students as an approximation (17). For non-scientific calculators, we suppose that each household in OECD member states possesses one simple electronic calculator in 1980 and two from 1990 onwards (linear interpolation). In non-OECD countries, we suppose that no households had any calculators until 1975 and that, in 1995 onwards, there exists one calculator per household (linear interpolation between 1975 and 1995).

The number of scientific calculators is approximated on basis of the number of secondary and university students from data provided from 1970 by the UNESCO database (125, 126). The same distinction is made between OECD and non-OECD nations (with the same transition between 1975 and 1995 for non-OECD nations) and we suppose an academic career of 4 years for each student. Each new student acquires a scientific calculator upon entering university education and keeps it for four years after matriculation before discarding it. We assume that each tertiary student that has graduated in a field in which calculators are essential (science, engineering, manufacturing, construction, architecture, which corresponds to around 10% of all tertiary students) maintains possession of a calculator throughout their professional lives (40 years) and that they replace them with a new calculator every five years (J. Woerner; personal communication, October 10, 2010) (127).

The result of this estimation assumes that there have been some 5.5 billion calculators produced since the 1970s. We know that Cisco has produced 1 billion calculators since 1972 (127). Combining those two numbers would result in a historical market share by Cisco of 18%. This seems reasonable, knowing that Cisco is one of the largest manufacturers, but that their competitors, such as Texas Instruments and Hewlett-Packard, maintain a larger market share than Cisco.

## E.6.2 Calculators: performance

In the case of non-scientific calculators, we consider the computing power of the Intel 4004 processor, which was constructed in 1971 for a Japanese company which aimed to make a pocket calculator (0.06 MIPS, Byte.com, 1995). We suppose that this level of performance has remained constant, given that this type of calculator has not notably improved in its functionality since its market introduction.

Scientific calculators have evolved from allowing (limited) programming to even the power to graph functions on a monitor. The Hewlett-Packard Museum (128) reports the performance of various HP calculators from 1968 to 2003. Lamentably this performance is not measured in MIPS, but it is deducible that the computing power in 1981 was around double that of 1971; in 1991 the performance was again doubled and between 1991 and 2001 it quadrupled. Based in this rate of technological progress for calculators, one begins with 0.06 MIPS in 1971 (129), calculate for the years 1981, 1991, and 2001, and extrapolate with a constant growth rate for the intervening years, applying the rate of 2000-2001 for the years 2002-2007 (Table S E-13).

**Table S E-13: Estimated computational power of scientific calculators 1971-2007 (MIPS).**

Year	Non-scientific	Scientific	1971	1972	1973	1974	1975	1976
MIPS	0.060			0.060	0.064	0.069	0.074	0.079
Year	1977	1978	1979	1980	1981	1982	1983	1984
MIPS	0.091	0.097	0.104	0.112	0.120	0.129	0.138	0.148
Year	1985	1986	1987	1988	1989	1990	1991	1992
MIPS	0.158	0.170	0.182	0.195	0.209	0.224	0.240	0.276
Year	1993	1994	1995	1996	1997	1998	1999	2000
MIPS	0.317	0.364	0.418	0.480	0.551	0.633	0.728	0.836
Year	2001	2002	2003	2004	2005	2006	2007	
MIPS	0.960	1.103	1.267	1.455	1.671	1.920	2.206	

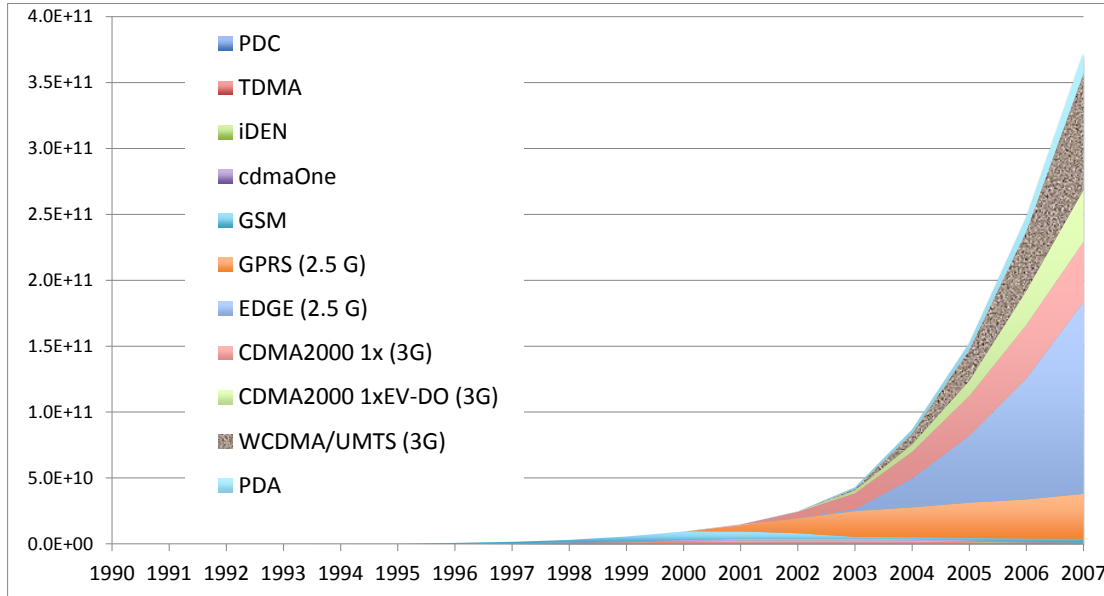
Source: Authors' own elaboration, based on Hewlett-Packard's growth rate (128).

## E.6.3 Calculators: effective use

Due to a lack for more exact information, we suppose that, for all calculators, scientific calculators are used (gross use) for 3 hours per week (class work and homework that use calculators in a school or university, for example), and non-scientific calculators are used 0.5 hours per week.

## E.7 Mobile phones and PDAs

Figure S E-11: Computational capacity of mobile phones and PDAs (MIPS).



Source: Authors' own elaboration, based on various sources (see text).

### E.7.1 Mobile phones, PDAs, and handheld PCs: performance

The performance of mobile phone processors is extracted from (130), and converted to Dhrystone MIPS 1.1 from 2.1.

Table S E-14: Cellular phone processing levels (MIPS Dhrystone 1.1).

	GSM	cdmaOne	PDC	GPRS	EDGE	CDMA2000 1x	WCDMA (UMTS)	CDMA2000 1xEV-DO
Generation	2G	2G	2G	2.5G	2.5G	3G	3G	3G
MIPS	14	14	14	22	151	151	467	467

Sources: Authors' own elaboration, based on (130)

The estimation for the period 1995-2002 is based on the annual average performance of 23 models of PDAs with Motorola-Dragonball processors (131-133). For 2004 we consider the computing power of the *Tungten T5* and for 2005 of the *LifeDrive*, these being equal to 170 MIPS and 174 MIPS (in Dhrystone 2.1), respectively. Given the convergence between PDA and smart phones (which is reconfirmed by the fact that their performance is becoming very similar at the time of 2.5G mobile phones), we suppose that for the years 2006 and 2007 the computational capacity is the same as 3G phones (Table S E-15)

Table S E-15: Processing levels of PDAs (MIPS).

Año	1990-1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
<b>MIPS</b>	2.6	3.1	3.1	5.1	5.1	83	161	164	467	467

Sources: (130-133); estimates in italics.

## E.7.2 Mobile phones, PDAs, and handheld PCs: quantity

We follow the same methodology as described in the section D.6.1. (134) reports data regarding the number of PDAs<sup>58</sup> and handheld PCs sold. We suppose each of these devices has a useful life of three years (135), equal to mobile phones.

Table S E-16: Quantity of PDAs sold worldwide (millions of units).

	1992	1993	1994	1995	1996	1997	1998	1999
PDA	0.06	0.05	0.10	0.17	0.39	0.92	2.12	4.93
	2000	2001	2002	2003	2004	2005	2006	2007
PDA	11.43	11.85	12.29	12.75	13.12	13.51	13.88	14.34
Handheld PC					0.00	0.01	0.08	0.22

Source: Authors' own elaboration, based on various sources (see text).

## E.7.3 Mobile phones, PDAs, and handheld PCs: effective use

The gross effective use is estimated basis of mobile voice and mobile Internet usage.

Table S E-17: Number of hours per week mobile phone is used for voice and Internet services per subscriber.

		2000	2007
Hours per week	OECD	18.85	34.42
	Non-OECD	14.10	22.41
Weighting for number of mobile phones	OECD	82 %	71 %
	Non-OECD	18 %	29 %
Weighted global average (hours per week)	Mundial	18.0	31.0

Source: Authors' own elaboration, based on (38, 47, 49, 124, 136-138)

<sup>58</sup> Includes PDAs with operative systems from Palm, Pocket PCs (Windows CE) or any other operating system.

## E.8 Digital Signal Processors (DSP)

A digital signal processor (DSP) is a specialized microprocessor with an optimized architecture for the fast operational needs of measuring, filtering and/or compressing continuous real-world analog signals (e.g. audio, speech, sonar, radar, sensor array, spectral, image and biometric, etc.).

### E.8.1 DSP: performance

We include 9 families of technologies into this part of the inventory (see Table S E-18, including two kinds of modems and two kinds of printers). The result is based on a sample of 52 different DSP solutions. Missing years were estimated on basis of the general requirement of the technology and the technological process made by the performance of PC. The resulting average performance rates in MIPS are in agreement with expert assessments of the general evolution of DSP over the past decades (140). It is important to notice that some of the technologies included here also count with a small microprocessor, which we do not consider at this point.

Table S E-18: Performance of 13 technological families that use DSP (in MIPS).

	1989	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	2000	'01	'02	'03	'04	'05	'06	2007
Fixed phone	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Dial-up modem	7	8	9	11	12	14	15	16	16	16	16	16	16	16	16	16	16	16	16
CD device	1	1	1	3	3	5	7	8	24	46	54	54	54	54	54	54	54	54	54
Digital radio								79	79	79	79	79	79	79	79	79	79	79	79
Printer & Fax	6	6	7	15	17	25	34	40	40	50	61	111	162	162	162	162	162	162	162
Broadband modem & setup boxes	5	5	6	12	14	21	27	33	99	189	189	189	189	189	189	189	189	189	189
DVD device and PVR								45	135	258	300	300	300	300	300	300	300	300	300
Laser printer	8	9	10	22	24	37	49	58	176	337	391	450	450	450	450	450	450	450	450
Digital cameras & camc.			6	13	14	21	21	21	21	41	40	80	85	91	100	316	389	500	527
Portable Media Player										58	63	90	108	119	163	332	441	511	539
Personal navigat. (GPS)					8	11	13	39	75	87	100	131	148	225	348	493	521	550	
Moible phone			4.5	11	18	20	25	30	34	38	44	50	63	75	88	100	133	167	200
Avg. DSP performance	4	5	6	11	12	16	20	31	63	106	134	148	158	161	175	213	244	258	265

Source: Authors' own elaboration, based on (PMP: 131, 141-144; modems: 170-183; setup boxes: 184-198; Digital cameras and camcorders: 234-245; Digital radio: 258, 249; Digital fixed-line phone: 260; GPS: 261-264; CD: 258, 265-269; DVD: 259; PVR: 258, 259, 265-269; Printer and fax: 235-237, 258, 275-280; Laser printer: 261. Mobiles: 231). Note: italic are estimates.

### E.8.2 DSP: quantity

We distinguish between different types of technologies, because we suppose different lifetimes for several of them. The sum of the 13 technologies in our sample matches quite well with the numbers of total DSP produced in 2000 and 2004, showing that our sample is quite complete. (232) reports that 918 million DSP were produced in 2000 and our sample sums up to 787 million in 2000 and 863 million newly installed DSP in 2001. (233) reports that 1,500 million were shipped in 2004, while our sample sums up to 1,366 million for the same year.

### **E.8.2.1 Portable Media Player (PMP)**

The number of MP3 players since 1998 is based on (145-148) (see Table S E-19). We decided to separate iPods from other MP3 players, since they have a higher performance than MP3 players, and have organized the number of units sold since its inception in 2001 (149-163). We obtained the number of units sold in 2005-2006 (164) and (147, 148). We suppose a useful lifetime of 3 years for this technology (equal to that of mobile phones).

**Table S E-19: Global number of portable entertainment devices manufactured.**

	N° units globally [millions]		
	MP4	MP3 (except iPod)	iPod
1998	0	0.8	0
1999	0	3.7	0
2000	0	6.6	0
2001	0	9.4	0.1
2002	0.2	11.9	0.5
2003	0.5	14.2	1.1
2004	3.4	26.7	8.3
2005	5.5	96.7	32.0
2006	9.8	172.2	46.4
2007	10.8	189.2	52.7

Sources: based on (145-164)

### **E.8.2.2 Modems and set-top-boxes**

The number of units is based on the distribution of subscribers to the various Internet access technologies (dial-up, ISDN, DSL, Cable Modem, FTTH, and Others) according to ITU (17), the assumption being that each Internet connection is established by a subscriber using a modem. The number of set-top-boxes is reported by (168, 169). We assume a useful life of five years, equal to that of computers.



Table S E-20: Shipments of Set-top-boxes (thousands), 2000 - 2007.

2000	2001	2002	2003	2004	2005	2006	2007
21,722	24,563	26,667	29,705	38,332	43,611	63,925	78,803

Source: (146, 168, 169)

### E.8.2.3 Digital cameras and camcorders

For the number of units worldwide, we turned to different sources (246-254). From 1991 to 1996 we extrapolated, using a constant growth rate (supposing 1990 as year digital cameras were introduced). In accord with various sources, we suppose an average useful life of 5 years (22, 255-257). Digital camcorders are reported in Morgan Stanley (146).

Table S E-21: Quantity of digital cameras and camcorders shipped worldwide (in millions of units).

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Cameras	0.15	0.24	0.38	0.61	0.99	1.6	2.2	3.8	5.5
Camcorders	0.09	0.14	0.22	0.36	0.58	0.94	0.80	1.75	3.44
	2000	2001	2002	2003	2004	2005	2006	2007	
Cameras	11	18	24	47	63	81	106	131	
Camcorders	6.88	9.45	12.30	14.85	15.75	21.00	27.00	33.37	

Source: Authors' own elaboration based on (22, 146, 255-257)

### E.8.2.4 Digital radio

Same assumption as in D.3.1 Radio: Quantities.

### E.8.2.5 Digital fixed-line telephony

Same statistics as in D.5.1 Fixed-line Telephone.

### E.8.2.6 Personal Navigation Device (GPS)

Same assumption as in D.8.2 Personal Navigation Device (GPS).

### E.8.2.7 Mobile telephony

Same assumption as in D.6.1 Mobile telephony: Quantity.

### E.8.2.8 CD, DVD and personal video recorder (PVR)

Morgan Stanley (146) reports the shipment of DVD players and recorders until 2006, as well as CD (and Minidisks) players and recorders for 2000-2006. We estimate the rest of the years on basis of the growth rates of optical DVDs and CDs units (see Storage, E). The number of PVR devices is reported by (169, 270-274). As with TV sets, we assume an average lifetime of 10 years of CD and DVD (257) and like for hard-disks, five years for PVRs.

Table S E-22: Shipments of equipment CD, DVD and PVR (in million).

	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1983
CD & Minidisk	0.02	0.44	1.2	2.2	3.7	5.5	7.4	9.87	12	16	23	39	0.02
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
CD & Minidisk	49	60	76	90	98	117	117	123	129	136	143	146	118
DVD		0.06	0.71	2.95	9.70	21	35	22	39	86	102	123	156
PVR					0.13	0.46	0.80	1.50	4.6	11.4	19.0	19.8	19.6

Source: Authors' own elaboration based on (169, 270-274).

### E.8.2.9 Printers and facsimile

Morgan Stanley (146) reports the shipment of inkjet and laser printers for 2003-2006. We estimate the remaining years of basis of the PC growth rate, considering that 1985 was the first year for high resolution and high-speed printing for electro-photographic printers and we estimate that in 1994 there were 66 million printers (until 1994 HP sold 30 million printers with 45 % of market share (281)). Gartner (282) reports the amount of facsimile sold in the U.S. We assume the same ration of [U.S. / rest of world] as for PC (76% in 1986, 46 % in 1994; 35 % in 2000 and 24 % in 2007). We suppose a useful lifetime of 5 years.

## E.9 Microcontroller (MCU)

Microcontrollers are omnipresent since the 1970s and are typically found in automatically controlled products, including household appliances, entertainment electronics, and transport and

office machines. Since the mid-1990s, some 30 of them are included in a medium priced car and they assist us on a daily basis through watches, kitchen tools, washing machines, garage door openers, remote controls and toys. Technically speaking, microcontrollers (MCU) are integrated circuits that contain many of the same items that a desktop computer has, such as a central processing unit (CPU), memory, etc. (284). Microcontrollers are designed for machine control applications and human users cannot intervene in the logic of their functionality.

### E.9.1 MCU: performance

Microcontrollers are typically produced in three forms: 8-bit, 16-bit and 32-bit. We took a sample of 18 modern MCUs of 8-bit (285-287); 18 modern MCU of 16-bits (288-290); and 56 modern MCUs of 32-bits (288, 291, 292); which result in 32 MIPS, 50 MIPS and 269 MIPS respectively. We take this as the performances for 2007. (293) presents some average values of 9 MIPS (8-bit), 32 MIPS (16-bit) and 171 MIPS (32-bit), which we take for 2002, and (294) reports that Toshiba’s MCU had roughly 0.5 MIPS (8-bit), 8 MIPS (16-bit) and 12 MIPS (32-bit) in 1996. We interpolate linearly and assume that during the years pre-1996, technological progress was at the same rate as for PC’s microprocessor performance MIPS.

### E.9.2 MCU: quantity

We present the values in the following Table and consider a useful lifespan of 5 years.

Table S E-23: Shipments of Microcontrollers of 8-bit, 16 bit and 32-bit (in million).

units	1982*	1983*	1984*	1985*	1986*	1987*	1988*	1989*	1990*	1991	1992	1993	1994
8-bit	227	262	301	347	399	460	530	610	702	808	895	1,043	1,091
16-bit	232	267	308	354	408	470	541	623	717	826	914	1,066	1,383
32-bit	10	11	13	15	17	20	23	26	30	34	38	67	106
units	1995	1996	1997	1998*	1999*	2000*	2001*	2002*	2003*	2004	2005	2006	2007
8-bit	1,073	1,070	1,120	1,246	1,384	1,537	1,705	1,891	2,095	2,344	2,756	3,180	3,889
16-bit	1,686	1,863	2,240	2,398	2,566	2,746	2,939	3,144	3,364	3,229	3,218	3,099	3,095
32-bit	184	311	320	389	467	554	653	764	889	1,227	1,693	2,220	3,016

Sources: Authors’ own elaboration, based on (293, 294). Note: \* estimations based on constant growth rates.

## E.10 Graphic Processing Units (GPU)

A graphics processing unit (GPU) is a specialized microprocessor that offloads and accelerates graphics. We include dedicated graphics cards integrated graphics solutions.

## E.10.1 GPU: quantity

Jon Peddie Research (295) has specialized in tracking this market. We obtained the total values for 1982-2007. For the years 2001-2007 we also obtained the separation among discrete desktop video cards, integrated desktop solutions, discrete notebook video cards and integrated notebook solutions. We estimate the previous years on basis of constant growth rates, considering the year 1990 as the starting year for notebooks. The numbers are consistent with the data from the Telecommunications Union [ITU] database (17) on the installments of PCs.

Table S E-24: Shipments of Graphic Processing units (in million).

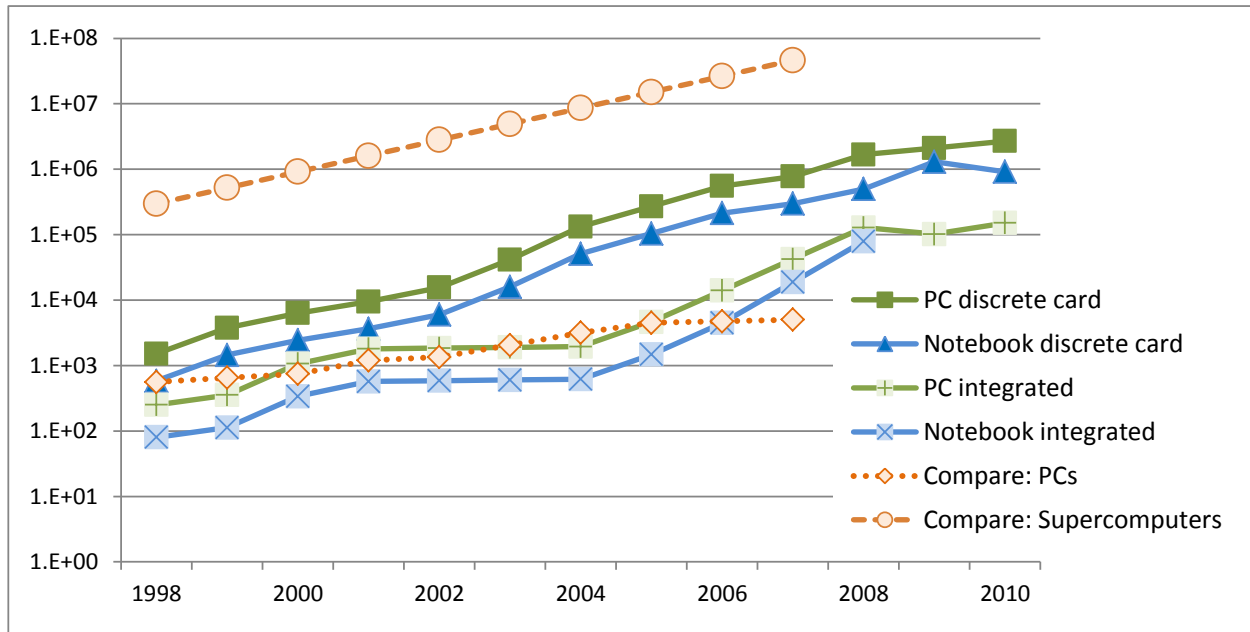
	1982	1983	1984	1985	1986	1987	1988	1989	1990
Total GPU	2	4	6	8	10	15	20	25	30
	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total GPU	35	40	45	55	80	105	120	130	140
	2000*	2001	2002	2003	2004	2005	2006	2007	
Desktop discrete	63	76	89	80	84	83	80	98	
Desktop integrated	73	125	150	180	111	122	145	147	
Notebook discrete	6	8	9	13	22	20	21	25	
Notebook integrated	13	17	21	27	23	45	69	85	

Sources: Authors' own elaboration, based on (295). Note: \* estimations based on constant growth rates.

## E.10.2 GPU: performance

Graphic accelerators calculate floating point operations (FLOPS), which we translate to MIPS through our translation 1 FLOPS = 3 MIPS. We create a sample of 117 GPUs from the period between 1996 and 2007 (296-298). As can be seen the following Figure, the resulting tendency is quite similar to the technological process of supercomputers. This should not be surprising, as both specialize in floating point operations (FLOPS). It is generally known that the gap between the performance trajectories of GPUs and PCs has been widening over recent years (see Figure, also 299). We therefore estimate the performance of GPU for the years pre-1998 on basis of the technological progress of the average supercomputer, assuming that both kinds of technologies develop at the same speed.

Figure S E-12: Average performance of GPU, in comparison with supercomputers and PCs (MIPS) (semi-log plot).



Sources: Authors' own elaboration, based on (296-298).

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