


Economic Impact of Technology Standards

The past and the road ahead

September 2017

Authors: Jorge Padilla, John Davies and Aleksandra Boutin





This report was commissioned by Qualcomm Incorporated. All opinions expressed here are those of the authors, who are all employees of Compass Lexecon: Jorge Padilla, John Davies and Aleksandra Boutin, supported by Anubhav Mohanty and Sabire Ipek Demir.

Executive Summary

- 1.1** This report examines the economic impact of technology standards - which enable components from different suppliers to work together - on innovation, competition and thus consumer choice and welfare. Such standards exist in all industries but are particularly important in Information and Communications Technology. We show that the way in which these standards are developed and governed can have profound implications for the pace of innovation and intensity of competition.
- 1.2** We present evidence that industries such as mobile telephony, which are based on open standards agreed through voluntary participation in industry bodies, have an impressive record of innovation. Open standard-setting, with licensing of technology incorporated in the standard, allows many specialised firms to operate at all levels of the value chain - but most crucially in R&D - without needing to achieve a large scale. This leads to more competition, more specialised research firms and greater diversity in research.
- 1.3** However, these outcomes depend on the Standard Development Organisations (SDOs), which govern open standard-setting, striking the right balance between the interests of technology developers and technology users. If innovation is not sufficiently rewarded, this model ceases to work and standards must be established by other means. Examples from other industries and other times – in which standards have been set either by firms acting alone or by governments - suggest that these alternatives would result in a less successful, less dynamic economy.

Different approaches to setting standards

- 1.4** There are several ways to achieve standardisation. A standard can simply emerge, often because one supplier achieves pre-eminence in a network industry in which economies of scale and scope are important – as Microsoft did in PC operating systems. Alternatively, a standard could be imposed by a government or, more commonly, groups of governments, as happened in early mobile telephony or as still happens in TV broadcasting standards.
- 1.5** The communications sector, in contrast, has seen the rise of a third sort of standard-setting in which industry representatives agree technology standards on a voluntary basis in Standard Development Organisations, typically incorporating many different patented technologies into the standard. Modern wireless telephony standards developed and continue to be developed in this way, along with many

others in the ITC sector. Furthermore, this approach is spreading, not least because other industries are adopting wireless technologies in the 'Internet of Things'.

- 1.6** The mobile telephony industry has seen an impressive rate of growth and innovation, as well as a dynamic market structure in which new entrants continue to arise to challenge existing suppliers. Between 1994 and 2013, the number of devices sold each year rose 62 times or 20.1% per year on average. The cost of mobile subscriptions relative to maximum data speed has decreased 99% (approx. 40% per year) between 2005 and 2013. 4G technologies have enabled a 12,000-fold increase in capacity relative to 2G; data download speeds have increased to 250 Mbps for 4G from 20 Kbps for 2G.
- 1.7** It is no coincidence that this impressive performance has arisen from a highly competitive and diverse market structure. Downstream, more firms than ever are participating in handset manufacture and, upstream, each successive generation of wireless technology standards has wider technology ownership.
- 1.8** The TV industry, based on mainly government-promoted broadcasting standards, and the personal computer industry, based in part on Operating Systems acting as de facto 'proprietary' standards, have also been successful, but innovation and competition have at times been hampered by the standard-setting process, as indeed occurred in the early days of mobile telephony. These different experiences illustrate the way standard-setting can affect economic outcomes.

Open standards enable competitive and innovative industry structures to emerge

- 1.9** Standards are so pervasive in some industries that it is difficult to determine their effect, since there is no obvious way to simulate how those industries would perform in the absence of the standards. Without technology standards, many industries simply would not exist. Many studies have therefore sought to measure the incremental effect of standards by comparing growth rates in different countries and different periods and attempting to relate differences to the stock of standards. Such studies typically find that about 20 – 30% of GDP growth relates to the development of standards. Surveys show that firms consider standards important for performance, especially in the ICT sector.

- 1.10** Economists have also examined the effects of standards on specific industries. Industries such as mobile telephony and PCs, based on patented technology incorporated in standards, reduced costs and improved product performance many times more rapidly than other industries making little use of standards (even those also based on semiconductor technology and presumably benefitting from 'Moore's Law'). Standards lead to more rapid technology adoption: SMS text messaging developed using a standard previously developed for traffic management, for example, allowing rapid adoption, by avoiding a period of incompatible SMS systems.
- 1.11** Economics can help explain why standard-setting is valuable and why different approaches to standard-setting will result in different outcomes. Firstly, standards are obviously most beneficial when the value of a technology to the user depends on how many other users there are. These other users could be all of the same type, as when the value of a telephone depends on how many people you can call, or a different type, as when consumers' choice of operating system depends on how many software developers make apps for that operating system, and vice versa. In these circumstances, even without any formal arrangements, one or more common standards will usually develop.

Proprietary standards

- 1.12** If a standard simply 'emerges', it will often be a proprietary one, under the control of a single company. This is by no means a bad thing in itself, and it is usually preferable to no standard at all. However, the emergence of such a standard will often be through a 'standard war' between one or more competing standards, which can provide a beneficial choice of technology but can also result in slower adoption. For example, 2G mobile technology was adopted faster in Europe, with a single, government-promoted GSM standard, than in the US with two competing standards – but one of those competing standards, CDMA, was technologically superior. Standards wars can also result in the 'wrong' technology becoming standard. VHS videotapes and the QWERTY keyboard are often cited as the archetypes of standards that succeeded because of their advantages at the time, but might not have been the best technologies for the longer term.
- 1.13** Most standards create opportunities for suppliers of other, complementary products. For example wireless standards create opportunities for handset and other equipment makers. Innovation and investment by these complementary suppliers is often the most important driver of industry success and the way in which the standard is governed will be crucial for this. If a standard is closed so that only the proprietor can supply products, innovation will suffer. The best-known company operating largely closed standards is Apple, which perhaps distorts the picture as Apple itself is a highly innovative company for other reasons. However, even Apple's closed standard has been shown to result in slower introduction of

new technology than the more open Windows-Intel standard. Other companies with closed standards – such as RIM's Blackberry – have been much less successful.

- 1.14** Even a standard such as Windows, which is open to use by suppliers of complementary hardware and software, but under proprietary control of Microsoft alone, has drawbacks. Suppliers of complements are utterly dependent on the standard proprietor to maintain compatibility as it introduces new versions, to inform them about its technology so they can make best use of new features and above all not to exclude them from the market by – for example – incorporating their products as 'features' in new versions of the standard. IBM, Microsoft, Intel and other proprietary standard-setters have been accused of all of these. Aware of the concerns – and the chilling effects they could have on innovation and investment – such proprietors typically go out of their way to inform and reassure their 'ecosystem' partners. Some have even given up control of the standard, as Adobe did with PDF.
- 1.15** Economic studies of the handheld computer industry have confirmed the importance of openness. Operating systems open to third-party hardware and software enabled more innovation than closed systems, but there is also evidence that opening the operating system governance and development to market participants can raise innovation still further.

Government-promoted standards

- 1.16** An alternative is for governments to set standards. The TV and telecommunications industries in post-war Europe were dominated by state providers, so standards were established by states. Even in the US, however, federal agencies have often been responsible for setting standards and indeed one of the first important post-war standards decisions – the US FCC's recognition of CBS's colour broadcasting system – illustrates how a government standard-setter can make the wrong decision. The alternative RCA system, compatible with existing black and white sets, was more readily adopted by the market and the FCC had to reverse course.
- 1.17** European TV and telecoms standard-setting from the 1960s to the 1980s illustrates a more pervasive reason for concern about government involvement in standard-setting. At the time, national governments sought to promote technical standards in support of their domestic policy interests and not on the basis of technical superiority. During the era, standard-setting may have operated as a form of trade protection and provided at best only temporary advantages. In the 2G mobile telephony industry in the 1980s, this approach was reinforced by proprietary technology-owners, who were also active in the downstream market and selectively refused to licence technology particularly to the Japanese and Korean firms. This has changed over time, with an increasingly sophisticated understanding of the dynamics of standardization and with the deepening of the single European market, making national standards less likely if they

distort trade between European Member States. Furthermore, the European Commission plays no role in relation to the technical choices made in the European Standards; its role is to ensure that the standardization structures and procedures remain efficient, accountable and transparent. At the global level, however, there may still be differences: TV broadcasting standards continue to create incompatible regional blocs around the world, with domestic policy attentive government involvement especially in Latin America. Nonetheless, the underlying technology is more modular and thus the effects on competition, efficient production and trade are less dire.

Open standards set through voluntary participation in industry bodies

- 1.18** Bringing industry experts together in SDOs to set open standards has many advantages. Unlike proprietary standard-setting, in which investors might be deterred by fear of being 'held up' by a powerful standard controller, many different companies can directly contribute technologies to an open standard.
- 1.19** Furthermore, both 'sides' of the market – those developing technology and those seeking to embody it in products (or build products to work alongside it) – participate, in a form of 'user-driven innovation'. Unlike government-imposed standards, technologies will not be adopted for political reasons or any one interest but on the basis of a technical assessment by experts. Indeed, the governance arrangements in many SDOs work rather neatly to counter large participants: if there are few companies on one 'side' of the market, possibly possessing market power, they may be outnumbered in an SDO by participants from the other side, possessing voting power.
- 1.20** Quite apart from the obvious success of industries using this model, studies specifically of SDOs show that they work effectively: selecting efficient technologies, increasing those technologies' value by incorporating them in standards and attracting a wide and diverse membership.

Markets for technology

- 1.21** SDO's effectiveness depends crucially on their ability to create 'markets for technology' in which technology developers can realise the value of their investment and creativity by licensing the technology to 'implementers', such as firms manufacturing hardware. Such markets for technology do not arise only in standards-based industries, nor are they new. Modern scholarship has demonstrated that many of the inventions of the nineteenth century were commercialised through licensing; the image of industrial R&D occurring in a large manufacturing concern is largely a twentieth century development, which may now be passing. In the US especially, more and more R&D is carried out by smaller firms and in many industries specialist R&D organisations are emerging.

- 1.22** This has obvious advantages for innovation. Such separation creates the possibility of specialisation and more competition between alternative innovations. For example, in the semiconductor sector, chips are manufactured in 'fabs'. An efficient fab must be huge, so there are few of them. If the only way to receive payment for an innovation was to make and sell a chip using it, then only a few innovators would be present in the market. Instead, legal changes providing stronger intellectual property rights for chip design have led to more innovative 'fabless' firms that do not manufacture.

- 1.23** So: tradable intellectual property rights lead to greater diversity in R&D. They will also lead to greater incentives for R&D, if innovators are not dependent on one buyer but can sell to several, as will be the case with standard-compliant technologies. Indeed, it has been suggested that standardised technologies can increase workers' incentives to invest in skills for much the same reason: they can apply them working for several alternative employers.

- 1.24** If those rights are broadly available on Fair, Reasonable and Non-Discriminatory (FRAND) terms, as most SDOs contemplate, they lead to more competition among implementers too. This is precisely the structure we see in the mobile telephony industry with FRAND licenses available to mobile device makers, and increased downstream competitive entry, rapid introduction of innovations, increased productivity, and decreasing prices. More industries are moving to this model, often on the basis of standards incorporating patented technology licensed on FRAND terms.

Balancing interests of participants in the standard-setting process

- 1.25** SDOs are not uniformly the same, nor do their rules remain the same over time. Rules on licensing have been the focus of much activity and controversy recently, although the vast majority of rules changes in this area have been simple clarifying changes to the benefit of all parties. In some cases, however, tightening up on rules also effectively tips the balance against innovators, as with IEEE's recent policy change requiring licensors to abjure injunctions and recommending an approach to setting FRAND rates. There is some evidence that this is leading to sharply reduced participation by innovators.
- 1.26** Innovation is as risky as ever. Technology once developed will not automatically be accepted and standards too can fail, as the examples of WIMAX and Digital Audio Tape show. Furthermore, having developed technology, innovators can be just as dependent on implementers as implementers are on the technology. Open standard-setting has enabled impressive technological change in the mobile industry, producing great economic benefits. Rule changes that might imperil this should be considered with great care.



Contents

Section 1	Introduction	1
Section 2	Three different industries: Comparing standardization structure and economic outcomes	3
	Introduction	3
	The role of technology standards	3
	Developing standards	5
	Impact of standards on prices and quality	11
	Impact of standards on market structure and competition	16
	Impact of standards on technology adoption rates	22
	Conclusion	24
Section 3	How technology standards affect economic outcomes	25
	The economics of technology standards	26
	The economic effects of technology standards	30
	Developing standards: open voluntary processes versus proprietary and government-promoted standards	36
	Conclusions	44
Section 4	Markets for technology, enabled by Standard Development Organisations	45
	Introduction	45
	Markets for technology	45
	Overview of SDOs	53
	Balancing interests of different participants in SDOs	56
	Conclusions	60
Section 5	Conclusions	61
Section 6	Bibliography	63



Introduction

- 1.1** Many modern industries are heavily dependent on technology standards. These standards allow technology produced by different suppliers to work together. This report examines the effects of technology standards in specific industries and overall.
- 1.2** There have always been technology standards but they are more important today than ever, especially in the Information and Communications Technology sectors. We explain how standards affect economic outcomes using three case studies:
- Mobile telecommunications;
 - Television broadcasting; and
 - Operating systems for personal computers.
- 1.3** Our aim is to show how standards, and the way in which they have been set, have influenced the development and performance of these industries. We therefore begin in Section 2 with a comparative account of the three industries and particularly the way in which standard-setting has evolved and has affected industry development. The three industries, at different times, illustrate some important different ways in which standards can be set. These can be categorised in the following way:
- Without a specific institutional structure, the market might simply select one or more standards by choosing products that embody alternative standards and typically only one or a few winners will emerge. The resulting standards will be under the **proprietary control** of a few companies, like Microsoft's Windows.
 - Alternatively, **governments** could mandate standards and this has been the main approach for TV broadcasting standards and early mobile telecommunications.
 - A third option exists, however, which is voluntary participation in industry bodies (generally called Standard Development or Standard Setting Organisations – SDOs or SSOs) to set **open standards**. This approach is particularly prominent in telecoms standards but is becoming more widespread, as more industries (such as smart energy grids) incorporate telecoms protocols. The modern mobile telephony industry is demonstrably very effective at innovation and highly competitive – and it is our contention that its open standard-setting arrangements have a lot to do with this success.
- 1.4** Section 3 of this report examines how standards affect economic outcomes, drawing upon economic studies, the experiences of the case study industries and standard-setting in other industries, where appropriate. It sets out the economic theory, based around network effects and the relationship between companies at different layers of the supply chain, to show that standards can profoundly influence industry structure. Standards themselves solve certain problems of economic co-ordination and incentives. *Open* standards create opportunities for firms at many different levels of the supply chain, while proprietary standards or government-promoted standards are more likely to lead to large vertically-integrated firms dominating the industry.
- 1.5** If there are indeed significant economic effects arising from such open standard-setting then the institutional arrangements giving rise to them take on profound importance. We survey the Standard Development Organisations in Section 4, summarising economic studies of their effectiveness overall and very briefly touching upon the debates about their policies, particularly towards intellectual property rights (IPRs). If technology can be licensed through IPRs, the opportunities for specialist firms described above extend to pure R&D suppliers, leading to a choice of the best innovations in a 'market for technology'. These positive effects are visible not only in telecoms but also in US data on industrial R&D in technology-related sectors, which seems to show a profound shift towards smaller firms. SDO policies can affect the balance between incentives for technology creators, on the one hand, and technology users on the other, to participate in the standard-setting process. This participation by both sides of the market is a crucial feature of the SDOs' role.
- 1.6** Section 5 concludes, briefly summarising our key conclusions.
- 1.7** We provide detailed accounts of the interplay between standard-setting and the development of each of our three case study industries in annexes to the report.¹

1 The annexes document can be found on our website compasslexecon.com/highlights/



Three different industries: Comparing standardization structure and economic outcomes

Introduction

- 2.1** The process of developing technological standards is complex and is influenced by various interests. The various stakeholders include the firms and organisations developing the technologies for use in the standards, the standards adopters, consumers, and also national governments looking to use standards to promote policy interests.
- 2.2** On the one hand, standard setting can be voluntary: where industry participants agree on a process for collaborating, to various degrees, in developing, establishing and adopting standards. On the other hand, standards can be government-mandated: where the national government plays a central role in the standard development process.
- 2.3** There may also be instances where technologies, either under open licenses or proprietary, are adopted as de facto standards. In the case of proprietary technologies, the organisation owning the technology decides on the rules for the use and adoption of the technology.
- 2.4** Standard setting is dynamic and continually evolving. For example, the second generation of mobile telephony was characterised by voluntary standards in Europe, a fragmented market with multiple, market-driven standards in the US, and a government-mandated standard in Japan. In later generations, standards have been developed globally.

- 2.5** The nature of standardisation can have a significant impact on the structure of the industry, its rate of growth and innovation. The aim of this section is to explore the role of standardisation structures on economic outcomes using industry case studies. We argue that having open standards results in more competitive and dynamic markets for innovators and lower prices and better quality for consumers.
- 2.6** We describe and contrast experiences of standard setting and its economic effects by looking at three industries:
- mobile telephony;
 - PC operating systems ("O/S"); and
 - television broadcasting.
- 2.7** Mobile telephony was characterised mainly by voluntary standards, operating systems by proprietary standards, television broadcasting by state involvement in the development of standards.
- 2.8** Annexes to this report describe how standards have influenced the development of these industries in much greater detail.

The role of technology standards

- 2.9** Standards underpin some of the biggest and most dynamic industries in the world. Table 1 provides an overview of the key macroeconomic indicators for the US for the standard-reliant industries analysed in this report.

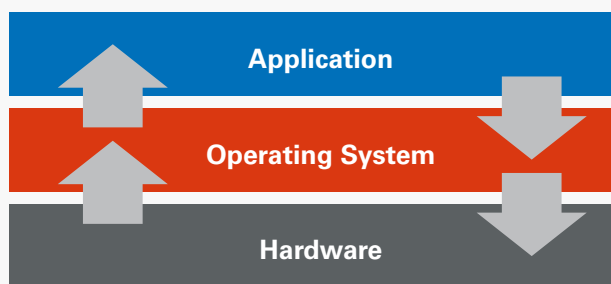
Table 1: Key US macroeconomic indicators, by industry

	Mobile Telephony	Television broadcasting	Operating systems
Size (2014, USD billions)	245.1	79.6	543.8
Size growth (1990-2014, CAGR)	12.0%	2.1%	8.0%
Employment (2014, thousand jobs)	168.3	227.5	2,200.6
Standards	Wireless protocols and many others decided through SDOs	Regional standards (Analogue: PAL, NTSC, SECAM; Digital: ATSC, DVB, ISDB, DTMB)	Proprietary and open-source operating systems

Notes: "Size" refers to the US domestic industry output in billion 2014 dollars. "Size growth" is the compound average growth rate of domestic industry output from 1990 to 2014, using chain weighted (2009) dollars. "Employment" is measured by the number of jobs in thousands. Data series used for "Mobile telephony" is "Wireless telecommunications carriers (except satellite)" with NAICS code 5172; for "Television broadcasting" is "Radio and television broadcasting" with NAICS code 5151, and for "Operating systems" are "Software publishers" with NAICS code 5112 and "Computer systems design and related services" with NAICS code 5415.

Source: Bureau of Labor Statistics, Office of Occupational Statistics and Employment Projections. "Monthly Labor Review" published on December 2015.

Figure 1: The role of operating systems in PCs



Source: Compass Lexecon

- 2.10** The standards underpinning these industries have evolved significantly over time. In general, standards enable compatibility between various participants of the ecosystem, allow for interoperability of products, wider network effects, and faster advancement of the technology by contributions from a wider pool of innovators. We discuss the specific role played by standards in these industries in the rest of this section, and the evolution of the standards in the following section.

Mobile telephony standards

- 2.11** Mobile communication standards determine how voice and data are transmitted over the mobile network.
- 2.12** The first generation (1G) of mobile telephone systems were 'analogue' communication standards. Voice calls were transmitted to radio towers using analogue signals and then transmitted between radio towers and the rest of the telephone systems using digital signals.
- 2.13** The next generation of mobile telephone systems - second generation, or 2G - used digital transmission throughout the network. This allowed a much higher quality of voice communication compared to analogue technology. The use of

digital signals also allowed for the introduction of Multimedia Messaging Services, Wireless Application Protocol (WAP) and the transmission of data.

- 2.14** Subsequent generations of mobile telephone systems (i.e. 3G and 4G) have led to significant increases in the quality of voice and data transmission enabling mobile telephones to serve a variety of functions. Declining usage costs as well as infrastructure development costs have made mobile telephony increasingly accessible.

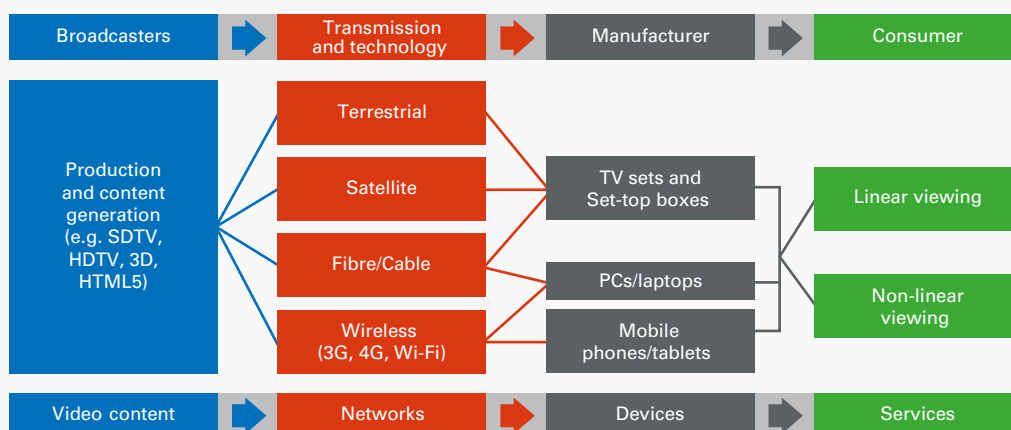
Operating systems

- 2.15** An O/S manages computer hardware and software resources and provides common services for computer programs. An O/S links the consumer, through application software, to the underlying hardware. The application software interfaces with the O/S, which in turn communicates with the hardware.
- 2.16** This hierarchy ensures that the application software can run on different hardware. However, the application software is O/S-specific. In other words, an application designed for a specific O/S runs only on that O/S and needs modifications to be able to run on another O/S.

Television broadcasting

- 2.17** In the early days of television, broadcasters would record and convert television content into analogue signals that networks would broadcast via terrestrial transmission to television sets. All three components of this ecosystem - broadcasters, transmission networks and devices (i.e. TV sets) – adopted a standard format for picture and sound signals.
- 2.18** Figure 2 below depicts the layers of the modern television ecosystem. Many of these options were not available in the early days of the television, where the only format was an analogue signal, via terrestrial transmission, into TV sets, for the purposes of linear viewing (watching at the time it was being transmitted).

Figure 2: TV ecosystem



Source: Adapted by CL from DigiTAG (2014), Figure 5.

2.19 Television signals have now evolved to digital signals, and can be transmitted via cable networks, satellites and wireless networks. These signals can be watched on devices such as smart phones and tablets in addition to TV sets.

Developing standards

2.20 As discussed earlier, standards structures can be voluntary or government-mandated. Also, technologies which are either open or proprietary can evolve into *de facto* standards.

2.21 In the next section, we present a summary of government-mandated standard setting in television broadcasting and mobile telephony. We then discuss how standard setting in mobile telephony has evolved into a voluntary system with diminishing government involvement. Finally we discuss *de facto* technological standards in PC operating systems. A more detailed review of standard setting in mobile telephony, television and PC operating systems is presented as the Annex A, B, and C to this report.

Government-mandated standards in television

2.22 In the age of analogue TV, technical standards were mostly determined by governments to promote the interests of their national manufacturers and (often state-owned) broadcasters.

2.23 Through the 1940s, Radio Corporation of America (RCA) and Columbia Broadcasting System (CBS) competed to establish their colour TV system as the new standard in the US. The Federal Communications Commission (FCC) wanted to introduce the colour TV technology to the US market as soon as possible, and adopted the technologically superior CBS standard in 1950. However, because the alternative RCA system was backward compatible with the incumbent monochrome standard and the installed TV base, and because RCA was a leading manufacturer of TV sets, the RCA system had higher market success. In 1953, FCC had to replace the CBS standard with the backward-compatible RCA standard, which then became the National Television System Committee (NTSC) standard (Shapiro and Varian 1999; Elen (2014).

2.24 The United States officially endorsed NTSC as its colour television transmission standard in 1953. It was later adopted by Japan and some Latin American countries.

2.25 To promote its own electronics industry and the production of local content, France promoted the *Séquentiel Couleur à Mémoire* (SECAM) standard and created an alliance with the Soviet Union on colour television technologies. This standard was adopted in many former French colonies in Africa, as well as the Soviet Union. In order to avoid paying the high SECAM license fees, Germany created the Phase Alternation by Line (PAL) standard, which was eventually adopted by most of Europe. Thus, three alternative technologies were created for analogue colour broadcasting (Wu et al. 2006; Fickers 2010).

2.26 These standards had about 95% of their technology in common, but all promised to improve upon the deficiencies of NTSC through different colour subcarriers, or variations in the number of horizontal lines (Crane 1979). The United States' NTSC system came to be mocked as the '*Never Twice the Same Colour*' system due to its low colour stability, which became the primary target of SECAM advertisements. Meanwhile, the direct French government political involvement in the development of the SECAM standard was mocked as '*Supreme Effort Contre Amerique*', and the development of PAL in response from Germany as the '*Provocation Allemande*'.

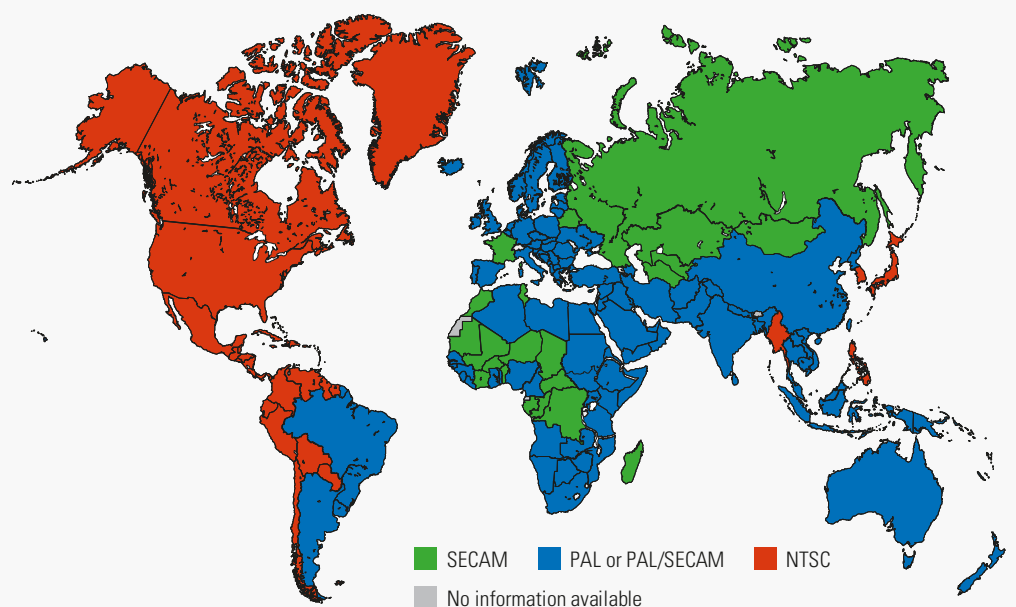
2.27 Technical experts from the developed world regularly convened at CCIR² conferences to agree on international telecommunications standards. These conferences were, according to a representative of the British Post Office 'technical, detailed, and cooperatively progressive' because 'without unanimity on vital technical issues international telecommunication is inhibited, if not impracticable. Thus the conduct of these Study Groups has always been on the basis of discussion, (...) and eventual erosion of the areas of disagreement' (Meriman 1965, as quoted in Fickers 2010).

2.28 Nonetheless, the heavy involvement of government authorities in the CCIR colour television Study Group meetings and the lack of decision-making power of the technical experts created a political, controversial, and uncooperative atmosphere in the CCIR meetings of 1965 (Vienna) and 1966 (Oslo), and the conferences dissolved with PAL and SECAM as the two rival European standards.

2.29 The lack of consensus at CCIR meetings resulted in a fragmented global market. Governments adopted standards as a protectionist measure to promote the interests of national manufacturers, which were sometimes state-owned, and national broadcasters, which were almost invariably state-owned. The resulting picture of the analogue TV world in Figure 3 is more based on political and economic affiliations (some of them obsolete) than any technical motive.

² CCIR stands for International Radio Consultative Committee. It was created in 1927 at the International Radiotelegraph Conference in Washington "to study technical and operating questions related to radio communications and to issue recommendations on them", holding regular international meetings. In 1992, International Telegraph Union's (ITU) three main areas of activity were organized in as: telecommunication development, radiocommunications, and telecommunication standardization. The CCIR was renamed the Radiocommunication Sector (ITU-R). (ITU, "Focus on Radiocommunication").

Figure 3: Analogue colour television standards around the world



Source: Adapted by CL from Angulo et al. (2011), Figure 1.

- 2.30** Different product standards and the resulting incompatibility prevented consumers from choosing foreign manufacturers' products. This technical barrier was largely eliminated with the invention of integrated circuits compatible with multiple standards in the early 1980s.
- 2.31** Politicized standard-setting policies were coupled with direct trade restrictions against higher quality and cheaper imports from Asia. In particular, Japan entered the US and European markets first through exports then, when its exports were restricted, through foreign direct investment in local production facilities³. In Europe, Japan had to wait for the expiry of the patents of analogue TV standards and licensing permissions (specifically chosen to protect domestic manufacturers) to enter the market (Burton and Saelens 1987, Gaillard 2007).

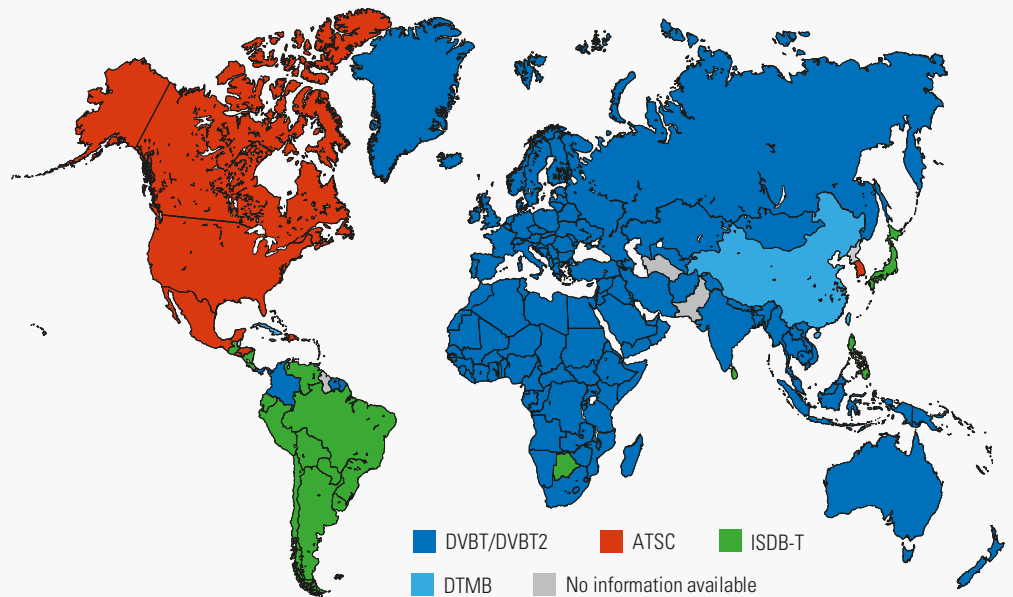
HDTV and the digitisation of television

- 2.32** Digital TV continues to be characterized by politically-influenced regional standards. In this section, we will summarize the global competition in high-definition television, which transitioned into the global competition in digital television. By construction, high definition signals need to carry more information in the signal and they aim for higher quality image and audio. Since digital transmission can pack more information into a smaller bandwidth and offer lower interference-related errors (Angulo et al. 2011), exploration in analogue high-definition technologies naturally led to the development of digital television standards.

- 2.33** Japan, which had adopted the American NTSC analogue standard, started working on enhanced quality technology in the 1960s. This developed into an analogue high-definition technology (MUSE Hi-Vision), which Japan proposed in the 1986 CCIR conference to be endorsed as the global High Definition TV (HDTV) standard. Japan's HDTV began broadcasting in 1989. However, the adoption of the Japanese HDTV transmission system was slow. Despite the transmission system being of much higher quality than NTSC, high-definition programming was scarce and the widescreen television sets that employed the standard were too expensive (Wu et al. 2006).
- 2.34** The US and Europe, fearing complete domination of their electronics markets by Japan, delayed the approval of the Japanese analogue high-definition standard to allow their national industries to develop rival and intentionally incompatible standards (Lee 1996).
- 2.35** In Europe, the European Union funded the Eureka 95 project to create a new high definition standard to be used in all of Europe. This project developed the satellite-based HD-MAC standard, which could not achieve market success because the interests of satellite broadcasters were not in line with those of high-definition set manufacturers. The project ended in 1995. Instead, the industry decided to work on a standard as directed by the market environment rather than the EU, and developed the PALplus system. Although PALplus quality was inferior to HD-MAC, it achieved higher market success (Wu et al. 2006).

³ In 1977, the US government used an "orderly marketing agreement" (OMA) to limit Japan's exports to not exceed 70% of its exports in 1976. Within two years, Japan's share of US colour TV market fell by eight percentage points. However, this share was captured by Japanese joint-ventures or plants in Taiwan and Korea, instead of domestic American producers. This forced the US to also negotiate OMAs with them (and later with Mexico and Singapore) in 1979. These restrictions led to an increase in Japanese foreign direct investment in the US, because imports of subassemblies were not restricted. (Burton and Saelens 1987; Baldwin and Green 1988).

Figure 4: Digital television standards around the world



Source: Adapted from the DVB map available at <https://www.dvb.org/resources/public/images/site/dvb-t2_map.pdf>.

2.36 In the US, the FCC Advisory Committee on Advanced Television Service (ACATS) requested proposals for the new US standard to replace NTSC. As in earlier analogue technologies, there was a significant degree of government involvement in the development of regional high-definition technologies. For instance, the US Labour Secretary Robert Reich wanted FCC to take into account the number of American jobs to be created in its selection of the HDTV standard (Lee 1996). In 1993, ACATS recommended that the companies that put forward the four chosen proposals should combine their efforts to develop the next all-digital system, and 'the Grand Alliance' was formed. The Grand Alliance developed the digital ATSC system, approved by the FCC in 1997. ATSC is currently implemented in the NAFTA countries (US, Canada, Mexico), as well as in El Salvador, Honduras, and South Korea (Lee 1996, Angulo et al. 2011).

2.37 In light of the all-digital television standards developed in the US, Japan also abandoned its analogue high definition standard in favour of an all-digital standard. This shift came with the pressure of major electronics manufacturers as well as the direct involvement of Ministry of Posts and Telecommunications in 1997. The Ministry founded the *Association of Radio Industries and Business* (ARIB) in 1995, which developed the Integrated Systems Digital Broadcasting (ISDB) standard as the Japanese digital television standard. ISDB standard is currently implemented in Japan and (with important modifications) in South America (namely, Argentina, Brazil, Chile, Costa Rica, Ecuador, Peru and Venezuela) (Angulo et al. 2011).

2.38 Again, in response to the all-digital standard created by the US, the EU decided to support the European industry to develop the European digital standard. A consortium similar to the American Grand Alliance and the Japanese ARIB was formed in Europe from the key representatives that developed the high-definition PALplus standard: the DVB Group. The DVB Group developed DVB as the European digital television standard. Currently, the group has more than 200 member institutions and companies from around the world. The DVB standard is the most widely adopted standard around the world with all of Europe, Middle East, Central and Southeast Asia, most of Africa, and Oceania. In addition, Uruguay, Colombia, and Panama also implement the DVB standard (Angulo et al. 2011).

2.39 Lastly, China developed its own digital television standard, DTMB, which was largely based on the European DVB.

2.40 Figure 4 presents a world map of digital television standards in September 2016. Contrasted with the analogue standards NTSC, SECAM, and PAL; we observe less fragmentation intra-region, but more fragmentation globally. NAFTA countries all adopted the American ATSC standard, but this time Japan insisted on its own ISDB standard. This fragmented Latin America between the American ATSC, European DVB, and the Japanese ISDB. Meanwhile, Europe, which was strictly divided into two camps in the analogue age, came together in the digital technologies thanks to the presence of the European Union. Lastly, China emerged as a new player in the television industry.

Government-mandated standards in early mobile telephony

- 2.41** In the late-1970s and the 1980s, the telecoms industry was dominated by monopolies in the US, Japan and in Europe, almost all of them state-controlled. Naturally, the national governments often had significant influence on standards development. Standards were mandated by the government in all regions except in Nordic countries where the governments played an 'accommodating' role by agreeing to cooperate in the development of a pan-Nordic system and left the standardisation to the public telephone operators and manufacturers such as Ericsson and Nokia (van de Kaa and Greeven 2016).
- 2.42** The first analogue cellular network was launched on a commercial basis in Japan by Nippon Telegraph and Telephone (NTT) in 1979. The government had a lot of influence on NTT and therefore mandated the development of the NTT wireless standard (van de Kaa and Greeven 2016).
- 2.43** In the US, the 1G standard, called Analogue Mobile Phone System (AMPS), was developed by AT&T/Bell and Motorola. The AMPS standard was set as the uniform standard for digital communications for the US by the Federal Communications Commission (FCC) in 1982. The decision in 1982 by the US to adopt a single standard led to many other countries choosing AMPS over NMT. For example, Canada, South Korea, the UK and Hong Kong adopted AMPS or a similar technology (Gandal et al. 2003).
- 2.44** In Europe, in the early 1980s, countries developed their own 1G standards – there were nine competing standards in Europe. However, as mentioned above, the Nordic mobile telephone operators cooperated to develop a pan-Nordic system called Nordic Mobile Telephony (NMT) standard, which was introduced in 1981. This standard was later adopted in Saudi Arabia, Thailand, Algeria, Spain, the Netherlands, Belgium and Switzerland (Bach 2000).
- 2.45** National governments sought to use 1G standards as a means to ensure the future competitiveness of their manufacturers. However, their attempts to protect the national manufacturers by using incompatible national standards led to weak competition in their respective markets and contributed towards the decline of national manufacturers largely due to lack of scale. The success of the NMT standard encouraged European governments to cooperate on the next generation of mobile telephony standards, as we now discuss.

The rise of industry-led standard-setting in mobile telephony

2G mobile telephony in Europe

- 2.46** The use of the NMT standard in international markets (see above) brought Nordic equipment manufacturers success; Nokia and Ericsson controlled roughly 20% of the world market for mobile phones in 1985, while all other European manufacturers together held less than 10%. In an industry characterised by significant economies of scale, successful

cooperation in the Nordic countries strengthened their manufacturers vis-à-vis their international competitors. Meanwhile attempts at bilateral and multilateral cooperation between other European countries had failed due to their concerns about their domestic industries (Bach 2000).

- 2.47** European national operators realised that localized solutions to the development of mobile communications did not make long-term economic sense. To overcome high R&D costs, they wanted to exploit the economies of scale inherent in global market penetration.
- 2.48** To explore the feasibility of collaboration, the French and German national telecoms authorities raised the question at the CEPT (European Conference of Postal and Telecommunications Administrations) in 1982. CEPT included the national telecommunications administrations of 26 countries, composed of mainly technicians and research engineers. Device manufacturers were not included in the official deliberations but were represented by their respective national governments (Bach 2000).
- 2.49** The CEPT is obliged to accept mandates from the European Commission to take specific actions to harmonise the use of radio spectrum in Europe. However, the European Commission plays no role in relation to the technical choices made in the European Standards; its role is to ensure that the standardization structures and procedures remain efficient, accountable and transparent. (European Commission 2003).
- 2.50** In 1982, the CEPT established the 'Groupe Spéciale Mobile' (GSM) to develop a standardised system to promote spectrum efficiency, allow international roaming, reduce costs, and improve quality and services. Decisions in the GSM were to be made through unanimous agreement among its members. The key players were the national governments in France, Germany, UK, Italy, and the Nordic countries. GSM, following technical deliberations, decided to pursue a digital standard which would enable a more efficient management of scarce frequency bands; provide high speech quality; include features such as speech security and data communications; and allow smaller and cheaper devices (Bach 2000).

The GSM members agreed on the specifications for 2G GSM standards in 1987, which drew on several of the eight component proposals submitted by European industry consortia in 1986. This standard was called the 'Global System for Mobile' communications (GSM), retaining the same three-letter abbreviation. In September 1987, mobile network operators across Europe signed a Memorandum of Understanding to introduce GSM networks by 1991. 2G mobile telephony in the US.

- 2.51** US standardisation development was even more starkly characterised by a shift from the government-mandated AMPS standard in 1G, to a market-driven strategy for 2G systems. The US Federal Communications Commission, FCC, did not mandate a specific standard in the US and carriers were free to choose whatever standard they wished. This resulted in the presence of multiple standards (Gandal et al. 2003).

Box 2.1: Single standard vs fragmented market

In the 1990s, Europe had a common standard for 2G telephony whereas the US had a fragmented market. In Europe, callers paid for the calls; whereas in the US, receivers paid. This led to a situation where US consumers kept their phones switched off, reducing the value of the service. Possibly as a result of this difference, adoption rates in the US were behind those in Europe in the 1990s. In June 2002, US mobile penetration rate was at 40%. At that point, most countries in Europe had surpassed the 70% threshold.

Moreover, US device manufacturers found it difficult to take advantage of scale economies and produce affordable equipment without a unified market. It was only in 1998 that US sales of digital phones (of all technologies) first surpassed analogue phone sales (10.1 vs 7.9 million units). In Europe, the tipping point occurred in 1995 — three years earlier.

The contrasting experiences from the two jurisdictions illustrate a dilemma: the US experienced slower adoption as a result of its fragmented standards. However, the CDMA standard, as a next-generation standard, averred to be technically superior to GSM, enabled an evolution path to innovative technologies. Such dilemmas are inevitable but high quality industry-driven standard-setting institutions can help minimise them.

- 2.52** Filling the FCC regulatory vacuum, the major telecom companies formed a voluntary consortium, the Cellular Telecommunications Industry Association (CTIA). The CTIA launched a systematic evaluation of various technological alternatives in 1985. This was endorsed by cellular operators and major equipment manufacturers, including Motorola, AT&T, Nortel, Ericsson, and IMM (Grant 2000).
- 2.53** In 1989, based on its commercial readiness and availability, the CTIA consortium initially settled on a standard called 'IS-136' which was similar to but not the same as the European GSM standard. For example, both standards used Time Division Multiple Access (TDMA). This private sector attempt at de facto standardization could potentially have led to the emergence of a single 2G standard in the US as in Europe — although without regulatory oversight (Cabral 2009).
- 2.54** However, in 1991 Qualcomm developed a competing technology called CDMA, (Code Driven Multiple Access). Several industry players regarded Qualcomm's CDMA technology as superior to TDMA, and some operators began adopting CDMA instead of TDMA. In 1993, the CTIA published Qualcomm's CDMA technology as the 'IS-95' standard (Cabral 2009).⁴
- 2.55** The US market featured both standards. By 2003, there was nearly equivalent nationwide coverage in the US for both the CDMA and TDMA standards. This coverage was achieved without the FCC (or any other regulatory body) mandating a standard and without nationwide roaming (Gandal et al. 2003).

Converging to a global standard – 3G mobile telephony

- 2.56** The International Telecommunications Union (ITU) developed a set of specifications for 3G under the title of 'International Mobile Telecommunications-2000' (IMT-2000). Through the 1990s, various national standard development organisations, such as the European Technical Standards Institute (ETSI), started developing 3G technologies through international standards bodies, such as 3GPP. These international standards

organisations helped combine these technologies into standards that qualified under the ITU's 3G IMT-2000 specifications. For example, 3GPP was the standard body behind the 'Universal Mobile Telecommunications System' (UMTS) developed by Nokia that was an upgrade to GSM (2G) networks in Europe but was not compatible with the existing infrastructure. While this was based on the existing core GSM technologies, it incorporated a wideband-CDMA technology (W-CDMA).

- 2.57** 3GPP2 was another international standards body, and was behind the competing 3G standard 'CDMA2000' which was developed by US network providers and was compatible with the existing infrastructure. The proponents of the two standards were not able to agree on a single standard so the two standards were developed in parallel. The US tried to avoid the multiplicity of standards described above and put pressure to create a set of global standards (CDMA2000), but ETSI adopted a slightly different standard for the EU (W-CDMA), incompatible with the other international systems.
- 2.58** As participants failed to reach a compromise on IMT-2000, it appeared that the same sort of worldwide network incompatibility that had characterised the 2G world would be carried over into the 3G technology. However, a coalition of network providers called the 'Operators Harmonization Group' (OHG)⁵ succeeded in securing a compromise between the competing camps in 1999. Rather than adopting a single standard for IMT-2000, 3G handsets were required to be able to function in any network employing one of the standards of the 3G 'family', i.e. the CDMA2000 and W-CDMA (Bach 2000).

Transition from 3G to 4G

- 2.59** The ITU developed a set of specifications for 4G under the title 'IMT-Advanced' in the early 2000s.

⁴ In this study, in line with the literature, we refer to the 'IS-136' and the 'IS-95' standards as TDMA and CDMA respectively, and the European GSM standard, which also uses TDMA technology, as GSM.

⁵ The OHG founding members included Bell Atlantic Mobile, Bell Mobility, BellSouth Cellular, China Mobile, China Unicom, DACOM, DDI, Hansol M.Com, IDO, Japan Telecom, KDD, Korea Telecom, LG Telecom, Microcell Connexions, NTT DoCoMo, Omnitel, SingTel, SK Telecom, Sprint PCS, Telefonica Moviles, Telesystem International Wireless, T-Mobil, Vodafone AirTouch, and VoiceStream Wireless. (OHG 2000)

- 2.60** As with 3G, various organisations developed technologies and brought them together through international standards bodies as standards qualifying under the 4G 'IMT-Advanced' specifications. 3GPP developed the LTE standard which was proposed as an upgrade to the 2G and 3G networks. The IEEE (Institute for Electrical and Electronic Engineers) and the Chinese Ministry of Industry and Information Technology (MIIT) also developed alternative technologies, namely WiMax and TD-LTE (Van de Kaa and Greeven 2016).
- 2.61** 3GPP's LTE system (and also its upgraded version, LTE-Advanced) provide a wide range of additional services beyond those in IMT-2000. These standards were approved in 2008 and widely adopted as the standards for 4G. The ITU recognized LTE and WiMAX to be 4G technologies, as they provided significant improvements over the existing 3G technologies, even if they did not fully satisfy the requirements of IMT-Advanced. Later versions of LTE such as LTE-Advanced was IMT-Advanced compliant. While the IEEE-sponsored Wimax was also accepted as a 4G standard, it was not successful in achieving meaningful penetration in the market.

De facto standards: the example of PC operating systems

- 2.62** In contrast to the open voluntary standards that are the main focus on this paper, PC operating systems ("O/S") have been developed as proprietary standards, under the ultimate control of a single firm. Market structure and the direction and pace of technological innovation have been influenced by this feature of the industry.
- 2.63** The PC industry has been shaped by various standards wars between vertically decentralised O/Ss, with Microsoft's O/Ss emerging as the market leaders. Vertically integrated O/Ss, such as Apple's OS and IBM's OS/2, have a marginal role. Table 2 lists the main O/Ss and their sponsors in the PC industry.
- 2.64** The history of PC O/Ss started with a relatively brief standard war resulting in a proprietary standard, Microsoft's MS-DOS and Windows, being adopted by nearly the whole market. Following the launch of the first PC in the early 1980s, Microsoft licensed its O/S to all PC manufacturers, charged low licensing fees and provided tools to application developers to facilitate positive network effects. Microsoft's open ecosystem allowed it to become more innovative and open to technological developments, compared to its competitors with a closed ecosystem, such as Apple. The large number of hardware producers and application

developers competed in driving prices lower and pushing innovation forward.

- 2.65** However, the release of the Windows versions was slower than desired by other members of the value chain, such as Intel, which manufactures the processors powering Windows PCs. Although Intel desired the release of a new Windows version every two years so that they could fully exploit the new advances available with its improved semiconductors, Microsoft released a major new version every four to five years, slowing the innovation rate. In contrast to open standards, Microsoft could decide the speed and type of innovation without any collaboration with others in the value chain.
- 2.66** Apple's iOS was less open than Microsoft's, and its releases were even less frequent than those of Microsoft's. Apple did not license its proprietary O/S to other PC manufacturers. In contrast to Apple, Microsoft had a vertically disintegrated ecosystem and focused only on the O/S layer. Microsoft relied on outsiders for hardware, but it collaborated closely with them to optimize the performance of its O/S.

Contrasting the development of PC O/S and Smartphone O/S

- 2.67** In contrast to the PC story, the story of Smart phone O/S illustrates a relatively longer standard war. Google's open source Android replaced gradually the dominant O/S sponsors, such as Nokia's Symbian and RIM's proprietary O/S for Blackberry.
- 2.68** One important reason for Android's rise is that it is provided for 'free' without license fees to handset producers. However, 'free' meant 'paid for in another way' since Google's business model is based upon the provision of free services to users on which it makes money from advertising. Indeed, Google's approach to combining Android O/S with Google Search and Maps is now the subject of a high-profile European Commission competition investigation (which is ongoing at the time of writing). It is at least arguable that this is no better for consumers than charging a license fee – it is simply a different way to recoup the innovation costs of the O/S.
- 2.69** It is unclear whether Android's success can be seen as a triumph for open source, as the way Google develops Android is closer to a proprietary standard than a truly open-source standard. For instance, Google does not collaborate with others in the value chain and strictly manages the

Table 2: Key PC O/Ss

O/S	Sponsor	First shipped	Type
MS-DOS, Windows	Microsoft	1981	Proprietary licensed
System OS, OS X	Apple	1984	Proprietary
Linux	-	1991	Open source

Source: Tanenbaum and Bos (2014).

Table 3: Change in US price levels, 2003-2009 (Compound annual growth rate)

Industry	Product	Yearly change in prices
Mobile telephony		
	Carriers	-5.4%
	Cellular phones	-13.0%
Operating systems		
	Electronic computers	-19.2%
	Software publishing	-0.9%
TV		
	Radio/TV broadcast and wireless telecommunication equipment manufacturing	0.2%

Source: Cellular phones: Byrne and Corrado (2015), Table B.1, "Byrne-Corrado index".

All other prices: Federal Reserve Economic Data (PPI by Industry: Wireless Telecommunications Carriers PCU517210517210; PPI by Commodity for Machinery and Equipment: Electronic Computers WPU1151; PPI by Industry: Software Publishers WPUFD4131; and PPI by Industry: Radio/TV Broadcast and Wireless Communications Equipment Manufacturing PCU3342233422).

development and compatibility of new Android versions to avoid fragmentation and to speed up the release of new versions. However, it does allow modification of the O/S and in many ways makes use of the community of users and other developers as do the standard development organisations we shall discuss in this report.

The impact of proprietary standards on innovation

2.70 While standards can help create efficiency, the O/S story shows that proprietary standards, managed by a single firm, are more likely to result in inefficient standards wars, the choice of inferior technologies and in anti-competitive market structures and behaviour. As a 'gatekeeper', the standard holder has less incentive to innovate. PC manufacturers using Microsoft's 'semi-open' standard introduced new chips more frequently compared to Apple, with its closed standards.

2.71 Proprietary standards are also associated with slower innovation in the associated markets. For example, newer technologies, such as cloud computing, have relied on open-source programmes despite the strong dominance of proprietary software such as Windows in the PC market. Summarising the benefits of open source software for innovation, The Economist stated "*Without open-source programs like Linux, however, cloud computing would have been stillborn. Old-style "proprietary" software was too expensive and hard to adapt*" (The Economist 2016).

Impact of standards on prices and quality

2.72 Price levels in standards-reliant technology industries have declined over the last few decades.

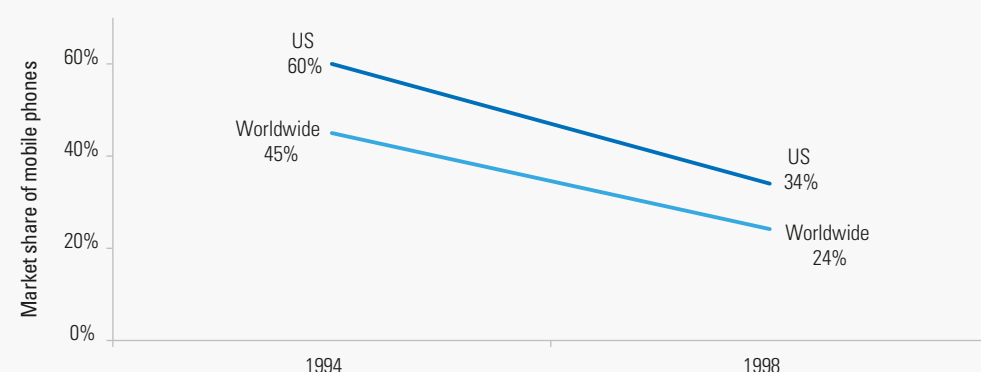
2.73 In the US, price levels for wireless telecommunications carriers and cell phones declined by 5.4% and 13.0% per year on average during 2003-2009. The price levels for electronic computers and software publishing declined by 19.2% and 0.9% per year on average respectively. Prices of radio and TV broadcasts increased by 0.2% per year on average in the same period.

Price impact of government involvement in analogue television standards

2.74 Incompatible regional analogue television standards created nontariff barriers to trade in TV sets and, hence, increased concentration and reduced competition in these products. In 1967, for example, the average price of a television in France was 80% higher than in Germany and 50% higher than in Italy (OECD 1970, cited in Gaillard 2007). An internal note for the French Ministry of Information defended the necessity of the SECAM system to foster domestic manufacturing as follows: "The prices of production in Germany are lower by 25% to 30% than the prices of production for the same materials in France. Under these conditions, if Germany and France adopt the same system, the French industry will be in direct competition without contingent protection or customs with West German industry" (French Government Archives, cited in Fickers 2002). Incompatible national standards limited imported TV sets have only 6% market share in France in 1970, to increase to 19% in six years (Gaillard 2007).

2.75 Although German manufacturers had higher productivity than the French, they could not compete with Japanese manufacturers. Therefore, the limited licensing in Europe to Japanese firms in 1970s was tied to direct trade restrictions and quotas on Japanese imports (which was also the case in the US) (Burton and Saelens 1987; Baldwin and Green 1988, Gaillard 2007). Manufacturing costs in Germany were twice more the costs in Japan. The sales quotas initially led Japanese firms to invest in local production facilities (as they did in the US); and they finally competed fully with the expiry of patents in 1982. In the mid-1980s, German television manufacturers were overtaken by their competitors (Gaillard 2007).

Figure 5: Motorola: US and worldwide share of mobile phones sold (1994 and 1998)



Notes: IDC Worldwide Quarterly Mobile Phone Tracker data available since 1995, which is substituted for 1994.

Source: Market shares for the US: Crockett (1998); Worldwide: IDC Worldwide Quarterly Mobile Phone Tracker.

Prices in mobile telecommunications

2.76 Consumer prices for mobile telephony devices have been falling even as the range and quality of services have massively improved. A study by Galetovic et al. (2015) found that the 'quality-adjusted price' index for mobile devices decreased by 7% per year, compared to 2.3% per year in industries also built on semi-conductors but which were not based on standards. The average price of smartphones decreased by 22% between 2008 and 2013.

2.77 However, the early mobile phone industry had a much worse record of price and performance improvement. Until 1982, local telephone services in the United States were provided by a single company, AT&T, which leased telephones made by its Western Electric subsidiary to businesses and households. During the period before 1982, the quality-adjusted, relative price of cable phone equipment was declining at a steady rate. This pattern reversed in the 1980s when the first mobile phones—all produced by a single manufacturer, Motorola—entered the U.S. market. Motorola's initial product, the DynaTAC 8000X, had a price of \$3,995 (about \$9,400 in 2015 dollars), weighed more than a kilo, and had a battery life of a half hour.

Impact on prices of limiting competition using IPR

2.78 When a number of European operators required the manufacturers to sign a declaration to license the whole GSM community on FRAND terms, the US company Motorola chose not to accept this declaration, and only entered into a limited number of cross-licences with selected parties in Europe. Several European companies (such as Matra from France and Dancall from Denmark) as well as Japanese companies failed to get the necessary licences. Virtually all equipment was supplied by the companies that took part in the cross-licensing scheme: Ericsson, Nokia, Siemens, Alcatel, and Motorola.

2.79 As with the French TV producers, this partial protection from competition was ultimately unsuccessful. Figure 5 shows the decline in Motorola's market share in the US between 1994 and 1998 and in the worldwide market between 1995 and 1998, i.e. before and after the emergence of 2G technologies in the US.

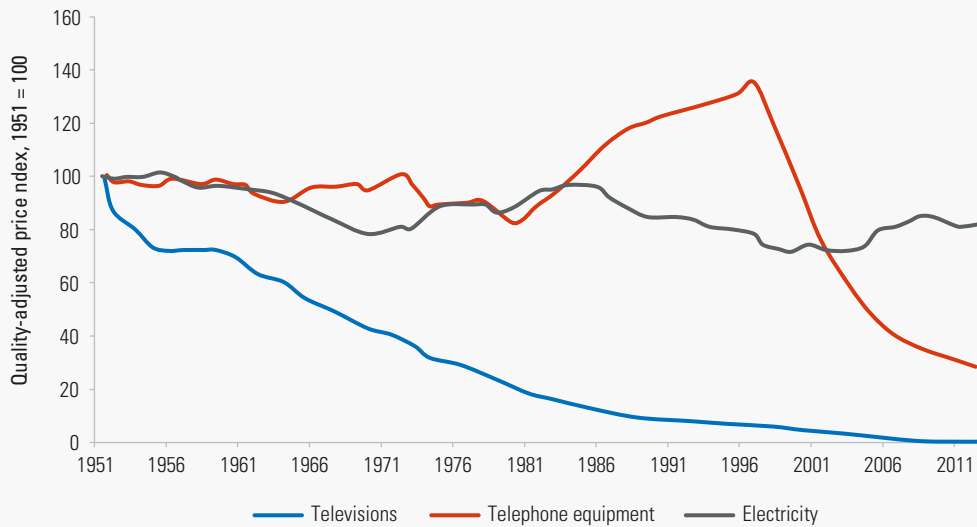
2.80 With limited competition, the quality-adjusted relative prices of phones in the US continued to climb until 1997. Around that time, Motorola's dominance was challenged by multiple manufacturers of 2G cell phones competing for market share. Motorola was slow to respond to the onset of digital 2G technologies in the US. From that point onwards, and through both the 3G and 4G revolutions, the price of telephone equipment fell by 10 percent per year on average.

2.81 Figure 6 shows the minimal but steady decline in cable phone quality-adjusted prices before the invention of mobile phones (until 1982), the price hike in the first years of mobile phones during which Motorola refused to license its technology on FRAND terms (1982-1997), and the significant drop in quality-adjusted prices with the later development of 2G, 3G, and 4G technologies.

2.82 GSMA (GSM Association) estimates that the effective price per minute is 63% lower in 2014 than it was in 2004. (GSMA 2014). Another measure of mobile market prices is the average revenue per user (ARPU) in the retail mobile market; the European Commission estimates that ARPU in EU27 declined from € 211 per year in 2010 to € 162 per year in 2014⁶.

6 European Commission, (Digital Single market), http://digital-agenda-data.eu/datasets/digital_agenda_score-board_key_indicators/visualizations. (Indicator Group: Mobile market. Indicator: Average Revenue per User (ARPU) in the Retail Mobile Market. Selected countries: European Union. <[http://digital-agenda-data.eu/charts/see-the-evolution-of-an-indicator-and-compare-countries#chart={\"indicator-group\":\"mobile\",\"indicator\":\"mob_arpu\",\"breakdown\":\"TOTAL_MOB\",\"unit-measure\":\"euro\",\"ref-area\":\"EU27\"}](http://digital-agenda-data.eu/charts/see-the-evolution-of-an-indicator-and-compare-countries#chart={\)>).

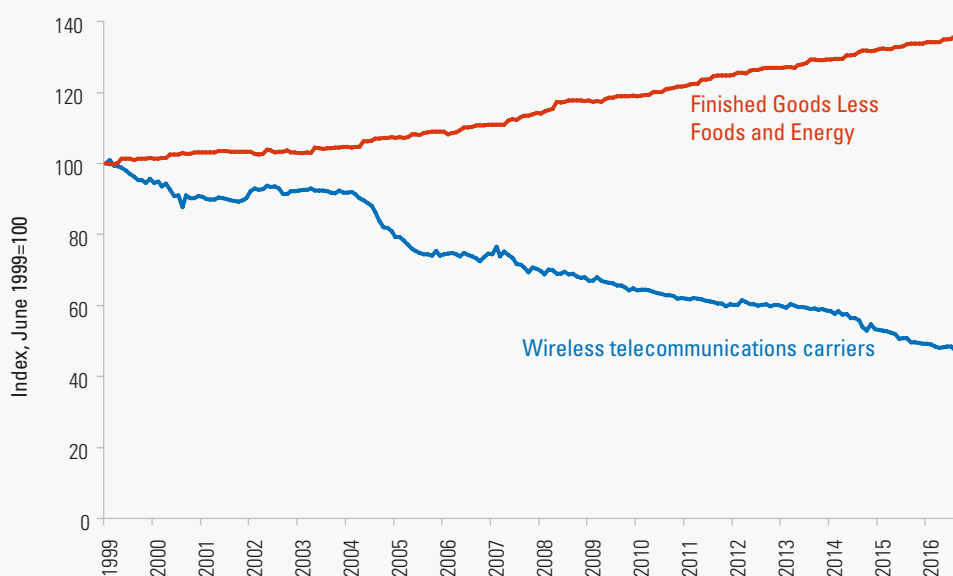
Figure 6: Quality-adjusted relative prices of telephone equipment, TVs and electricity (US data), 1951–2013



Source: Adapted by CL from Galetovic et al. (2015), Figure 5.

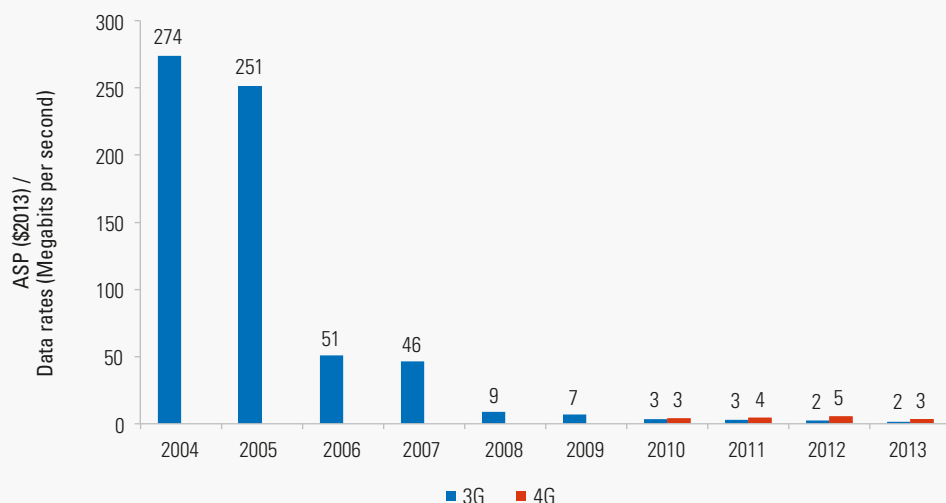
2.83 The price of mobile usage has also declined rapidly along with the price of equipment, as shown in the quality adjusted producer price index for wireless telecommunication carriers in Figure 7. Furthermore, the average selling price of handsets utilising 3G and 4G technology, divided by one measure of quality - maximum data download rates - dropped by 99% in just nine years from 2004-2013.

Figure 7: Wireless telecommunications carriers quality-adjusted prices, US 1999-2016



Source: Federal Reserve Economic Data (Producer Price Index by Industry: Wireless Telecommunications Carriers PCU517210517210; Producer Price Index by Commodity for Final Demand: Finished Goods Less Foods and Energy WPUFD4131).

Figure 8: Cost of mobile telephones per data download speed (\$2013/Megabits/s)



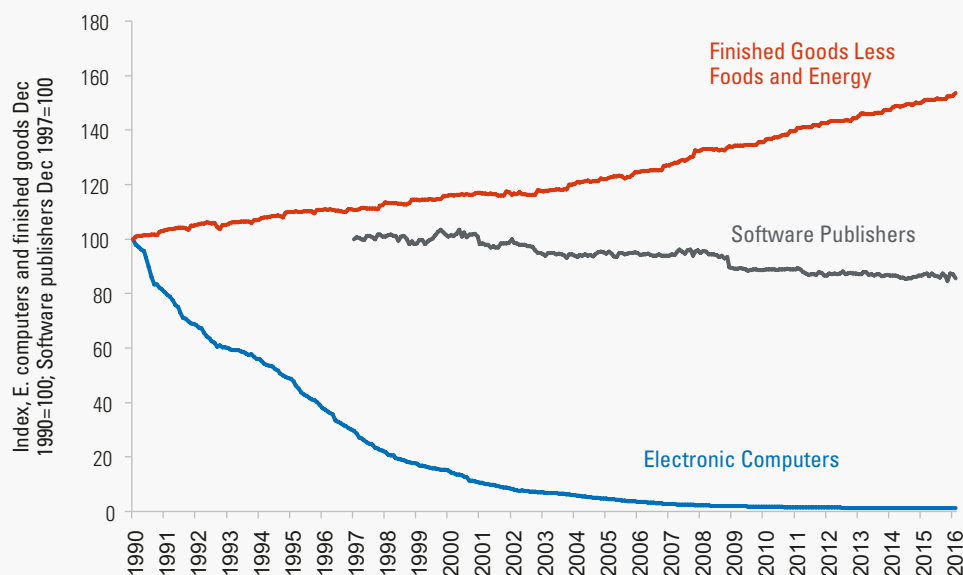
Source: Average selling prices of handsets deploying each technology: Galetovic and Gupta (2016), Figure 8. Maximum download data rates for each technology: Gupta (2015), Figure 2.

Prices in PC operating systems

2.84 For products related to the PC O/S-related industry, prices have fallen rapidly while productivity has increased, albeit not as quickly as in mobile telecoms.

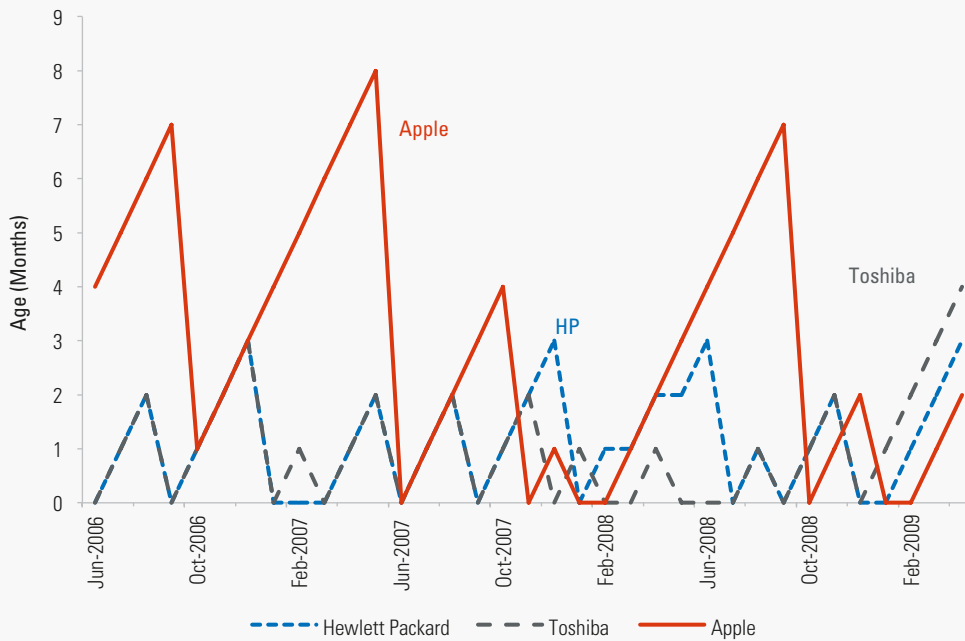
2.85 In the US, the quality-adjusted producer price index for electronic computers declined by close to 99% since 1990. Figure 9 contrasts this to the overall price levels in the US (PPI for final demand excluding food and energy), which have increased by 50% since 1990.

Figure 9: PC market quality-adjusted prices, US 1990-2016



Source: Federal Reserve Economic Data (PPI by Commodity for Machinery and Equipment: Electronic Computers WPU1151; PPI by Industry: Software Publishers PCU511210511210; and PPI by Commodity for Final Demand: Finished Goods Less Foods and Energy WPUFD4131).

Figure 10: Adoption of Intel CPUs, June 2006-March 2009



Source: Adapted by CL from Copeland and Shapiro (2010), Figure 3

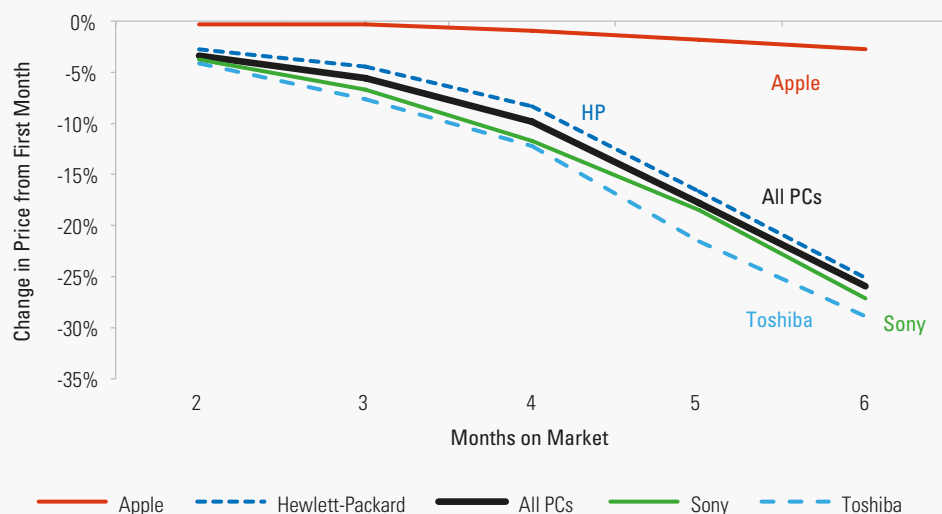
2.86 As explained earlier, operating systems are *de facto* standards that exhibit different degrees of openness. Apple's system is essentially closed to independent hardware producers while open to software applications; Windows is a proprietary standard which is solely controlled by Microsoft but open to many different complementary products (hardware and software), and Linux is open source.

2.87 There is clear evidence that more open systems lead to faster innovation. Copeland and Shapiro (2010) found that Apple introduced new chips less frequently than Wintel based manufacturers. Figure 10 plots the age of the CPU since its launch by Intel in the latest version of Apple, Toshiba and Hewlett-Packard PCs. The vertical axis shows the age of the CPU (i.e. months since the CPU's commercial launch). For example, in October 2006, Apple's PC had a CPU that was launched in September 2006. The September 2006 CPU was used until June 2007.

2.88 Figure 10 shows that the rate of product introduction was much faster for Wintel PC manufacturers than for Apple. Toshiba and Hewlett-Packard were twice as often the first to adopt a new CPU (12 and 14 months out of 35, respectively) as Apple (7 out of 35 months). Further, Hewlett-Packard and Toshiba rarely kept a CPU beyond three months, while on three occasions, Apple's newest CPU available was seven months old.

2.89 Furthermore, the same study found that Apple's prices did not decline significantly over the product cycle, presumably because it was not facing new, higher-performance competitors. Figure 11 shows that Apple's prices declined by less than 5% six months following the launch of the corresponding Apple PC whereas the price of PCs in general declined by 25% on average in the six months following its launch.

Figure 11: Price Declines over product cycle from first month



Source: Adapted by CL from Copeland and Shapiro (2010), Figure 4.

2.90 While Apple is perceived to be a highly innovative company despite being a 'closed standard', there are several other examples of closed IT systems that have failed. One such example is the handheld computer (also known as the Personal Digital Assistant, or PDA) industry. Boudreau (2008) found that opening the complementary products – allowing independent hardware producers to use the operating system as a standard – was associated with a five-fold increase in the introduction of new products. Boudreau also found that *opening the platform itself had a beneficial effect*. Allowing other suppliers some degree of influence or control over development of the operating system also resulted in faster innovation, albeit the effect was much less than opening up to the production of complementary hardware.

2.91 The evidence indicates that with standards, prices are lower and the quality is higher. The effect of standards on price and quality is greater when standards are not fragmented. One reason for this is that standards can promote market competition, and greater diversity in innovation, as we now discuss.

Impact of standards on market structure and competition

2.92 All three industries - television, mobiles, and O/S - are associated with competitive hardware markets that implement the standards or design complementary products. Their hardware markets exhibit low concentration and high entry and exit rates. However, only mobile telephony has a diverse R&D sector in which smaller innovators can compete to contribute to the standard, whereas the R&D sector for television and O/S are highly concentrated.

2.93 Table 4 details the competitive hardware market structure for all three industries. Concentration can be measured by the Herfindahl-Hirschman Index ("HHI") ranging from close to zero (indicating a large number of small firms) to 10,000 (a single monopoly firm). The HHIs for mobile phones and LCD TV manufacturers are less than 1000, indicating highly competitive markets, and the HHI for PC vendors is 1578. Concentration can also be measured by the total market share of the top three firms, "CR(3)". The smaller the market share of top three firms, the more competitive the market.

Table 4: Concentration levels in hardware markets for mobile, television, and O/S industries (Global, 2016)

Industry	HHI	CR(3)
Mobile phone manufacturers	608	36%
LCD TV manufacturers	828	43%
Computer manufacturers	1578	61%

Source: Figure 12, Figure 14 and Figure 15.

Table 5: Diversity of the upstream R&D associated with the three industries (top 5 patent holders' combined share, global)

Industry	Diversity
Mobile telephony	Multiple contributors of technology and becoming more diverse as the standards have become complex and larger. Top 5 patent holders' combined share in: 2G: 69%; 3G: 58%; 4G: 48%.
Operating systems	Microsoft and Apple create 100% of the R&D of their O/Ss.
TV	Top 5 patent holders' combined share in: ATSC: 98%; DVB-T2: 83%.

Source: Table 7 and Table 8.

2.94 Although all three industries have many competing firms in manufacturing, only the mobile telephony industry has multiple providers in the R&D market as well. This illustrates an important theme of this report: that open, voluntary standards provide opportunities for niche technological firms to get involved in R&D and contribute to large-scale technology projects without needing to vertically integrate into equipment manufacturing.

2.95 For example, Neul, a small company with less than 200 employees founded in 2010, was a major contributor to 'weightless' standards. 'Weightless' is a set of open standards developed by a Special Interest Group comprising 1400 members including large firms, such as Qualcomm and Huawei. The 'weightless' standards govern communication between devices - the 'Internet of Things' - which builds on the fifth generation of mobile telephony: 5G. In 2013, Neul produced a chip which was the first implementation of 'weightless' standards. Neul was acquired by Huawei in 2014.

2.96 Table 5 presents the diversity in the upstream mobile telephony market, contrasted with the concentrated R&D markets of television and O/S, using the total share of the top five patent holders.

2.97 These measures of concentration should be interpreted carefully. The increase in the number of firms with SEPs does not necessarily mean more competition. However, these firms are likely to have alternative technologies for the same purpose, and therefore compete with each other to be included in the SEP. More importantly, even if these firms were not competing against each other, the variety of firms

provide is likely to bring more diverse perspectives compared to a single innovator.

2.98 The decrease in concentration among patent holders (i.e. the greater number of firms with SEPs) also cannot be used to draw conclusions on the value of the patents or the reasonableness of the licence conditions. Rather, the data shows that more firms are competing to have their technology included in standards, and may in fact suggest that the technology that is ultimately included is more valuable than in earlier generation standards because the patented technology will be included in the later generations only if there is a consensus to do so.

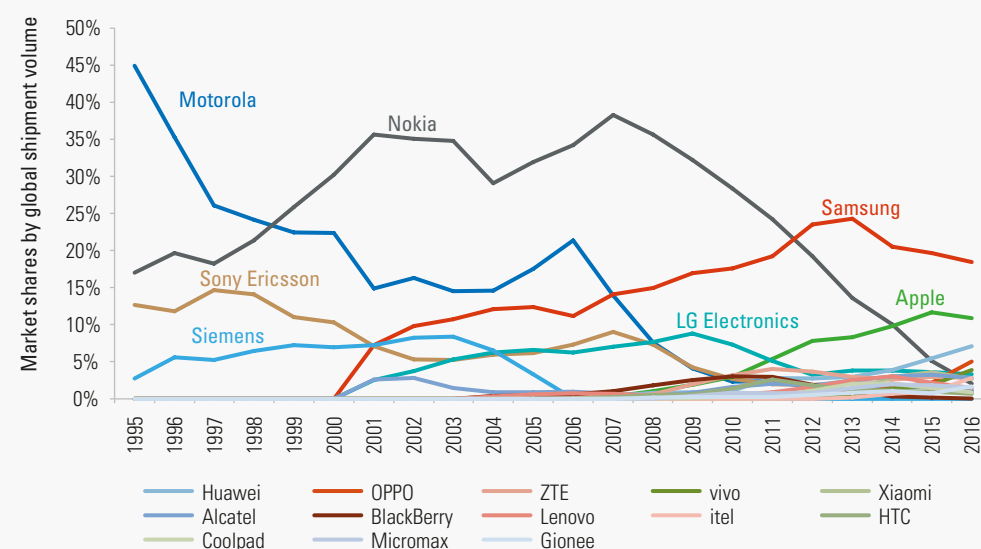
2.99 Next, we discuss the market dynamics of the three industries.

Mobile telephony

2.100 Of the three industries, mobile telephony shows the most market dynamism, with a large number of equipment manufacturers and specialist R&D firms.

2.101 The competitive nature of the industry can be seen in how winners and losers emerge over time in Figure 12. In the beginning of the 1990s, Motorola lost its position as the largest manufacturer to Nokia. However, after 14 years of being the market leader, Nokia lost its position to Samsung in 2012. In recent years, Chinese manufacturers such as Huawei and Xiaomi have risen to become among the largest device manufacturers. Another important feature is the increasing competition in the market place starting around 2005, with many firms holding small market shares as opposed to a handful of big players.

Figure 12: Global market shares of handset manufacturers, 1995 to 2016



Notes: Sony Ericsson data also includes sales of Ericsson (1995-2001) and Sony (2012-2016). Manufacturers with largest market shares indicated on the chart; legend only includes smaller manufacturers.

Source: 1995-2003 sales are from Strategy Analytics and 2004-2016 sales are from IDC Worldwide Quarterly Mobile Phone Tracker.

2.102 The success of firms (defined in terms of market share) in the mobile communications market is strongly related to the evolution of standards. Funk (1998) finds that in each generation of technology, the most successful firms were from countries or regions whose mobile communication systems became world-wide standards.

2.103 The study finds evidence that North American firms were successful in the provision of services and infrastructure based on the North American 1G standards (AMPS/TACS), whereas Nordic firms were successful in the provision of services and infrastructure based on the Nordic NMT standard. Similarly, for 2G, Nordic companies were the most successful for GSM-based products; North American firms were the most successful for CDMA-based products; and Japanese firms for PDC-based products.

2.104 Table 6 shows the market shares of firms producing equipment that conformed to the standard in place where those firms were headquartered⁷. Such 'domestic standard' firms had between 50% and 100% of the phone sale market and between 60% and 100% of the infrastructure market in the 1990s. Funk (1998) concludes that domestic firms gain a significant competitive advantage when their country's standard is selected as the global standard. This helps explain the interest of governments in promoting 'their' national standards – in early mobile phones as in the various generations of TV broadcasting: a government-promoted standard can have the effect of a protectionist policy for domestic industry. However, like trade protectionism, any such benefits are likely to be transitory because they shield firms from truly tough competition. For example, the increase in Samsung's market share relative to that of Nokia and Ericsson can be attributed to the adoption of a worldwide standard.

Table 6: Domestic bias in mobile phone subscriptions and sales, 1990s

Standard	Subscribers connected to the infrastructure of domestic firms for the standard, out of all subscribers	Mobile phone sales of domestic firms for the standard, out of total unit sales
AMTS	60%	70%
TACS	70%	50%
NMT	98%	55%
NTT	100%	100%
GSM	98%	60%
PDC	80%	95%

Notes: Data gathered during 1993-1997 by Funk (1998).

Source: Funk (1998), Table 4.

Table 7: R&D – shares of SEPs in mobile telephony standards

SEP owning entities	Count (%) of 2G SEPs	Count (%) of 3G SEPs	Count (%) of 4G SEPs
Top 2	1,208 (42%)	2,188 (30%)	2,424 (23%)
Top 5	1,951 (69%)	4,197 (58%)	5,125 (48%)
Top 10	2,385 (84%)	5,616 (78%)	7,664 (72%)
Top 20	2,648 (93%)	6,524 (90%)	9,708 (91%)
Top 40	2,802 (99%)	7,088 (98%)	10,476 (99%)

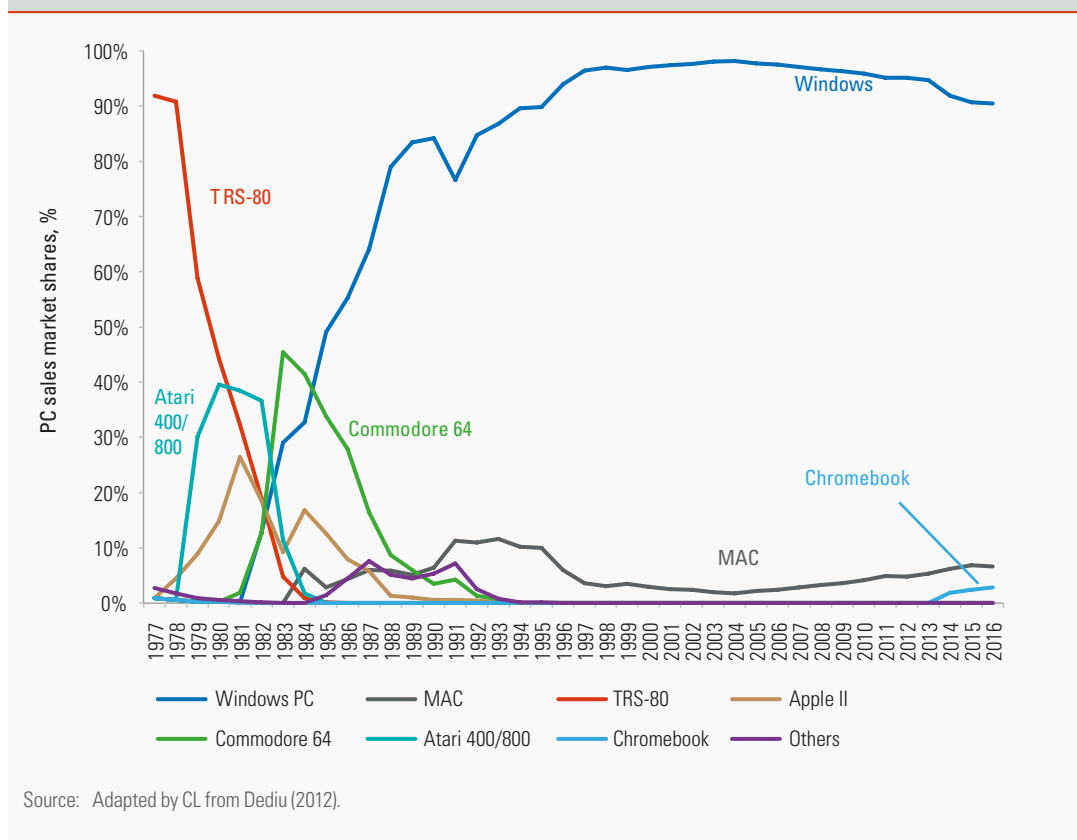
Source: Padilla and Llobet (2017).

2.105 Upstream, technological innovation was also more concentrated in earlier generations of mobile telephony. Each generation of mobile technology has been based on a wider pool of research while building on elements of previous generations. The share of the top two, five and ten firms' share of inventions is lower for 4G than for 3G and for 2G. Table 7 below shows the number of Standard Essential Patents (SEPs) and the shares held by the top companies.

PC operating systems

2.106 There has historically been little competition in the PC O/S market. Since the launch of the IBM PC in the early 1980s, Microsoft has been the largest O/S sponsor in the market. From 2002 to 2016, the share of Microsoft's Windows has been over 90%, with Apple's OS X and Linux at shares each less than 5%. Figure 13 also shows that Atari 400/800 and the Commodore 64 were market leaders for brief periods in the late-1970s and early 1980s, but are negligible in the O/S market now.

Figure 13: PC O/S market shares, 1977–2016



2.107 Development of O/Ss for PCs illustrates many of the economic effects of the de facto emergence of standards, which will often end up controlled as a proprietary standard by a single company. An 'eco-system' of complementary products forms around an O/S and their incompatibility with other O/Ss creates network effects: users (application developers and end-users) both want to have an O/S on which there are many other users. These effects cause the market to tend towards concentration, possibly via a standards war.

2.108 The more open approach taken by Microsoft compared to Apple may well have been a significant factor in its victory in that standards war. The Microsoft ecosystem overall may have been more innovative as well as cheaper because of the large number of competing hardware producers and applications developers. Windows has prevailed as the majority PC O/S despite state-sponsored, commercial and open-source challengers.

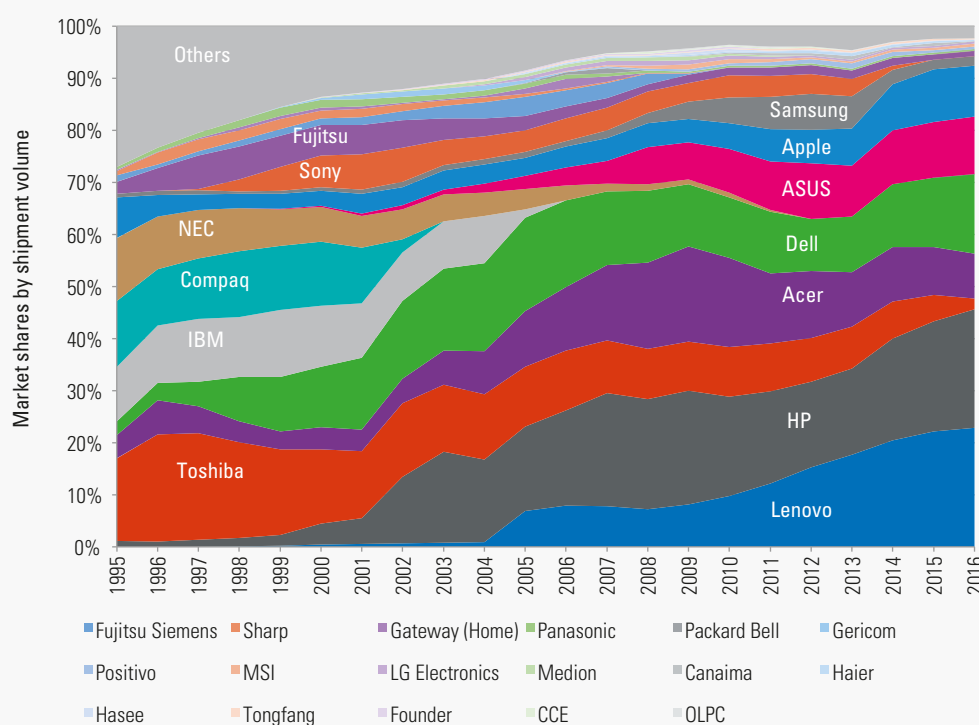
2.109 Since 1996, there has been a lot of dynamism in the hardware market; with new entrants and smaller players growing and market leaders from the late 1990s either being taken over by other companies or being forced out of the market. Acquisition of IBM's PC business by Lenovo and Compaq's acquisition by HP are two such examples. Both firms were market leaders in the late-1990s but began to shrink in the early 2000s. Lenovo and HP, which acquired these firms, were the market leaders in 2016. New players have also managed to enter the market successfully. Asus, which entered the PC market in 2007, was

the fourth largest manufacturer in 2007. Figure 14 shows the evolution of PC market shares from 1996 to 2016.

2.110 Microsoft's Windows has always been and remains a proprietary system. Many of the downsides of proprietary standards that we examine later in this report stem from standard wars. However, in this case, any such war was brief and won decisively by Microsoft early on, keeping the adverse effects minimal. Nonetheless, the company has been accused of taking advantage of its ownership of this central standard, to maintain the market position and relevance of Windows. Most famously, the US and European competition authorities have accused Microsoft of leveraging its O/S market power to extend monopoly to other businesses and of withholding compatibility information from competitors.

2.111 Similar concerns have been raised about other de facto proprietary standards owners such as Intel and, in the 1980s, IBM. Whether such concerns were valid or not, developers of complementary hardware and software are dependent on a platform owner not stranding their existing products without warning, or even opportunistically taking over their niche (for example by incorporating additional functionality into the O/S). Proprietary standards owners therefore seek to commit not to behave in this manner, consulting and informing other firms in the ecosystem on new designs. However, such activity does not approach the degree of consultation that emerges inevitably in an industry-based standards-setting body, where both sides of the market are represented.

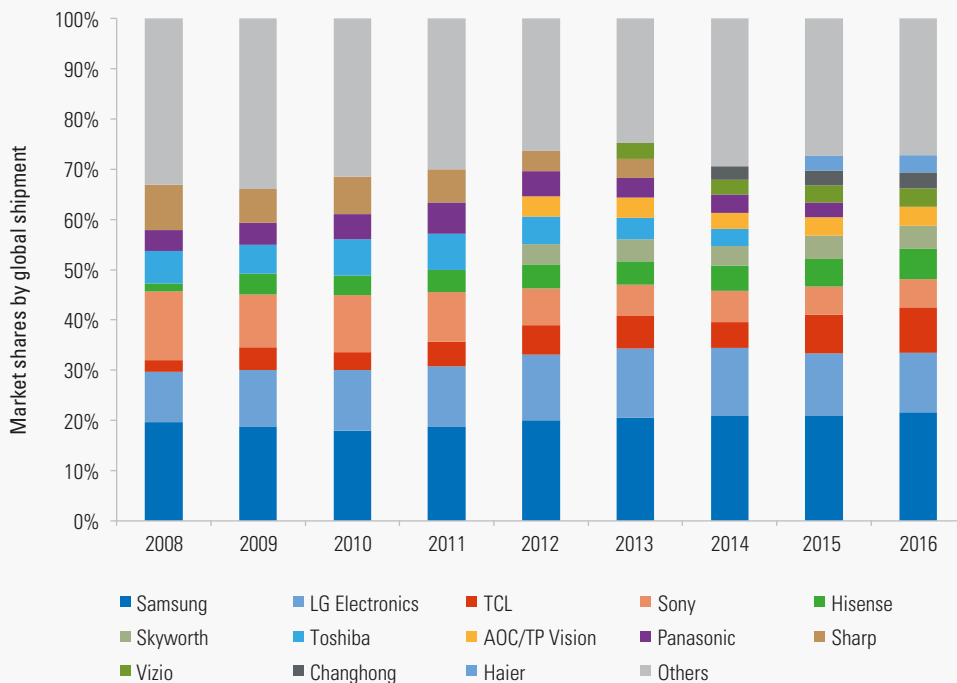
Figure 14: Global market shares of PC manufacturers, 1995-2016



Notes: Manufacturers with largest market shares identified on the chart; legend only includes smaller manufacturers.

Source: IDC Quarterly Personal Computing Device Tracker - PCD Final Historical, 2016Q4

Figure 15: Global market shares of LCD TV manufacturers, 2008-2016



Source: Adapted by CL from Statista chart <<https://www.statista.com/statistics/267095/global-market-share-of-lcd-tv-manufacturers/>>.

2.112 The upstream market for proprietary O/S is controlled by the firm that owns the O/S. For example, Microsoft is the sole firm involved in R&D for its O/S. Therefore, the upstream market for the corresponding O/S lacks the diversity that would be present in an industry such as mobile telephony based on more open development of standards.

Television

2.113 Today's market for LCD television equipment is less concentrated than that for PC O/S but more so than that for

mobile telephony equipment. Throughout 2008-2016, four firms - Samsung, LG, TCL and Sony – have held close to 40% of the market. Since 2012, there has been new entry capturing small market shares.

2.114 There are a handful of firms that own patents for digital TV standards. ISDB-T transmission standard patents are owned by ten companies, DVB-T2 patents by seven companies, and ATSC patents by nine companies. As shown in Table 8, top 5 patent owners own 83% of the patents for DVB-T2 standards and 98% of the patents for ATSC standards.

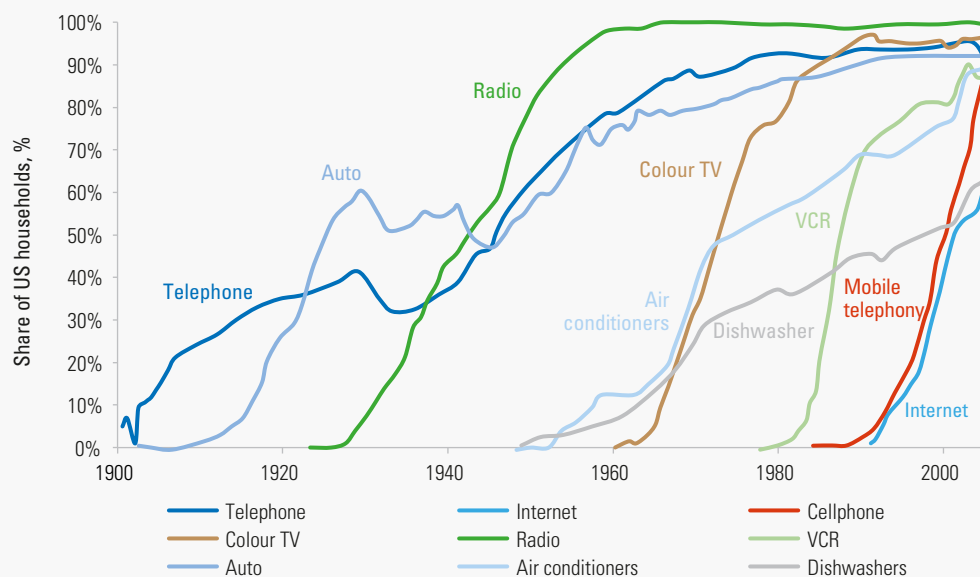
Table 8: R&D – shares of inventions in digital television broadcasting standards

Patent owning entities	ATSC Count of patent families (% of total)	DVB-T2 Count of patent families (% of total)
Top 2	249 (89%)	6 (50%)
Top 5	275 (98%)	10 (83%)
Top 10	281 (100%)	12 (100%)

Notes: We use patent families to avoid double counting innovations registered in multiple countries. ATSC patent list does not include patent family information; therefore, we use each patent owner's largest number of registrations in a country instead (since the same innovation is not registered multiple times in the same country). This proxy might underestimate the true number of patent families if the patent owner registered different innovations in different countries. Nonetheless, our argument about limited diversity in the R&D market holds: There are only nine patent owners for ATSC, seven for DVB-T2 and ten for ISDB-T, compared to numerous manufacturers implementing the standards. Although we know the list of contributors to ISDB-T, we do not have complete information on the number of patents contributed by smaller patent owners. Hence, ISDB-T is not included in Table 8.

Source: ATSC patent families: MPEGLA (<http://www.mpegla.com/main/programs/ATSC/Pages/PatentList.aspx>); DVB-T2 patent families: Sisvel (<http://www.sisvel.com/images/documents/DVB-T2/Patents.pdf>); ISDB-T patent families: ARIB (http://www.arib.or.jp/english/html/overview/doc/6-STD-B31v2_2-E1.pdf).

Figure 16: Technology adoption rates



Source: Adapted by CL from Felton (2008), as cited in McGrath (2013).

Conclusions

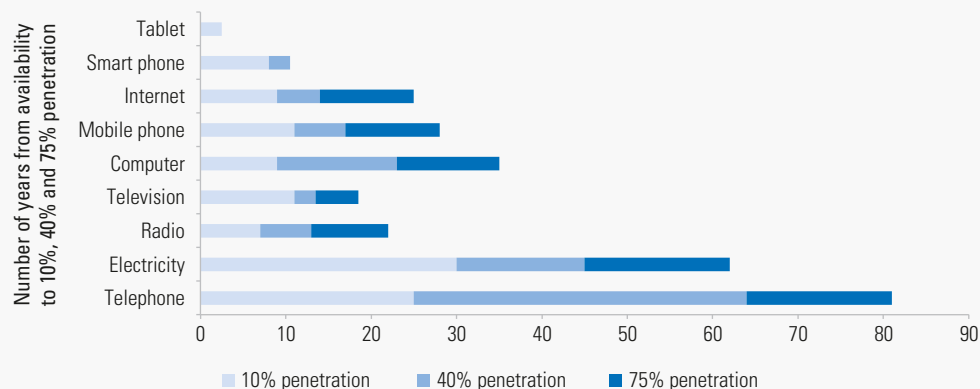
2.115 In this subsection we summarised the evidence on the impact of standards on market structure and concentration. We find that standardised technology industries lead to unconcentrated downstream industries, where competition is fierce and entry and exit is frequent.

2.116 However, there are different implications for upstream markets, depending on how standards are set. With open, voluntary standards, a number of smaller firms can contribute to standards development without having to take part in the rest of the supply chain. This characteristic of voluntary open standards leads to a diverse upstream market with a large number of players, where smaller players are successful in incorporating their technologies in the standard.

Impact of standards on technology adoption rates

2.117 The rapid growth in telecoms subscribers, accompanied by the dynamism in the ecosystem, has made mobile technology one of the most rapidly adopted technologies in history. Figure 15 below, shows how long it took various categories of products, from radio to the Internet, to achieve different penetration levels in US households. It took decades for the telephone to reach 50% of households, beginning before 1900. It took only a decade for cell phones to accomplish the same penetration in 1990.

Figure 17: US technology adoption rates, years from consumer availability until 75% penetration



Source: Adapted by CL from DeGusta (2012).

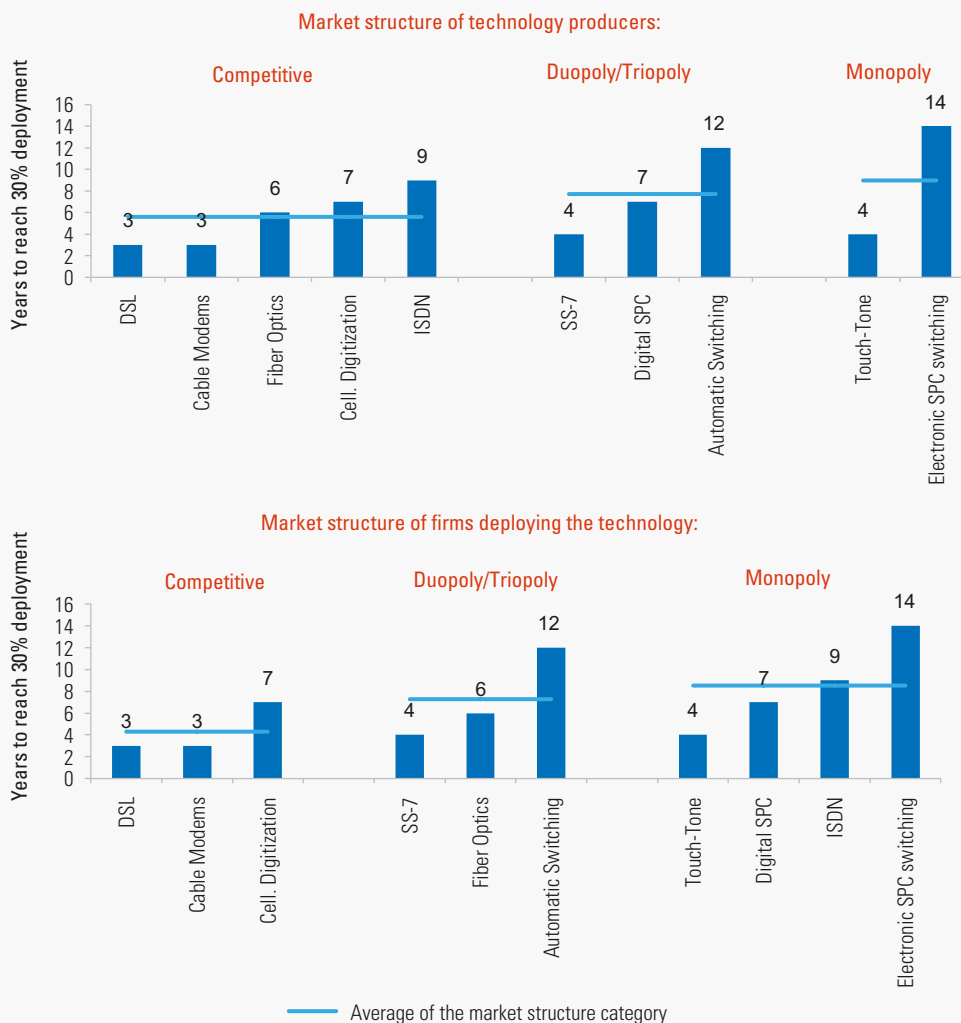
2.118 There is clearly a general trend towards faster adoption, but the radio and TV industries also showed faster adoption than several more modern inventions, so there is more to this than merely a quickening pace of change.

2.119 Figure 17 shows more rapid adoption of mobile telephony, especially smartphones, than for other technology-based industries. It took 30 years for electricity and 25 years for telephones to reach 10% adoption but less than five years for tablet devices to achieve the 10% rate. It took an additional 39 years for telephones to reach 40% penetration. Smartphones, on the other hand, accomplished a 40% penetration rate in just ten years after 2002.

2.120 There are several industry-specific and history-specific factors that may influence the adoption of technologies. Econometric evidence, which controls for these factors, suggests that the pace of adoption is influenced by the market structure. In a high-level review of ten telecommunications technologies in the US, Shelanski (2000) found a positive correlation between the pace of deployment and market structures, with quicker deployment being associated with more competitive markets.

2.121 Figure 18 summarises the findings of Shelanski (2000) on the ten telecommunication technologies, grouped first by the market structure of their producers and then by the market structure of firms deploying the technology. The time taken to reach 30% deployment varied from four to fourteen years under monopoly, from four to twelve years under duopoly/triopoly, and from three to seven years with more competitive industry structures.

Figure 18: Years from first adoption to 30% penetration, by market structure



Source: Adapted by CL from Shelanski (2000), Figure 10.

Conclusion

- 2.122** While the standards structure has evolved in all three industries reviewed in this paper, mobile telephony was characterised mainly by voluntary standards, operating systems by proprietary standards, and television broadcasting by government-mandated standards.
- 2.123** The nature of standardisation can have a significant impact on the structure of the industry, its rate of growth and innovation. The evidence and examples discussed in this section indicate that the standards structure in mobile telephony technology may partially explain its success in these regards.
- 2.124** Hardware markets – implementing standards or designing products complementary with them - for all three industries studied in this section have competitive market structures, with low concentration and exhibiting high entry and exit rates. However, only mobile telephony, which has open standards, has a diverse R&D sector in which smaller innovators can compete to contribute to the standard.
- 2.125** Consumer prices for devices have been declining in mobile telephony despite continuous advances in technology which have massively improved the range and quality of services available. For products related to the PC O/S-related industry, with largely closed standards, prices have fallen rapidly while productivity has increased, but not as much as those in mobile telecoms.
- 2.126** In other words, for mobile telephony, relative to the other industries, the *pace of technological development* is rapid and also the industry exhibits *competitive market structures* at different levels of the supply chain. It is our contention that the standard-setting process, and incorporation of patents within those standards, has a lot to do with the success of mobile telephony in bringing about better economic outcomes.
- 2.127** In the next section we examine how standards – and the way they are established and updated - might have a *causal effect* on economic outcomes, particularly through enhanced innovation and competition.

How technology standards affect economic outcomes

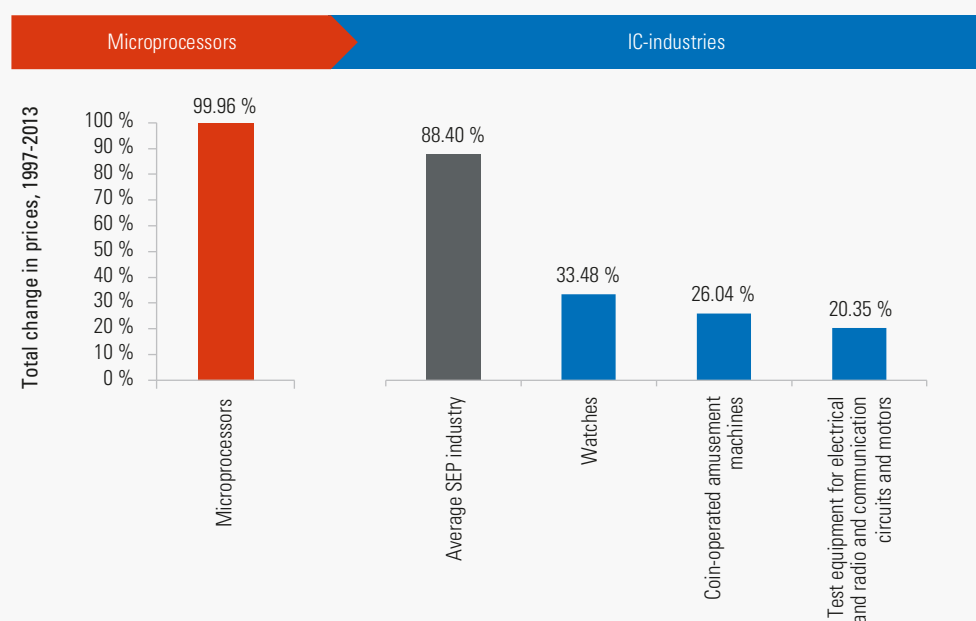
- 3.1** How can technology standards help explain the different outcomes we see in the three case studies? In this section we examine how standards – and the way they are established and updated – might affect economic outcomes, particularly through enhanced innovation and competition.
- 3.2** There are many different ways in which an industry can organise property rights and innovation. Some industries require technology standards, and in some cases, those standards are set by an industry body with broad and voluntary participation. The telecommunications industry – and, increasingly, other industries making more use of telecommunications technology⁸ – set standards in this way, with implications for market structure. Different firms operating along the supply chain – technology innovators, component manufacturers, handset producers, app developers and many others – need to agree on technical standards for many reasons, including allowing their products to work with one another. Without standards this varied ecosystem could not exist. Compared to its earlier days where standards were proprietary or government-mandated, the telecommunications industry has experienced rapid technological progress and competitive markets for the resulting products, as standards have been set through broadly-based industry bodies with voluntary participation.
- 3.3** This model will not suit all industries. Whether standards are important or not depends on the characteristics of the industry – especially the degree of network effects (i.e. whether the value of a product to a user increases when more others are using it). Some industries – such as pharmaceuticals – have a strong role for IP but make little use of standards. Even if the industry requires technology standards, they may be proprietary, with ultimate development rights resting in a single company. This can be effective, but will often lead to monopolisation of the market and ‘standards wars’ between companies seeking such monopolies can lead to inefficient outcomes. Standards developed by government can also lead to inefficient technological choices, often intended to promote local production.
- 3.4** The choices over the standard-setting process cannot be seen simply as policy options, to be adopted or rejected. Different ‘choices’ by different industries will reflect the different characteristics that those industries possess. We are not, therefore, suggesting that other industries should necessarily follow the example of the telecommunications industry in incorporating patented innovations in voluntary open standards.

However, we do suggest that the structure and performance of the telecommunications sector illustrates the effectiveness of those arrangements, which are likely to become still more widespread as ‘Internet of Things’ technologies develop.

- 3.5** When we claim that technological development in the mobile telephony industry ‘works’, we mean two things: that the pace of *technological development* is rapid and also that the industry exhibits *competitive market structures* at many levels of the supply chain. This competition itself helps to maintain the pace of innovation, and is also likely to ensure that innovation is directed in ways that meet end-consumers’ needs.
- 3.6** As we have seen, mobile telephony has been one of the quickest technologies to be adopted. For example, it took decades for electricity and the internet to reach 50% of US households but it took mobile telephony less than a couple of decades (Felton 2008, as cited in McGrath 2013). The market has changed and grown rapidly over the last two decades. Between 1994 and 2013, the number of devices sold each year rose 62 times or 20.1% per year on average. The number of device manufacturers has increased from one to 43 over the last two decades, and market concentration levels among manufacturers have declined since 2001 (Galetovic and Gupta 2016).
- 3.7** The cost of mobile subscriptions relative to maximum data speed has decreased 99% (approx. 40% per year) between 2005 and 2013. 4G technologies have enabled a 12,000-fold increase in capacity relative to 2G; data download speeds have increased to 250 Mbps for 4G from 20 Kbps for 2G (BCG Perspectives 2015).
- 3.8** It is our contention that the standard-setting process, and incorporation of patents within those standards, has a lot to do with this success.
- 3.9** Of course, it could be argued that the industry’s success simply reflects the kind of technology involved: that this is simply Moore’s Law in action, because the scope for productivity growth and innovation has been greater in communications technology than in other industries. If so, then possibly innovation in this industry would have been even better with a different approach to developing standards. That is not an easy proposition to test, as so much would need to be different in the ‘counterfactual’ it proposes. However, an attempt has been made to test it by comparing the evolution of price indices of four products all using densely packed integrated circuits, some of which depend heavily on standards (‘SEP industries’) and some of which do not

8 Such as smart grids, self-driving cars and more generally the “Internet of Things”.

Figure 19: Quality-adjusted price reduction in microprocessors, standard-reliant products and other “Moore’s Law” products, 1997 – 2013



Notes: The ‘average SEP industry’ includes PCs, telecommunications, TVs, video, photographic and audio equipment.

Source: Producer price index for microprocessors: Federal Reserve Economic Data (PCU33441333441312).

All other prices: Galetovic et al. (2015), Figure 3.

(see Figure 19)⁹. Over the period 1997 – 2013, the price index for the average SEP industry decreased from 100 to around 10, while the other three products experienced far smaller decreases, to levels around 65 and higher.

3.10 In the rest of this chapter, we will seek to explain why this should be:

- First, we provide a brief overview of the economics of technical standards;
- Second, we consider how the existence of standards in an industry contributes to good economic outcomes, particularly through encouraging technological innovation and competitive markets.
- Third, we consider how the different methods of setting standards affects these outcomes: contrasting proprietary standards of a single sponsoring firm and government-promoted standards with the standards set through voluntary open participation that are the subject of this report;
- Last, we summarise these findings and note that the system they describe depends on the institutions that maintain it – the Standard Development Organisations – ensuring that both innovators and implementers are rewarded for participating in it. How they achieve this delicate balance will be the subject of the next chapter.

The economics of technology standards

3.11 Our focus is on technology standards, especially insofar as they enable compatibility and interoperability (as opposed to minimum quality standards or health and safety standards).

3.12 In this section, we sketch out the economics of such standards. A technical standard for is a set of specifications such that one product meeting those specifications can be expected to work with another product that also meet them. Generally, these compatible products will be **complements**, rather than substitutes, in demand. We note how such standards can allow consumers and producers to **take advantage of network effects**, resulting in a more effective and efficient industry. They also affect the industry structure and investment, by **solving potential hold-up problems** when investments in complementary products are relation-specific.

3.13 These benefits create circumstances in which *de facto* standards might simply emerge, without explicit co-ordination, through the interaction of buyers and sellers in the market. However, the timing and choice of standards resulting from this uncoordinated process might not be efficient. The market might take too long to ‘decide’ upon a standard, or for that matter it might tip towards an inefficient standard too soon. This can occur even in markets where the players are small and without market power, but in practice standards will often be promoted by competing powerful firms, in which case these problems might be exacerbated. Finally, for this section, we note that industries with rapid technological progress will

9 Based on a study by Galetovic et al (2015).

face particularly acute difficulties of this kind, as the standard must evolve, greatly increasing the co-ordination problem.

- 3.14** This section therefore sets both the benefits and the difficulties of co-ordinating standard-setting (and later in this report we will consider the different means of doing so).

Complementary products

- 3.15** Formally, two products are complements if demand for one goes up, when the price of another goes down – as opposed to substitutes, for which demand falls if the price of the other goes down. Electric cars and electricity are complements, electric cars and petrol cars are likely to be substitutes. Complements might require the presence of one another (electric cars do not work without electricity) or not (electricity will continue to be sold with or without electric cars). Different inputs combined to make a single product will often be complements (such as the steering wheel and the wheels in a car). Frequently, technology will determine whether products are complements or substitutes, although consumer tastes will matter too. It is not at all obvious from the technology, for example, whether Facebook and Twitter are substitutes (alternative ways of communicating) or complements (people tweet about their Facebook posts).
- 3.16** The economics of complementary products are very different from those of substitutes. In particular, when different suppliers price substitute products independently, this is competition and is likely to lead to low prices. Each independent supplier takes no account of any harm to its rival in lost sales from low prices, so it sets prices lower than would a monopolist of both products, who would care about revenues from both. However, when different suppliers price *complements* independently, the resulting prices are likely to be higher than would set by a monopolist, for a symmetrical reason. Each independent supplier takes no account of the benefit to the other producers in increased sales from low prices, so sets prices higher than would a monopolist of both products, who would care about both. This is called the ‘Cournot effect’.
- 3.17** The multiple components combined into a phone handset are mainly complements and the multiple technologies combined into a standard will usually be complements too. Consequently, the Cournot effect is potentially important. It is essential to bear in mind that mechanisms to avoid the Cournot effect may look anti-competitive, because we are used to considering the effects on substitute products. However, in the case of complements, these mechanisms might in fact have the effect of reducing prices.
- 3.18** When suppliers of complementary products need to invest, there can be a co-ordination problem. If (for example) investment in hardware and software is required, then there is a danger of underinvestment unless participants can invest in a co-ordinated manner. Investment in hardware creates cheaper and better hardware, thus raising demand for software and increasing incentives to invest in software

and vice versa. Standards help co-ordinate such investments, providing reassurance that technologies will be compatible (and indeed, an open process of developing standards can achieve more direct co-ordination, through ‘user driven innovation’ as we shall explore later).

Standards and network effects

- 3.19** Technology standards are particularly important in industries exhibiting ‘network effects’: when the value to one user increases, the more other users there are. ‘Direct’ network effects arise when users value the presence of similar users. For example, when telephone networks started, the benefit of possessing a telephone was slight, because any one owner would know few other people who owned one. As telephones became more common, the value of having a telephone increased. ‘Indirect network effects’, in contrast, arise when there are two or more different types of users, such as consumers and app developers for an operating system, for example. The more consumers are using an operating system (“O/S”), the more attractive it is for developers to produce apps for that O/S, and the more apps there are, the more consumers will value the O/S. Indirect network effects can work either in both directions or in just one way: advertisers value web sites with more consumers, but the reverse is generally not the case. However, even in this example, consumers may benefit if the presence of more advertisers pays for better content on the web site.
- 3.20** When network effects are present, standardisation is likely to be valuable. Without standards, customers might be segmented into smaller markets, committed to specific technologies. They might lose out on direct network effects (with two incompatible telephone networks, for example, consumers would not have such a wide choice of whom to call, or would need to buy two telephones). If only indirect network effects are present, suppliers would get less value out of developing products for many separate markets, could miss out on economies of scale and competition would be weak between suppliers each specialising in just one independent customer segment. All of this raises costs and is likely to diminish technical progress too.
- 3.21** Standards themselves need not embody particularly high technology. Around 20 BC, the Roman engineer Vitruvius spelled out tests of “good water” and ten different standard sizes of lead pipes and consistent gradients for aqueducts (Russell 2007). Two of the best known compatibility standards of all – standardised railway gauges and the QWERTY typewriter keyboard – define not so much technologies as almost arbitrary rules. In each case users gain value from the ability to switch between different suppliers’ products without having to buy new equipment or learn new skills.

Box 3.1: Incompatibility kills: Fire hydrants¹²

The Great Baltimore Fire started on Sunday afternoon, February 7th, 1904, perhaps from a cigarette falling into the basement of the John Hurst & Company building. Fire companies from as far as Washington D.C. and New York arrived in Baltimore to assist in fire-fighting a few hours after the fire started. Unfortunately, most of them could not help as their hoses did not fit Baltimore hydrants due to a difference in the design of the hose connection threads. The Great Baltimore Fire was finally put out thirty hours after it started.

In 1905, the National Fire Protection Association established a standard diameter and number of threads per inch for hose couplings and fire hydrants. Despite this, on Sunday, October 20, 1991, the U.S. experienced another urban fire disaster in Oakland, California. Fire engines having the 2.5 inch (standard) hose couplings could not connect to the 3 inch couplings on Oakland fire hydrants at the time. The fire claimed the lives of 25 people including a police officer and a firefighter. By 2004, 18 out of the 48 biggest US cities had installed the national standard hydrants (Seck and Evans 2004).



Standards as a solution to the hold-up problem

3.22 Standardisation of this sort helps solve the classic 'hold up' problem of opportunistic ex-post exploitation of an asset-specific investment.¹⁰ Consider a situation in which two companies have investment opportunities that would, if carried out, commit the two to a bilateral relationship. For example, a power company might consider locating its generating plant next to a coal mine. The problem is that the coal mine could take advantage of its position, after the power plant has been built, to raise prices (or the power plant owner to lower them, depending on which player has the stronger negotiating position, defined mainly by its alternative options). Of course, this can be prevented with the right contractual terms before the plant has been built, but the future is uncertain and it might not be possible for the two parties to specify exactly how prices or other conditions of supply would respond to every eventuality. The more uncertain the future, the more residual uncertainty there must be from any contract.

3.23 The problem is not one of unequal bargaining power. In this example, even if the coal mine has all the bargaining power once the investments are made and, hence, all the risk is on the power producer, the coal mine owner has a problem too, because the power company will be reluctant to invest.¹¹ Indeed, both companies have a problem, and if it is large enough, a solution is to merge into a single vertically-integrated company, eliminating the divergent interests that the two would have, allowing an efficient response to any uncertain developments in the future.

3.24 Technological developments provide a particularly stark example of this hold-up problem. Earlier, we examined an example from the TV industry, when colour television was introduced. Colour television requires many different players to invest. Equipment manufacturers need to invest in plant to build the equipment, broadcasters need to invest in

equipment to create colour images and transmit them, and customers need to be prepared to invest in colour televisions. Technological progress will be slow if any of these groups of participants is not prepared to take the risk of investing before it is clear that their investment will be compatible with the other elements of the system.

3.25 Standardisation on a single approach for the entire market is a solution to the problem because investors will know that their investments will be compatible with and will benefit all actual and potential buyers and sellers. Keyboard layouts, for example, are a problem almost of pure co-ordination – like deciding which side of the road to drive on. QWERTY might have been rather an arbitrary choice (although some dispute this) but once established, it will persist. Although there are some variations (France uses AZERTY), there is no obvious advantage to having more than one standard. Railway gauges are a bit more varied: broader gauges can support larger, faster and more expensive trains, and require more space for longer curves. This partly explains why there remain multiple gauges, with narrower gauge for mountain railways, for example, but obviously there are advantages to train operators of standardisation too.

Excess inertia and excess momentum in standardization

3.26 These benefits will only be realised if a standard covers an entire industry: it can be costly if more than one standard exists within a single industry.

3.27 This could be a permanent condition, with several standards persisting in an industry, or it could be temporary – a period in which two or more rival standards compete before the industry moves to adopt just one.

3.28 We examine 'standard wars' in more detail later. For now, we will note that ordinary consumer behaviour, even in the absence of strategic behaviour by rival sponsors, can lead to some very inefficient outcomes when there are multiple

¹⁰ Developed mainly by Oliver Williamson: see Williamson (1975) for example.
¹¹ Demonstrated mathematically in Tirole (1986).

¹² Image taken from <https://commons.wikimedia.org/wiki/File:Green_Valley_fireplug.jpg>.

standards. Firstly, there can be ‘excess inertia’ when buyers and producers (‘participants’) persist with an inefficient standard even if they would collectively be better off all shifting to a better, new standard. This occurs because no one participant has the incentive to do this alone. For example, Nintendo dominated the ‘third generation’ video games market in the US in the late 1980s with its 8-bit consoles. In 1989, Sega and NES introduced 16-bit machines with greatly superior capabilities, but sales of these superior technologies in that year were less than 10% of Nintendo’s, primarily because of the limited variety of games available. Game developers need a large user base and users want a wide variety of games. So, switching to the new technology was slow. It took until 1991 before the market shifted to the superior 16-bit technology and Nintendo responded with its own 16-bit console (Gallagher and Park 2002).

3.29 Secondly, in contrast, there can be excess momentum, when the decision of an early adopter causes the market rapidly to lock into a new, inefficient technology even when a better technology exists. For example, the standard railway gauge is generally considered to be inefficiently narrow and was so even at the time of first adoption. George Stephenson, in his proposal for the Liverpool and Manchester railway, which opened in 1830, used a gauge **based on existing gauges for mining tracks (for unpowered vehicles) of 4’ 8½”**.¹³ Rivals for the same project proposed 5’6”, in recognition of the capabilities of the new technology. Even in the early nineteenth century, Stephenson’s narrow gauge was recognised as a constraint on engine power and it is generally agreed to be an inefficient standard but it became the most common standard globally as a result of this first mover advantage (Puffert 2002).¹⁴

3.30 Whether an industry sustains multiple standards or defaults to a single standard will depend on the strength of network effects as well as the costs of switching. These costs will tend to increase over time, as more and more investments are made in the ‘installed base’ of each of the alternative standards. However, the *benefits* of switching to a common standard will often increase over time as well. Just this sort of development has happened in many countries in railways, where initially local railway systems using multiple standards developed into continental networks which could take advantage of network effects on a larger scale and thus faced a stronger incentive for compatibility than had been apparent when they were built.

3.31 In 1860, seven different railway gauges were in use in the USA, but just over half the track **was of one standard: 4’ 8½”**, as in Britain. The next most common was 5’, mostly in the Southern US. Congress took advantage of the

temporary absence of the Southern states during the Civil War to mandate the 4’ 8½” **gauge as standard for new transcontinental lines**, so it was clear that this gauge would only become more dominant. However, track, engines and rolling stock all represent prior investments in a given gauge (although some adapter technologies are available, such as sliding axles), so there was considerable resistance to full consolidation. Discussions and disagreements between the Southern railway owners in the years leading up to this changeover clearly illustrate the role of costs and benefits, as those owners of networks bordering ‘Northern’ standard-gauge networks favoured switching over, while those in the Southern ‘interior’ did not. When change finally came, it was remarkably quick: the South changed over to the new gauge, altering 11,000 miles of track, in the space of just two days in 1886 (Puffert 2000; Shapiro and Varian 1999).

3.32 India attempted a similar project, as it aimed to rationalise its four railway gauges through ‘Project Unigauge’. In 2006, the Ministry of Railways estimated that it could **save ₹14 billion per year, if it converted 10,000 km at a cost of ₹170 billion** (Raghvendra 2006).

The evolution of standards in innovative industries

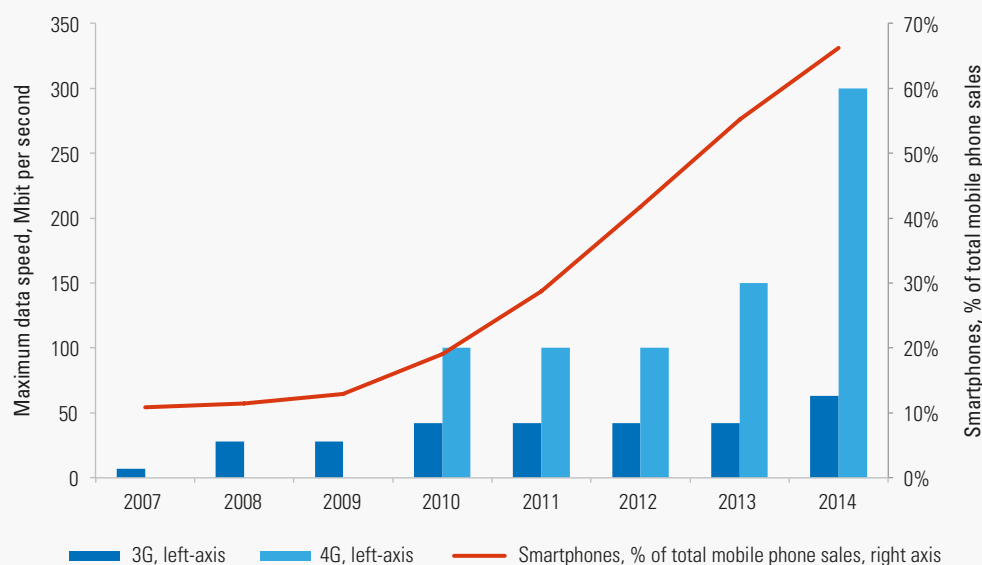
3.33 The standards we want to focus on here have an additional element: they cover fast-changing technologies that are still in the process of development. In the ICT sector especially, standards not only need to change to reflect continuous technical advances, they also incorporate technical advances. There is an interaction between the standard-setting process and the process of technical discovery. New technology within a standard changes that standard and also changes the incentives for technical progress for complementary products within and outside that standard.

3.34 Development of mobile data transmission and smartphones shows how updated standards create opportunities for new products (smartphones, apps and the services layer) and widespread adoption and improvement of those products itself creates further pressure for improvement of the standard. Data speeds and smartphone sales have increased together, in a joint process in which technological development of the standard has been essential.

¹³ The gauge was declared a British standard in 1845. Sadly, the story that the gauge itself reflects an ancient standard created by the ruts and axle widths in use on British roads, ultimately going back to the wheel base of a Roman chariot, is almost certainly a myth.

¹⁴ Puffert (2002) notes: “Beginning in the mid-1830s, however, some British locomotive builders found their ability to develop increasingly powerful, easily maintained engines constrained by the 4’ 8.5” gauge, while certain civil engineers expected that a broader gauge would promote improved stability, smoothness of ride, speed, and capacity. As a result, a few short lines adopted 5’0” (1524 mm.) and 5’6” for what they initially expected to be isolated local networks. When the lines were reached by the expanding Stephenson-gauge network, they converted immediately.”

Figure 20: Technological development of data speeds, standards and smartphones



Source: Data speeds: Gupta (2014), Figure 2.

Share of smartphones in total mobile phone sales: IDC Worldwide Quarterly Mobile Phone Tracker.

3.35 Pre-existing standards can spur the development and adoption of new technologies. For example, the availability of standards governing ISDN and wireless telecommunications eased both the development and the diffusion process of SMS text messaging (Brusoni and Corrocher 2006). In a study of fifty heterogeneous high-tech products introduced since 1850, Ortt and Egyedi (2014) found evidence of the positive relationship between standards and regulations and the pace of technology adoption. The impact of standards on the pace of adoption was found to be stronger if the technology was closely related with other technological standards and if the technology was radically new.

The economic effects of technology standards

3.36 How are economic outcomes affected when an industry has technology standards?

3.37 This is not an easy question to answer directly, as in most cases industries either have standards or they do not, depending on the fundamental economic factors described above. There are therefore no studies attempting to quantify in total the effects of compatibility standards on the economy, because there are simply no counterfactuals to which to compare the existing reality¹⁵. Industries in which standards provide strong benefits will generally have some form of standard, whether formally imposed or not. There have been attempts at measuring the macroeconomic effects of standards in general – typically including all government-

imposed standards, including health and metrological standards as well as compatibility standards and we summarise the findings below.

3.38 We conclude by describing qualitatively the effects of compatibility standards on market structure and market outcomes and examine some illustrative examples, where the adoption of standards has clearly led to technological advances or to enhanced competition.

The macroeconomic impact of standards

3.39 While the effects of standards will often be industry-specific and difficult to measure, the effects of 'standards' broadly defined have received more attention from economists. Standards play a vital and often invisible role in supporting economic growth through their role in boosting productivity and innovation, and in supporting international trade. The wider economy benefits because standards, in the findings of a study of the UK¹⁶:

- help businesses enhance the quality of their products and efficiency of their processes;
- reduce the variety of goods and services to an optimal level for minimising costs;
- facilitate inter-operability of products and processes; and
- efficiently make technical information available to all firms allowing an effective and less costly inter-firm exchange of information.

¹⁵ Just as it would be hard to estimate the benefits arising from the fact that everyone in drives on the same side of the road in any one country.

¹⁶ CEBR (2015)

Table 9: Summary of macroeconomic studies of effects of standards

Study	Geography	Period	GDP growth	Contribution of standards	Contribution of standards (% of GDP growth)
Blind, Jungmittag and Mangelsdorf (2011)	Germany	1992-2006	1.1%	0.7%	63.6%
CEBR (2015)	UK	1921-2013	2.4%	0.7%	29.2%
Jungmittag, Blind and Grupp (1999)	Germany	1960-1990	3.3%	0.9%	27.3%
Miotti (Afnor) (2009)	France	1950-2007	3.4%	0.8%	23.5%
Centre for International Economics (2007)	Australia	1962-2003	3.6%	0.8%	22.2%
DTI (2005)	UK	1948-2002	2.5%	0.3%	12.0%
Haimowitz and Warren (SCC) (2007)	Canada	1981-2004	2.7%	0.2%	7.4%
CEBR (2007)	Denmark	1966-2003	No econometric relationship found		

Source: Blind (2015).

Contribution of standards to GDP growth

3.40 By encouraging innovation and increasing productivity, standards have a positive impact on GDP growth. Estimates of the economic impact of standards on GDP growth are quite varied. Table 9, below, summarises a few key papers studying the link between GDP growth and standards. These studies typically seek to explain the development of GDP in a country as a combined effect of multiple inputs, such as capital stock, labour supply and so on, including the total stock of standards as an input. The results typically find that standards contribute between 7.4%-63.6% of GDP growth depending on the geography and period covered.

3.41 The contribution of standards is higher for developed economies with higher standardisation activities such as Germany, France and the UK. On the other hand, the impact of standards on GDP is lower for countries with lower standardisation activities (Canada, Australia and Denmark) or emerging economies (China) (Blind 2015).

3.42 While these studies consider only the impact of formal standards, informal standard setting efforts (e.g. through consortia) may also have an additional impact on GDP growth, but it is hard to measure these standards and therefore still harder to assess the effect on growth.

3.43 Overall the macro-economic studies are a rather crude, broad-brush approach to estimating what must be a rather complex set of effects, so the specific numerical findings should be treated with caution. Nonetheless, they are indicative evidence of the generally positive effect of standardisation on the economy.

Impact on international trade

3.44 The impact of standards on international trade is more varied. Studies looking at all sectors, especially manufacturing,

find that common standards tend to be “trade creating”.¹⁷ However, standards set by importing countries that impose requirements on exporters can constrain imports, for example in agricultural products (Moenius 2006).

3.45 The impact of standards on trade between countries with very different standards regimes can be negative. Czubala et al. (2007) focus on exports from Sub-Saharan Africa and find that if EU countries have standards that are not harmonised to ISO standards¹⁸, then these can deter imports from Sub-Saharan Africa. The use of ISO by exporters was found to be associated with an increase in exports, and this was found to be stronger for exports from developing countries (Clougherty and Grajek 2008).

Impact on individual businesses

3.46 A survey of 527 UK companies in 2015 found that standardization contributed to an aggregate increase in Gross Value Added (GVA¹⁹) of £6.9 billion per year, equivalent to 3% of the total GVA of all industries investigated in 2014.

3.47 Overall, the ICT industry observed the largest increases in GVA as a result of standardization, equivalent to £2.1 billion per year (see Figure 21). Firms within the life sciences and healthcare industry and the food and drink manufacturing sector also observed large rises in GVA as a result of standardization: equivalent to £1.8 billion and £1.1 billion respectively per year.

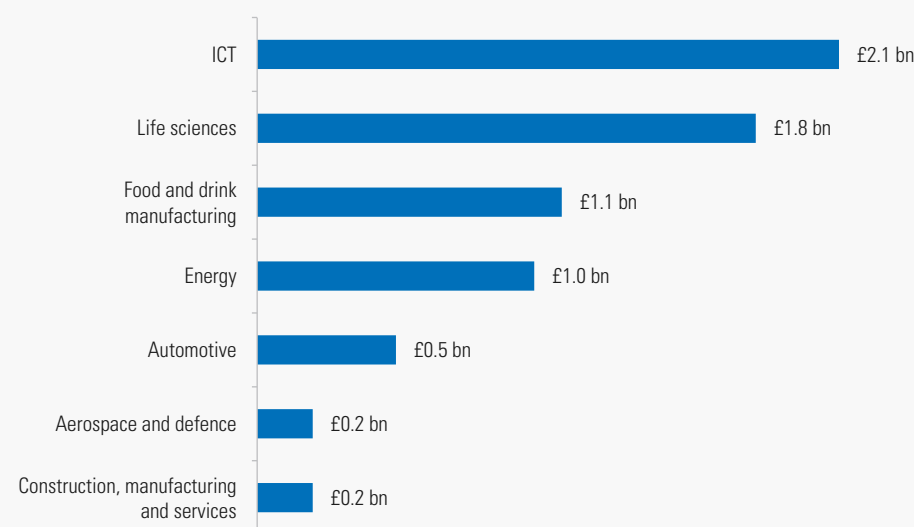
3.48 The survey also found more than 80% of the businesses surveyed find that standards make their businesses competitive “by demonstrating to the market that their products and services are of a high quality” (CEBR 2015).

¹⁷ See, for example, Blind and Jungmittag (2005) and Swann et al. (1996).

¹⁸ Standards certified by the International Standards Organisation, which can be taken as a measure of global acceptance.

¹⁹ A measure of output: the value of products produced by an industry less their material costs (i.e. profits plus labour). At the national level, GVA is equal to GDP plus subsidies and less direct taxes.

Figure 21: Increase in Gross Value Added that can be attributed to the use of standards, annual estimates based on 2012 survey data



Source: CEBR (2015)

3.49 Similar evidence on firms' perception of standards was also found in France and Canada. In France, Miotti (2009) finds that two-thirds of the surveyed firms perceive that standards positively affect their turnover. Similarly, interviews conducted by the Standards Council of Canada found that standards allow firms to innovate better and introduce new products while also reducing costs and increasing productivity (Haimowitz and Warren 2007).

Standards, trade and development

3.50 A standard opens up markets for complementary products, so the wider the geographic scope of the standard, the greater the scope for increased competition and innovation as a result of standardisation. It seems obvious that the unprecedented rate of economic development in Asia over the past 20 years has a lot to do with the presence of standards, particularly in the IT sector, enabling specialisation in the manufacture of high technology products even without a domestic R&D base. The OECD (2013) has attributed much of the growth of developing country exports to the existence of standardised platforms in this sector, for example.

3.51 As discussed in our TV case study in Annex B, the presence of a proprietary incompatible standard in Europe protected by patents prevented the entry of Japanese TV manufacturers. Telefunken, owner of the PAL technology, refused to provide Japanese firms with licenses until 1970, ultimately harming European consumers by reducing competition, having an effect similar to a trade barrier. Even after this legal barrier expired, Japanese firms' penetration of the European TV market was significantly lower than their presence in the US market, which shared a common standard: NTSC²⁰. Even by the early 1980s,

Japanese producers' share of the US market at about 45% was three times that of their share in Europe, at about 15% (Burton and Saelens 1987). Similarly, Funk (1998) finds a strong correlation between the standard chosen by consumers and the 'home' standard of telephone providers – the regional standards for 2G mobile effectively acted to partition production as well as consumption, reducing the scope for global competition in mobile phones²¹.

3.52 Standards change the way firms can interact with Global Value Chains (GVCs). A standard provides many points at which a producer can contribute value-added, breaking up the supply chain that otherwise might occur within a vertically-integrated multinational firm. Baldwin (2011) sees this as a positive development, noting that a less 'lumpy' supply chain – i.e. one in which a producer can participate with a relatively small investment can – has created new opportunities for participation in hi-technology industries and illustrates this with examples of East Asian export-led growth. Athreye and Cantwell (2007) look at the effects of licensing technology and international investment, finding a rather more mixed picture. There are specialised roles emerging in global supply chains, with only a few countries (not all of them the established industrial countries) responsible for innovation.

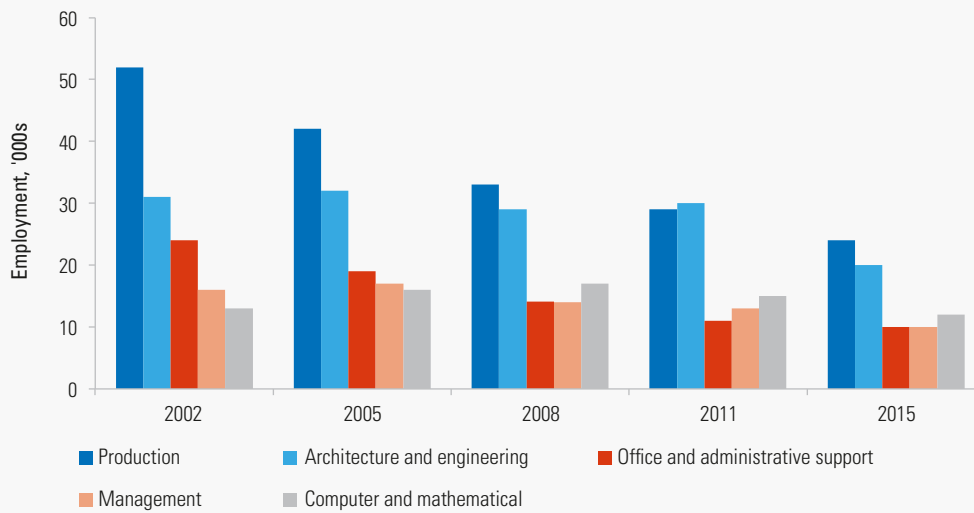
3.53 The telecommunications manufacturing industry in the US shows the effects in industrial countries: higher-skilled jobs in design and management are retained while manufacturing jobs have declined²².

²¹ We discuss these findings again when considering government-imposed standards later.

²² There is a 'glass half full/glass half empty' sense to some of this debate. The US losing lower-skilled jobs while retaining higher-skilled ones is criticised by some in the US as 'exporting jobs' and criticised by some development scholars as providing emerging economies only with low-end jobs. These criticisms cannot both be valid – arguably, neither is.

²⁰ We should note that both the United States and European countries maintained more formal trade barriers against many Japanese imports as well, during this period.

Figure 22: US employment in telecommunications manufacture, 2002-2015



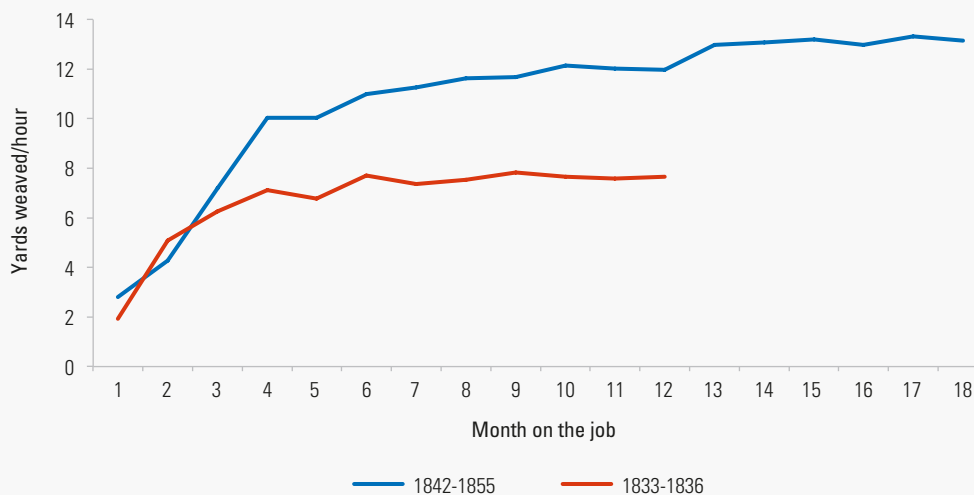
Source: Occupational Employment Statistics (OES) and US Bureau of Labour Statistics.

3.54 Some commentators, such as Ernst (2016) have noted that the gains for trade to developing countries might be constrained by technical standards, as it is difficult for producers not themselves owning valuable patents to move into the higher end of global value chains. However, before the modern globalisation era, for the most part developing countries did not manage to enter high-technology industries at all. The macro-economic results from emerging economy participation in global value chains are very clear and very positive indeed for developing countries.

Good jobs at good wages? Rewards for skill development

3.55 Finally, for this section, we rather speculatively advance another potential benefit of compatibility standards: better outcomes for skilled workers. Standards help solve the hold-up problem between two firms, but they could also solve it for individuals seeking employment contracts with firms. Just like firms themselves, individuals undertake investments that make them more valuable. This has been well illustrated by Bessen (2015), who demonstrates in numerous cases from the Industrial Revolution onward that almost all experienced workers – even those in apparently menial roles - develop valuable skills.

Figure 23: The learning curve for loom tenders (yards weaved/hour)



Source: Adapted by CL from Bessen (2003), Figure 2.

3.56 However, whether those workers are themselves able to capture the value of their increased skills does not depend just upon their productivity but upon how transferable those skills are, to another employer. If they are specific to the machines and the layout used by only one employer, they are not so transferable and so there is no competitive constraint upon the employer to reward such skills.

3.57 With standardised techniques, on the other hand, skills may also be transferable. Bessen (2003) notes that wages for weavers did not typically improve as soon as more productive machinery was introduced and the chart above illustrates why. With faster machines, a more experienced worker could produce considerably more cloth because he or she (usually she) could run them efficiently. The productivity of experienced workers using later technology in the chart above is higher than those using the earlier technology. Yet as the chart illustrates, new workers with less than three months experience produced no more in the later period than the earlier one. New machines raised overall productivity, but in a competitive market wages will be set by opportunities elsewhere, and if a worker's experience counts for nothing at a new firm there is no reason to expect wages to increase to reflect these more productive machines. An experienced worker will benefit only if she can transfer her expertise to a new firm – which is precisely what happens with technological standardisation. With standardisation, then, we would expect to see a differential between the wages of experienced and inexperienced workers, possibly increasing as technology raises the productivity of the former group.

3.58 A similar story can be told for employment and wages for what we would now call secretaries, following standardisation of QWERTY keyboards. Bessen's examples for this standard mostly derive from experiences more than a hundred years ago, but the same process will surely have occurred more recently as office IT hardware and software standardised in the 1980s and 1990s. When PCs and similar computers first arrived in the office, there were multiple standards and workers skilled in for example document formatting and production would need to commit to learning the interface and functionality of a given programme. Today, Microsoft Office has a large market share, greatly diminishing this problem, albeit through a proprietary standard²³.

3.59 In a more standardised environment, the rewards to skilled work will be higher, because more of those skills are potentially transferable to competitors. This does not simply improve the balance of rewards as far as employees are concerned; by raising the returns available to investing in skills, it increases value overall. Indeed, if the skilled workers themselves contribute disproportionately to innovation and economic growth overall, all will benefit.

The impact of standards on competition and innovation

3.60 One way in which standards can promote innovation and competition is by enabling specialist firms. Because a standard enables one product to work with many others (among other benefits), a small producer of specialised products can access a large market of consumers who need not be technically sophisticated. As an example, in 2014, there were some 380,000 active application developers supplying around 1.4 million applications to Google's Android smartphone operating system.²⁴ Standards provide suppliers of all sizes with access to a large market. In 2010, Rovio Entertainment, a small application developer company in Finland, developed one of the most successful applications at that time, Angry Birds. In the first six months after its release, around 2.4 million users downloaded the application.²⁵

3.61 As well as facilitating the entry of new, specialised firms, a standard can create a more competitive marketplace by increasing the size of the market. Most obviously, moving from a national to a regional to a global standard will increase the number of producers of whatever products use that standard.

3.62 Perhaps the most beneficial standard ever created was the containerisation of goods transport (Levinson 2008). Containers are merely metal boxes, but by virtue of coming in just two standard sizes, they have transformed world trade. They also illustrate how rapidly a truly superior innovation can succeed, regardless of the scale of the industry concerned. Containers were a vastly more efficient technology. Levinson (2008) gives the example of the cost of loading a cargo ship in New York, which fell from \$5.86 per tonne in 1956 to \$0.16 in 1966. The productivity of dock workers increased by a factor of 20.

3.63 Obviously, there was a direct efficiency gain but there has also been an indirect benefit resulting from increased competition. Containerisation makes different ports and different shipping lines closer substitutes for one another and thus spurs competition. The effect has been particularly noticeable in ports. Large container ports compete with other ports in their region (remarkably, ports on the West and East coasts of the USA have been found to be in competition),²⁶ while bulk ports for products that are not suitable for containerisation continue to serve a niche hinterland.²⁷ By studying differences between the timing of containerisation on different routes, Bernhofen et al. (2016) can distinguish the effects of containerisation from other trends in global trade, to find that this standardisation process caused a 700% increase in bilateral trade on the routes they studied.

²⁴ Last visited on 2 February 2017, <http://blog.appfigures.com/app-stores-growth-accelerates-in-2014/>

²⁵ Last visited on 8 February 2017, <http://blogs.wsj.com/source/2010/05/12/angry-birds-smartphone-app-takes-off-for-rovio/>

²⁶ See Slack (1990), who notes that trans-Pacific exports from the Eastern US increasingly travel by train to West Coast ports, the transfer of containers from rail to ship now being only a minor cost.

²⁷ See Guerero (2014) for an overview and case studies from France. More generally, OECD (2015) examines competition in liner shipping, noting the primary role for containerisation in increased inter-port competition.

²³ Although Bessen (2003) also notes that a rapidly changing technological standard has the opposite effect – diminishing the value of learning by doing and putting experienced workers on more of a par with new arrivals.

Box 3.2: Standardisation of machine tools leading to competition and innovation

Numerically controlled machine tools (“NCMT”) provide one of the earliest examples of valuable standardisation in what we would now call ICT. Because NCMTs are used for a wide variety of tasks and hence have different performance requirements, they were typically controlled using different numerical coding formats. Moreover, different vendors were involved in the supply of post-processors, controllers and machine tools, complicating the interface between these components.

In the 1950s, the abundance of numerical coding formats and interface issues in NCMT resulted in market segmentation and prevented the realisation of economies of scale. These also increased expected cost from technological obsolescence for users. Consequently, competition among vendors was weak, and the diffusion of NCMT was slow.

From the late 1950s onwards, standards for numerical coding format and interface were adopted reducing variety and facilitating competition among specialised vendors of components. Link and Tassey (1988) found that nine interface standards adopted between 1973 and 1984 quadrupled the speed of diffusion of the NCMT technology in the post-1974 period compared to the pre-1974 period.

3.64 As *The Economist* put it: “In other words, containers have boosted globalisation more than all trade agreements in the past 50 years put together. Not bad for a simple box.”²⁸ By connecting different parts of the world, containers have probably also done more for competition than has almost anything else, too.

3.65 A more perverse illustration of the way standards increase competition can be seen in examples of firms deliberately choosing not to conform to standards in order to insulate themselves from competition. Standardisation permits a supplier to take advantage of network effects but also potentially increases the scope for competition between the standardised firms.²⁹ Deliberate incompatibility can therefore be a tactic to avoid competition. Most new railway lines, for example, naturally choose compatibility with their neighbours, incompatible gauges being chosen only by isolated lines that do not expect to become interconnected. However, in his account of the standardisation of railroad gauges in nineteenth-century America, Puffert (2000) notes a rare exception, in the “Erie Railroad” which sought first legal guarantees against interconnection (by forbidding it in its charter) but then by deliberately building it to a gauge that was incompatible. They did this on what the author describes as a ‘childish theory’ that they would be more profitable without interconnection, monopolising the traffic to their destination. About forty years after construction, the railroad owners eventually recognised the commercial pressures to interconnect and converted to standard gauge.

3.66 Similarly, mobile handset and other portable electronics manufacturers have maintained different charger systems while recently starting to converge on USB-C interfaces, encouraged by the European Commission. The Commission itself emphasises the benefits of standardisation through reduced waste and customer convenience but there have been competition and price benefits too. A study for the EU estimated the retail price

of a proprietary charger at around €5, compared to €2.50 for a standalone generic charger, even though a survey suggested a slightly higher manufacturing cost for the micro-USB (Risk and Policy Analysts 2014). A standalone iPhone mains charger cost €19 in the Apple Store³⁰. This cost differential can be seen as a measure of the competitive benefits of standardisation. There is probably a quality difference between different chargers, but equally this difference could even understate the cost differential to the customer, who would not have to buy a new charger for each new electronic device after standardization. By using standardized interface, the consumer would not be locked into any particular proprietary solutions and manufacturers would compete on price and innovation.

3.67 A standard creates opportunities for innovators to create new technologies that are compatible with it, but those technologies are out in the open – anyone can play. This contributes to innovation. Contrasting the rapid development of micro-computers with established mainframes in the 1970s, Bresnahan and Greenstein (1999) compare the more rapid progress of the “anarchic rabble” designing for the CP/M standard for micro-computers (the precursors to the PC, such as the Apple II, the Altair 8800, the Amstrad PCW or the Xerox 820) with the more sedate process of innovation by firms for their own proprietary standards. They comment: “It is clear that the CP/M rabble did not behave exactly the same as a platform sponsor would have. It made more mistakes of coordination. It may also have moved forward more rapidly by making piecemeal technical progress in components rather than waiting for a coordinated solution. It appears that speed is the benefit and coordination failure the cost of unsponsored platforms, or of multi-firm supply more generally.”

3.68 This ‘rabble’ was perhaps an early example of the innovative ‘ecosystems’ that can spring up around standards and standardised platforms in the IT sector. Wireless standards have led to innovative competition in handsets but, perhaps more radically, have enabled the development of apps for innovative services, creating entirely new industries.

²⁸ Last visited on 8 February 2017, <http://www.economist.com/blogs/economist-explains/2013/05/economist-explains-14>

²⁹ When network effects are strong, firms will therefore want to join standards, if they become weaker there may be multiple standards and for very weak network effects, no standards will be chosen at all, suppliers preferring incompatibility. Economides and Skrzypacz (2003) model this explicitly, deriving conditions relating mainly to network effects under which a single industry-wide standard will form.

³⁰ Apple supplies adaptors to comply with the European harmonisation.

3.69 It seems reasonable to suggest that standards that are more open (to be used by producers of complementary products) will create more innovation than closed systems. Apple operates a largely closed standard and is often cited as a counterexample. Perhaps it is, although we noted earlier an economic study demonstrating more rapid introduction of new hardware for the Wintel standard than for Apple's closed standard. Overall, Apple has clearly been a highly innovative company but it is an unusual one and there might perhaps be greater consensus that closed standards harm innovation were it not for this one – very significant - outlier.

3.70 A broader evidence base is provided by the handheld computer (also known as Personal Digital Assistants or PDAs) industry from 1990 to 2004, as Boudreau (2008) demonstrates. There was no standard industry architecture and products had different degrees of openness at various levels. Palm, Apple and Psion were vertically integrated into both hardware and operating systems, for example, while other operating systems were licensed to multiple hardware producers, either to develop as their own incompatible standard or to produce hardware to a common standard. In other cases, hardware manufacturers such as Geoworks and Montavista were able to take equity stakes in operating systems. Several of the manufacturers changed their policies over the period that Boudreau (2008) examines, so the data set contains significant variability.

3.71 The results showed that allowing independent hardware producers to use the operating system as a standard was associated with a five-fold increase in the introduction of new products, compared to closed systems. This was important because this industry had not stabilised on any common understanding of the capabilities or form of the products it was producing (which were eventually superseded by smartphones): hardware innovation was therefore the critical criterion on which different products competed.

3.72 In a later study, the same author went on to examine software innovation in the hand-held computer market, finding that increased numbers of software producers led to increased variety of software, illustrating the benefits of "letting a thousand flowers bloom" (Boudreau 2011). With more independent sources of innovation, the platforms were more innovative. As we shall see later, the increased use of standards and 'modularisation' of several industries is changing the way R&D is done, at least in the United States, with many more smaller, independent research outfits.

3.73 Boudreau's 2008 study of operating systems and hardware also found, however, that opening the platform itself had a beneficial effect. Allowing other suppliers some degree of influence or control over development of the operating system also resulted in faster innovation, albeit the effect was much less than opening up to the production of complementary hardware. This brings us to our next question, which is to examine not merely the effects of standards on innovation and competition, but to consider *why the way in which those standards are set matters*.

Developing standards: open voluntary processes versus proprietary and government-promoted standards

3.74 We noted above that different industry participants might have different preferences regarding a choice of standard. This might arise from the existence of prior investments in assets that are specific to the standard: QWERTY-trained typists would presumably want to all keyboards to be QWERTY, others would not. However, in most cases the costs and benefits to society are not necessarily the same for alternative decisions; so the question of who decides on a standard can be critical.

3.75 Broadly speaking, there are three approaches to setting standards:

- Proprietary standards: a firm or a small group of firms has the ultimate power to decide when and how a standard changes. Proprietary standards are usually de facto standards, emerging from behaviour in the market.
- Government standards: governments impose technical compatibility standards, whether to favour domestic firms and state-owned firms or when no industry-agreed solution seems possible.
- Voluntary open standards: an industry body which is open to all industry participants sets the standard, with some form of committee-based decision-making.

Proprietary standards

3.76 We define a proprietary standard here to be one under the control of a single firm, or small closed group of firms. A proprietary standard will typically bring many of the benefits that we identified above arising from standards, but compared to the alternative of open, voluntary standard-setting, proprietary standards have some potential drawbacks.

- They are more likely to lead to **inefficient multiple standards** in the market, if network externalities are important;
- The existence of multiple standards in a '**standards war**' of even limited duration can have some adverse effects.
- Such wars can result in the **selection of inferior technology**.
- A firm sponsoring a proprietary standard may have **weaker incentives for radical innovation** than would multiple firms contributing technology to a standard, because it replaces 'itself' rather than potentially replacing a rival.
- Proprietary standards that come to dominate a market are likely to lead to **market power**, worsening prices and quality and reducing the speed with which innovations diffuse in the market.
- A proprietary platform sponsor might behave **opportunistically**, exploiting its superior knowledge of the platform to displace suppliers of complementary products and thus deterring innovation in the ecosystem or – in some extreme cases – **use its market power directly to exclude** them from the market.

3.77 In our case study on operating systems³¹, we identified Microsoft's Windows as a proprietary standard. Microsoft also manages important standards for office software and document formats. Microsoft maintains a community of developers and informs them of changes when a new version is being developed. However, ultimately Microsoft owns and manages the standard. It might consult, and it might change its plans in the light of the responses it receives, but it has the final decision. This is very different from a broad, voluntary standard in which those same developers of compatible products may have a vote, or even a veto, over changes.

3.78 There are some advantages to proprietary standards, as anyone who has ever attempted to obtain a clear and fast decision from a committee will appreciate.³² Standard-setting organisations can work slowly, when a single decision-maker would be able to act more decisively. In practice, however, industries with proprietary standards do not seem to innovate faster than those with open standards. As we noted earlier, in the mobile telephony industry, more firms contribute technology to the standard with each generation, but innovation and adoption rates for the new technology have if anything been rising with each generation. The speed with which the committee reaches consensus is perhaps not as significant as the effect of broad-based standard-setting on the industry structure and on the incentives to innovate and disseminate the standard.

Multiple standards and standards wars

3.79 If standards are proprietary, there are likely to be incompatible competing standards at some point. If network effects are strong, this might take the form of a 'standards war' in which several alternative technologies compete to become the sole standard, whether through market choice or eventual government approval. Earlier, we discussed the colour TV wars in the US in the 1950s, in which the market chose a standard on the basis of backward compatibility, and the FCC was forced to endorse this. Strong 'indirect' network effects, arising from the benefits broadcasters and consumers each receive from increased numbers of the other on the same standard, made it inevitable that a single standard would emerge.

3.80 However, if network effects are weaker or in the absence of government intervention, two or more standards might persist. Apple's PC ecosystem persists as an incompatible alternative standard to Wintel, although the incompatibility is significantly less pronounced than in the 1990s.

3.81 Multiple incompatible standards that persist could segment the market, having potentially ambiguous effects on consumer welfare. When a new consumer (or for that matter an application developer) is considering which product to adopt, the standards are in competition. This will drive them to

improve quality, lower price and make technical progress. However, in markets with network effects, the presence of multiple incompatible standards will be inefficient³³.

3.82 Many competing standards do not persist – rather, there is a temporary period of competition (a 'standards war') followed by victory for one or other side and the collapse into a single proprietary standard. Competition to 'win' this war can be fierce indeed, but it will often not be beneficial for consumers. It might be that prices during the war fall well below levels that are sustainable, but this by itself serves to warn that prices in the future will be higher, when the war is over. Very low prices or excessive advertising and marketing activity during the period of the war might not benefit customers over the longer term³⁴. Furthermore, when the war ends, some customers will have chosen the wrong standard and might need to purchase replacements, or find themselves without complementary products. If customers have the foresight to anticipate either of these problems, they might delay taking up either of the competing standards until it is clear which has won, leading to slow adoption times of new technology.³⁵

3.83 The more evenly-matched are the competing standards, the longer the war will run. The three-year Blu-Ray vs HD DVD war that followed Sony and Toshiba's failure to agree on a standard in 2005 is an example, with the advantage held first by HD DVD and then by Blu-Ray. The contest was determined primarily by how many content providers had signed to each standard, so there was no obvious gain for consumers as a result of the war (and considerable losses from uncertainty and eventually stranded assets among those who had bought HD DVD).³⁶

Victory in a standard war between proprietary standards can go to the inferior technology

3.84 Such a war does not guarantee that the best product will win. Success in a standards war will go to the standard that most rapidly reaches a critical mass in the market, a point at which enough consumers and producers of complementary products have chosen its standard that the market 'tips' in its favour. One might expect that the market would choose the best technology, and there is evidence that this does indeed usually happen.³⁷

³¹ See Annex C.

³² Farrell and Saloner (1988) use a simple model of standard setting based on the war of attrition to compare standard setting in markets and committees. They conclude that while markets are faster, committees are more likely to produce coordination on a single compatibility standard.

³³ Economides and Flyer (1997), for example, show that in the presence of network effects, even an unregulated monopoly may be preferable to competition between incompatible standards using a theoretical model.

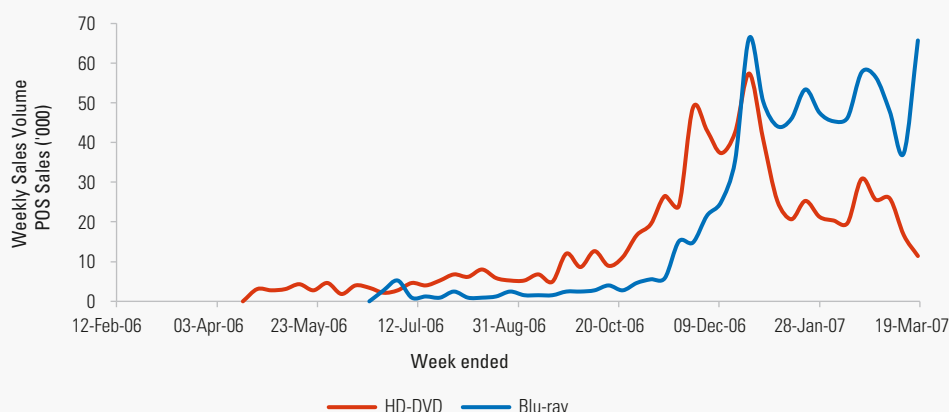
³⁴ This point has been demonstrated in economists' models of switching costs: see, for example, Farrell and Klemperer (2007).

³⁵ Farrell and Saloner (1985), in a formal model of competition between unsponsored standards refer to this outcome as 'excess inertia'.

³⁶ There are many non-academic accounts of this contest; for instance, this contemporary discussion: Last visited on 12 June 2017, <<http://freakonomics.com/2008/03/04/what-are-the-lessons-of-the-blu-rayhd-dvd-battle-a-freakonomics-quorum>>.

³⁷ That is not to say that the most technically advanced product should always win. A cheaper, lower-tech outcome might well be preferable to the most advanced solution. However, assessing this in practice will be difficult, as perhaps the more advanced and expensive system would have rapidly come down in price, had it become the standard, able to benefit from economies of scale.

Figure 24: The long war: HD DVD vs Blu-Ray, 2006-2007 weekly sales



Source: Adapted by CL from A.C. Nielsen VideoScan, as quoted in Yam (2007).

3.85 However, there are examples where the inferior standard does seem to have been chosen. For one thing, the market will be somewhat myopic. Factors that make one standard more attractive in the short term, thus driving early adoption, might not always produce the best standard for the longer term: the choice of technology might be path-dependent as Arthur (1989) notes.³⁸ QWERTY might be an example.³⁹ It is often claimed that the advantage of this keyboard layout lies in the way it reduces the likelihood of typewriter keys clashing, by separating the most commonly-typed letters in English, at a cost of less convenience to the typist. An alternative explanation is that the keyboard layout was suited to operators transcribing Morse.⁴⁰ Either way, this must have been irrelevant for most typists and machines even in the early days and is obviously of no significance at all for keyboards on modern electronic devices, yet the standard persists. The VHS/Betamax story is another often-cited example, as VHS won the war despite the technical superiority of the alternative Betamax standard. In each case, network effects strongly pushed the market towards selection of a single standard⁴¹.

3.86 We should note that there has been much debate over every well-known example of such inefficient outcomes of standards wars. Some commentators have gone as far as to state that “We are aware of no compelling examples of markets failing in the sense that the “wrong” choice of network, among feasible alternatives, was made” (Liebowitz and Margolis 1994, 146).⁴² Betamax may have been a superior video technology, but VHS tapes were sufficiently compact that an entire movie could be stored on one tape – rather an important technical and commercial advantage in itself. The shorter play-time of

Betamax tapes was an important limitation that seems to have been enough to lock in VHS’s advantage. However, this limitation was clearly temporary, as VHS tapes capable of storing a whole movie soon emerged. The outcome of the standard war was not irrational but was perhaps rather myopic.

3.87 VHS and Betamax were both sponsored by major companies, providing another reason why an inferior standard might emerge: when powerful economic actors have an interest in its doing so.⁴³ If instead of a neutral co-ordination problem between competing possible standards, there are alternative proprietary standards in which companies have invested (and in which they have hopes of future profitability), factors unrelated to the quality of the product will come into play.⁴⁴ In the ‘web browser wars’, Microsoft was accused of having bundled its Internet Explorer (“IE”) together with Windows, making it uneconomic for computer manufacturers to install the competing Netscape Navigator, which is generally held to have been the superior technology at the time. Furthermore, Microsoft did a deal with AOL, the largest web portal in the USA at the time, for IE to be designated its preferred browser (dashing Netscape’s hopes of coming to a similar deal), in exchange for display of the AOL icon in the Windows desktop environment.

3.88 Netscape lost the browser wars, despite having the superior product and despite intervention by the US and European competition authorities. As it turned out, however, the browser market has not by any means become a Microsoft monopoly. Network externalities in browsers are somewhat weaker than had been envisaged and it is possible for multiple standards to exist. If different products have different features and performance and especially if consumer can ‘multi-home’, as they can through multiple browsers on the desktop, then the market need not collapse into a single standard.

38 In more technical terms: if one standard has stronger private benefits but weaker network effects than another, that first standard may end up as an inefficient equilibrium.

39 David (1985) argues that QWERTY is inferior to the later Dvorak Simplified Keyboard and even the Contemporary ‘Ideal Keyboard’ but that once QWERTY was selected it was ‘locked in’.

40 See Yasuoka and Yasuoka (2011) who note that the ‘clashing keys’ story does not fit well with the QWERTY arrangement, as ‘er’ is such a common letter combination in English.

41 Osashi (2003) models the VHS/Betamax fight, estimating the size of the network effects, and concludes that Sony could have won the war had it invested more (presumably in low prices or sponsored content for the format).

42 The authors dispute the validity of both canonical stories of path dependence: QWERTY (arguing that tests show no inferior typing speed to the Dvorak keyboard) and VHS/Betamax.

43 Katz and Shapiro (1985) is the most commonly cited economic model of sponsored standards wars, and Farrell and Saloner (1985) for unsponsored standards wars.

44 Katz and Shapiro (1985) note that an inferior standard can emerge when an inferior sponsored technology is in a standards war with a superior but unsponsored technology, essentially because the sponsor can behave strategically (for example pricing low).

Proprietary standard sponsors that hold a monopoly may have reduced incentives to innovate

3.89 Proprietary standards might also lead to slower or less radical innovation, if the standard owner has such an advantage as not to fear replacement by a new competitor providing the 'next generation' of the standard.⁴⁵ Many economists have studied the relationship between competitive market structures and innovation and if the empirical literature can be summed up in a single conclusion, it is that a monopolised market⁴⁶ in general will not exhibit radical innovation.⁴⁷ Monopolists do have an incentive to improve their existing products and would have a stronger incentive to keep their monopoly market than would an entrant if after entry the market would be shared as a duopoly. However, a monopolist innovates to replace himself and therefore places a lower value on a disruptive innovation than would a rival who has nothing to lose (Arrow 1962). The disruptive innovation literature led by Christensen⁴⁸ has demonstrated that it is rarely if ever the existing incumbent firm in an industry that produces the radical innovations.

3.90 Proprietary standards might therefore lead to slow innovation and adoption, as well as potentially to inferior solutions becoming locked in as a standard.

Proprietary standards can lead to uncompetitive market structures, enabling anti-competitive behaviour

3.91 Less immediately, but perhaps causing more harm in the long run, a proprietary standard is more likely to result in an uncompetitive market structure that could harm competition in technologies complementary to the standard. The owner of the standard has a competitive advantage that derives from its knowledge of the inner details and the future development plans of that standard.⁴⁹ For example, operating systems interact with applications through so-called Application Programming Interfaces ("API") and knowledge of the structure and capabilities of those APIs will help a software developer produce more effective applications. Successful applications will need continually to update to take advantage of new generations of the O/S, but the O/S owner could pre-empt them with better competing products that make use of its proprietary knowledge of O/S⁵⁰.

3.92 One might imagine this power of ultimate decision-making is always in the standard sponsor's own interest, but it is not always so, because of the reactions of suppliers of complementary products. Developing applications for an O/S, for example, carries with it two risks of opportunistic behaviour: that the O/S will be updated without adequate consultation or preparation of the industry and that the standard sponsor might in some way raise the costs of accessing the platform or itself develop competing products to those third-party applications, undercutting third party applications developers. In short, there is a hold-up problem. In the light of such risks, third party developers might be reluctant to create software that is compatible solely with the proprietary standard. Proprietary standard sponsors wanting to maintain their base of application developers will recognise both of these dangers and also recognise that the solution is somehow to commit in advance not to undertake the opportunistic behaviour that could deprive third-party developers of the value of their products.

3.93 One way to do so is through repeated interaction – building a reputation not to engage in such behaviour. Intel is reported to have a conscious strategy to do this, based on (a) setting up an internal structure with separate divisional profit and loss to avoid such incentives, (b) disseminating intellectual property widely to assist entry for complement providers and (c) creating a separate unit (the Intel Architecture Lab) whose staff are rewarded for promoting the health of the ecosystem as a whole (Gawer and Henderson 2007). In the words of Dave Johnson, an engineering manager at Intel:

"The market segment gets hurt if third parties think: 'Intel, the big guys, are there, so I don't want to be there. They're going to crush me.' That's not good, and it's not what we want, because we're trying to encourage people to do these complementary things (Quoted in Gawer and Henderson 2007)."

3.94 Another is to give up control of the standard. Portable Document Format ("PDF") was launched in 1992 by Adobe. PDF was initially openly documented and free to implement by third parties, but technical developments were under Adobe's proprietary control. In 2008, Adobe released the full PDF specification as an open standard (ISO 32000-1) and started to share the control over PDF with third-party contributors, in order to increase the use and development of PDF as a response to the competitive threat from Microsoft's XML Paper Specifications ("XPS"), which was launched with Windows Vista in 2006. The release of PDF as an open standard made it more attractive to application developers and end-users and thereby secured PDF's position in the market. Although Adobe has no control over PDF, it derives revenues from professional developer tools and readers designed for PDF.

45 It is worth noting, however, that Katz and Shapiro (1986) also demonstrate conditions under which a standard sponsor proceeds too quickly to a new standard, essentially because the standard owner takes no account of the harm done to stranded customers. Such a move might not reflect rapid technological progress, however, as it might merely take the form of pre-announcements (see Farrell and Saloner 1986) – conduct of which IBM was accused in the 1980s.

46 This refers to the market structure before the innovation. It might be necessary for the post-innovation market structure to be a monopoly (whether through legal protection of IPR or a natural monopoly through network effects), to drive the innovation in the first place.

47 The question of whether more competition always results in more innovation is more open. The current consensus is that the relationship is likely to follow an inverted U-shape: both monopolised markets and highly competitive markets exhibit lower rates of innovation, with the maximum reached at a point in between the two. However, this model does not generally imply that deliberately reducing existing competition can ever enhance innovation since in its 'high competition' end, there is little actual competition, firms instead avoiding technological rivalry precisely because competitive conditions if they became rivals would be so fierce. See, for example, Aghion et al. (2005).

48 In numerous publications, for example Bower and Christensen (1995).

49 This was one of the complaints in the European Commission's investigation of IBM in the 1980s, Amdahl and Memorex having alleged that IBM was withholding details of new interfaces, discussed in Farrell and Saloner (1992).

50 For example, Baseman et al. (1995) note that Microsoft left undocumented some of its APIs, making it more difficult for competing applications developers to use them and also imposing the risk that, if they did discover and use them, their applications would later be stranded by an update of the unpublished API. The authors also note that Microsoft could use this information to make its own applications, such as Excel, work better.

3.95 In a way, any standard has certain monopoly characteristics. However, a proprietary standard creates the potential for further monopolisation, up and down the industry supply chain. This might not occur (there is a diverse ecosystem supplying the Intel standard, as there is supplying Apple's still more closed OS). Nor is this necessarily a bad thing – there are economic advantages to vertical integration and it would be unreasonable for competition authorities to insist upon the boundaries of the functions provided by – for example – an operating system to remain fixed for ever. However, proprietary standards clearly have resulted in inefficient outcomes, both technologically and through monopolistic market structures. There are alternatives, as we shall discuss.

Government-promoted standards

3.96 Government, in some form or another, provides one alternative to the problems described above. Governments (whether directly, or through regulators or nationalised operators) have been active in setting standards in all three industries we consider in our case studies, at both domestic and international levels.

3.97 In many cases a government-promoted standard will provide the benefits of standards that we have identified earlier in this report. In the previous section, we identified many disadvantages that can also result from proprietary standards. Government-promoted standards could be effective in dealing with these as well, in that:

- A government may either impose a de jure standard or at least provide a very strong steer towards a single de facto standard, avoiding the inefficiencies of multiple standards and standards wars within its own territory. However, standard-setting by national governments or regional bodies may well result in geographic fragmentation, with multiple national or regional standards.
- In principle, a government could select the optimal standard for the economy and the society, as governments will not have incentives to promote a given standard that can lead to inferior technologies. That said, while there are examples of governments supporting success stories, such as DVB-T, governments might pick the wrong standards because of a lack of technical expertise, or because they have political motivations to do so, as we shall discuss.
- Again, in principle, a government standard could avoid monopoly and the inefficiencies, slow innovation, and the possibility of anti-competitive behaviour that it creates. That said, government standards do often favour particular firms, creating monopolies in markets that might otherwise be competitive.

3.98 In some cases, this could be a helpful intervention to move what would otherwise be a slow-moving standards war (or discussion) forward, or to focus on longer term issues that might be important but would not be reflected in a purely market-based contest. The Korean government's intervention

in mandating 2G standards for mobile telephony allowed the Korean manufacturers to flourish and establish themselves as leading handset manufacturers (Jho 2007). Also, as the Japanese NHK insisted on an analogue high-definition TV standard, government involvement accelerated the development of the Japanese digital standard, ISDB.⁵¹

3.99 However, governments' records in 'picking winners' are poor, partly because they lack the incentives of a commercial developer to identify efficient technology. When intervening in a standards war, a government is a 'blind giant' in the phrase of David and Greenstein (1990), often brought in with little information during a short time interval in which to act before the market locks in a standard. Governments may pay excessive attention to purely technical standards, ignoring some more commercial considerations, as the RCA vs CBS standards war over colour TV illustrated.⁵²

3.100 Governments might also make bad technological choices not merely because of poor information but because of their motives. It could be that governments are typically too willing to compromise. When forced to choose between different technologies, each with their own lobbyists, there is a natural tendency to split the difference and try to find a compromise that in some way includes everyone. Similarly, governments might be too concerned to adopt gateway (converter) technologies that attempt to preserve compatibility between different technologies (David 1986, cited in David and Greenstein 1990).

3.101 The case studies provided some examples of how government-promoted standards have led to inefficient regionally-fragmented standards. This harmed trade and competition, leading to poor outcomes for consumers and possibly reduced innovation. In analogue colour television, for example, as we have previously noted, incompatible standards and industrial policies led to restrictions on Japanese participation in the market from the 1960s through to the 1980s, a time when Japanese products were cheaper. European consumers were less able to benefit from this market entry than US consumers, in part because the PAL standard prevented Japanese producers from diversifying from production for their home NTSC standard. Similarly, 2G mobile phone production showed very strong regional differences based on domestic production. Motorola's global market share fell in the 1990s as the GSM standard gained acceptance, for example, so Motorola dominated the market in the US, while Nokia dominated in Europe. In 2000, 63% of mobile phones sold in the US were produced domestically, compared to 25% or less for domestic and audio equipment.⁵³

3.102 Regional standards therefore created regional markets, with little competition between the manufacturers from different standard localities, with an effect similar to a trade barrier. Although freer trade is not always politically popular, it is very well established in the economic literature that competition

⁵¹ See paragraph B.62.

⁵² See paragraphs B.8-B.19.

⁵³ Attributed by Gandai (2001) to incompatibility of standards.

from foreign producers benefits both the exporting and importing countries, and spurs innovation and growth. Deliberately restricting trade (“filling your harbours with rocks” is the metaphor often used) is not a route to economic success. Internationally-incompatible standards, set by governments prevented by trade agreements from imposing more direct controls, are no better.

Open voluntary standards

3.103 An alternative both to proprietary standards set by a single firm and to government standard-setting is for standards to be developed through voluntary participation in open industry groups, particularly Standard Development Organisations.

3.104 We will discuss the details of how this takes place in the next section. For now, we will briefly sketch out the benefits that an open, voluntary standard provides, compared to the drawbacks of proprietary and government standards we developed above. We begin by discussing the definition of an ‘open standard’, as the term is not always used to mean the same thing.

The meaning of ‘open standards’

3.105 There are various definitions for ‘open standards’. Baron and Spulber (2015) define open standards broadly as standards created by SDOs. They note that these standards are commonly available and are not owned by a single firm or a group of firms. The UK Government defines an open standard for procurement purposes according to six criteria:⁵⁴

- a. Collaboration in a consensus-based decision process;
- b. Transparency in that process;
- c. Due process – the standard is adopted by a specification or standardisation organisation;
- d. Fair access and publicly available at zero or low cost
- e. Market support: the standard is mature and supported by the market; and
- h. Rights are licensed in a royalty free basis that is compatible with both open source and proprietary licensed solutions.

3.106 The European Commission Horizontal Guidelines prescribe that “*standard-setting should normally be open to all competitors in the market or markets affected by the standard unless the parties demonstrate significant inefficiencies of such participation or recognised procedures are foreseen for the collective representation of interests.* (European Commission 2011, §316)”

3.107 Thus, openness in this context relates to the ability to *participate in the process*. For example, the IETF defines itself as an open-standards organisation with no formal membership or membership requirements. All participants and managers are volunteers, although their work is usually funded by their employers or sponsors.⁵⁵

3.108 The European Commission Horizontal Guidelines also emphasize the importance of non-discriminatory **access** to the standard, especially where there are no competing standards available:

*The assessment whether the agreement restricts competition will also focus on **access to the standard**. Where the result of a standard (that is to say, the specification of how to comply with the standard and, if relevant, the essential IPR for implementing the standard) is not at all accessible, or only accessible on discriminatory terms, for members or third parties (that is to say, non-members of the relevant standard-setting organisation) this may discriminate or foreclose or segment markets according to their geographic scope of application and thereby is likely to restrict competition. However, in the case of several competing standards or in the case of effective competition between the standardised solution and non-standardised solution, a limitation of access may not produce restrictive effects on competition* (European Commission 2011, §294).

3.109 An open standard can therefore be seen as one which allows wide participation in the process of standard setting and use of the standard and this is the sense in which we use the phrase here. Open standard-setting takes place in formal standard development organisations but also in informal consortia around those organisations.

Benefits of open standards

3.110 We have set out above how standards – however they are set - can provide economic benefits through promoting efficiency, innovation and competition. We also discussed some specific concerns about proprietary standards, namely:

- Proprietary standards are more likely to lead to **inefficient multiple standards** in the market;
- Even if limited in duration, the existence of multiple standards in a ‘**standards war**’ can have some adverse effects.
- Such wars can result in the **selection of inferior technology**.
- A firm sponsoring a proprietary standard may have **weaker incentives for radical** innovation than would multiple firms contributing technology to a standard, because if it replaces ‘itself’ rather than potentially replacing a rival.
- Proprietary standards that come to dominate a market are likely to lead to **market power**, worsening prices and quality and reducing the speed with which innovations diffuse in the market.
- A proprietary platform sponsor might behave **opportunistically**, exploiting its superior knowledge of the platform to displace suppliers of complementary products and thus deterring innovation in the ecosystem or – in some extreme cases – **use its market power directly to exclude** them from the market.

⁵⁴ “Open Standards principles” policy paper, last accessed 12 June 2017, <<https://www.gov.uk/government/publications/open-standards-principles/open-standards-principles>>

⁵⁵ IETF “About”, last accessed 18 January 2017, <<https://www.ietf.org/about/>>.

3.111 We also discussed how government standards could solve some of these problems but potentially create others, namely:

- Standard-setting to promote national interests can lead to **multiple regional standards**, missing out on the efficiencies and competition available from a global standard.
- They might also choose **inferior technology**, whether through a lack of technical expertise or a political motivation, such as protecting the interests of domestic over foreign producers, regardless of which technology is best.

3.112 Open standard setting through a Standard Development Organisation can help avoid each of these sets of problems.

Avoiding multiple standards, standard wars and regional fragmentation

3.113 Clearly, an open standard-setting process can provide a single global standard, when to do so would be the most efficient solution. This is the idealised goal in most cases of standard development organisations - to take what could otherwise be an inefficient process of multiple standards vying for the market with a process of technical evaluation to select the standard. They are usually successful in doing so, as the emergence and continuing updating of global standards in mobile telephony demonstrates.

3.114 SDOs can and do endorse multiple standards; and in some cases, a standards war is fought in the marketplace while an SDO-based standardisation process is under way. Open standard-setting processes therefore do not necessarily eliminate the uncertainties associated with investing in products that are complementary to a standard. In any event, the standard might fail to secure user approval and fail in the marketplace even after adoption, as did Digital Audio Tape which failed to secure sufficient interest either among customers or music providers.

3.115 Another example of a standard that failed to attract commercial interest was WiMax. WiMax was a 4G standard that competed with the LTE standard. WiMax was backed by a number of large players in the ICT world including Sprint, Comcast, Time Warner, Bright House Networks, Google and Intel. However, after WiMax's launch in 2008, the majority of US network operators decided to adopt LTE as WiMax was not sufficiently mobile (there were technical difficulties in handing-off signal from one base station to another). The economies of scale that these operators generated made equipment for LTE cheaper than that for WiMax. In the US, Sprint, one of WiMax's backers, acknowledged that it had "bet on the wrong horse" and decided to move to LTE, and in 2015, Sprint decided to close its WiMax network.⁵⁶ WiMax saw some success in Russia, Mongolia, Pakistan and a few other countries, but was largely shunned in Western Europe.

3.116 Open standard-setting therefore in no way guarantees acceptance of a standard. It is one way to produce a standard that must succeed or fail according to its technological and commercial merits. However, there are good reasons to believe that this method is often more likely to produce good results than the proprietary and government standards we considered earlier, as we now discuss.

Selecting efficient technology

3.117 Standard development organisations mostly require that technologies selected as standards are technologically well suited to the industry. More generally, the standard development process is inherently technical in nature, at every stage, with needs and proposed solutions identified through technical discussion, despite any possible underlying commercial or national/political interests. In an open standard-setting process, for example:⁵⁷

- A technical need is identified; and, if agreed by the SDO as a whole, working groups consider how to meet it;
- Technical solutions can be proposed and submitted ahead of the standards meeting, giving participants time to evaluate the proposal;
- Each proposed solution is presented and discussed in open forum under a neutral chairperson;
- Depending on how the SDO is structured, voting or consensus decision on the basis of technical merit selects the proposal for the standard.

3.118 Part of the reason why SDOs select efficient solutions is a decision-making process based upon voting. Both the 'supply' and 'demand' sides of the market are typically involved in SDO decision-making. When one side has market power, it will typically be reflected in there being few firms on that side – in the extreme, a monopolist supplier of technology. Yet it is precisely in those circumstances that the supply side would have the fewest votes. 'Market power' and 'voting power' are somewhat balanced.

3.119 This process is not merely one of balancing competing interests. By bringing together both the supply and demand for innovations, an SDO can provide an interactive framework within which technologies responsive to users' needs can be developed. By bringing together both the demand and the supply side of the 'market for innovation' a Standard Development Organisation can take advantage of what von Hippel (1988) has called "user innovation".⁵⁸

⁵⁶ "Sprint CEO says WiMAX bet paid less than hoped", last accessed 12 June 2017, <http://www.pcworld.com/article/212878/Sprint_CEO_Says_WiMAX_bet_Paid_Less_Than_Hoped.html>

⁵⁷ Drawing upon the example of the 3GPP process described in Gupta (2015)

⁵⁸ von Hippel (1998) surveyed manufacturers and users of scientific instruments, finding that the majority of innovations came from (fairly sophisticated) users rather than manufacturers.

Innovation

- 3.120** In selecting efficient technologies and then in adding value to that technology by incorporating it in a standard, SDOs obviously provide incentives for innovation. They also avoid the monopolist's disincentive for radical innovation that results from displacing its own production. Although there will be innovators with patents included in a standard who would lose out when a new standard supersedes it, in a standard with broad participation the incentive and ability to avoid innovation will be low. Firstly, the implementer side of the market will in general prefer continued technical advance. Secondly, an innovator with a share of the value of a standard is in a very different position from a monopoly owner of a proprietary standard. Just as in competitive product markets, there is an incentive to innovate to form part of the next standard (and the common desire of multiple suppliers each to capture a larger share will drive them each to competitive innovation).
- 3.121** Much of the reasoning for how an open standard-setting process results in enhanced incentives for innovation arises from 'the market for technology' that it creates, which depend upon property rights as we shall examine later.
- 3.122** Earlier, we noted Galetovic et al.'s (2015) comparative study of technological progress measured through price changes in industries based upon standards and those that are not. As they note, phone, video and audio equipment prices fell, despite generally rising prices in the economy, indicating technical progress in those industries at a rate faster than for the economy as a whole. Perhaps more compelling were their findings that these industries experienced price reductions faster even than other electronics products (such as watches and gambling machines) that are not typically networked and are therefore likely to benefit less from standards.
- 3.123** Again, the evidence that open standards-setting promotes innovation is to be seen mainly in the performance of the industries- particularly telecoms – that make extensive use of this institutional approach.

Market power

- 3.124** Finally, for this section, open standard-setting fairly obviously avoids the problems of monopolisation of a platform, whether expressed through opportunistic behaviour to displace producers of complementary technologies or through abuse of market power. Unlike a proprietary standard-sponsor, an innovator participating in open standard-setting need not have valuable inside knowledge either of the standard itself or the process for updating it. Other firms in the ecosystem can take part in the standard development process and of course the standard is published. Indeed, the majority of participants in SDOs do not themselves put forward technology. They gain value from the information and networking in the meeting, and the ability to influence the standard, rather than from innovation. Nor can a standard itself be used anti-competitively to exclude rivals from an industry as a proprietary standard can be.

- 3.125** It is not straightforward to demonstrate the effect on industry structure directly. As we noted earlier, even sponsors of proprietary standards will not, in general, seek to exploit their privileged position or market power by usurping or excluding providers of complementary products. Earlier, we noted that Intel specifically aims to limit its own incentives to do so, recognising the value of the ecosystem around the platforms it creates. Also, one cannot simply compare market structures because within a single industry there may be many different approaches to standard-setting in the 'stack'. The mobile phone industry, for example, uses open standard-setting for radiotelephony but most operating systems are essentially proprietary.
- 3.126** The handheld computer segment provides a good experimental laboratory for the effects of openness that has been extensively studied by Boudreau (2008, 2011). Earlier, we noted the strong effects he found for the benefits of opening the complementary hardware market for a given O/S, with a five-fold increase in new products compared to a closed system. He also examined the effect of opening the platform itself by allowing hardware manufacturers (implementers) ownership and control stakes in the O/S. This is not the same as participation in an SDO (it was not open, but by bilateral agreement) but it does illustrate some benefits of bringing implementers into development of the standard itself and it could be interpreted precisely as a means of commitment to avoiding the opportunistic behaviour to which sponsors of proprietary standards could be tempted. Boudreau finds that openness of the O/S platform in this way also accelerated innovation, measured through new product launches, by about 20% compared to closed platforms. This is significantly less than the value of opening the complements market – better a proprietary O/S than a completely closed vertical stack – but nonetheless it represents a significant improvement in hardware manufacturers' incentives to innovate.

Interim conclusions on open standard-setting

- 3.127** There are many forms of standard-setting and obviously different approaches will be most appropriate in different circumstances. Proprietary standards at least have a strong advantage of coherence, and Apple has produced very innovative products despite its rather closed approach. Similarly, we would not want to suggest that compatibility standards imposed by government are always inefficient. On the contrary, sometimes a government imposed standard can be necessary to help co-ordinate change, or to deal with industry incentives that are not aligned with the objectives of the wider economy and society (the EU's decision on charger adapters, for example).

3.128 However, we have also shown that proprietary standards can exhibit the effects of monopoly (for example through weaker innovation) and the extension of such monopoly into other markets. Competing proprietary standards can represent effective competition but can also reflect inefficient standards wars that could end with the market locked into an inefficient technology. Government standards do not have these perverse incentives, but the government has other reasons to make poor technological choices, whether just through its lack of expertise or politically motivated decision-making.

3.129 An industry-wide Standard Development Organisation is therefore often an attractive solution to the basic problem of how to achieve innovative standards efficiently and through a competitive process. They are not perfect solutions - and they vary enormously as we shall see in the next section – but they do balance the interests of innovators and implementers, they bring technical expertise to bear on the technical problems and at their best, they do this in an open and transparent manner. It is not the only way to organise innovation, but those industries relying on this approach seem to do well.

Conclusions

3.130 In this section we have examined how open standards foster innovation and competition:

- Standards can solve the hold-up problem, creating more efficient markets by helping maximise the positive effects of network effects, while mitigating the adverse consequences from increased concentration in an industry.
- All kinds of standards can help create efficiency, but proprietary standards, managed by a single firm, are more likely to result in inefficient standards wars, the choice of inferior technologies and anti-competitive market structures and behaviour.
- Government standards can help solve these problems, but governments themselves both may make mistakes and risk being influenced by political or policy considerations that might distort standard-setting.
- Open standard-setting through voluntary participation in industry bodies is an alternative that will often provide a good solution to these dilemmas.

3.131 Some products incorporate many different types of standards. A careful study of a modern laptop computer in 2010 found that it incorporated at least 251 technical interoperability standards (Biddle et al. 2010). Of these 251, 44% were developed by consortia, 36% by formal standard development organisations, and 20% by single companies. In the 197 standards for which the authors could assess IPRs, 75% were developed under “RAND” terms, 22% under “royalty free” terms, and 3% using a patent pool.

3.132 There are a few industries that are characterised by strong network effects, important complementarities between different products (both within the supply chain and outside it) and opportunities for rapid technological progress. Such industries need standards and they will tend to take the form either of large vertically-integrated firms controlling the standard or of a more varied market for technology, supported by an open standard-setting process. The former may occasionally be necessary or inevitable, but the evidence suggests that the latter is more innovative, competitive and flexible. It is no coincidence that the wireless telephony industry exhibits these features.

3.133 Innovators and implementers must both see advantages in participating, for this open standard-setting process to work and to bring about the innovative and competitive market structures we have described and the resulting economic benefits. How the institutions that manage this process – the Standard Development Organisations – achieve this delicate balance is the topic of the next section.

Markets for technology, enabled by Standard Development Organisations

Introduction

- 4.1** Having discussed in previous sections how voluntary participation in standard-setting can support effective and rapid innovation, while allowing competitive market structures, we will now focus on the institutions that deliver these results: the Standard Development Organisations (SDOs) and on the role that their licensing policies play in creating markets for technology⁵⁹.
- 4.2** By ‘market for technology’, we mean commercial transactions in which only rights over technology are exchanged, allowing a business model in which innovators are rewarded directly for their creativity, without necessarily manufacturing physical products. SDOs and indeed standards themselves are not essential for such markets, as intellectual property rights (IPR) can be licensed or exchanged bilaterally. However, SDOs create a framework in which such markets can bring many suppliers of technology (innovators) together with buyers of technology (implementers, such as firms that will manufacture consumer products).
- 4.3** SDOs are responsible for realising many of the benefits of standardisation discussed in the previous section, including assuring users that they will not be locked into a technological solution that is largely incompatible with other systems and used by few others. This allows users to benefit from network externalities, where the technology’s value depends on the number of other users of the technology. These benefits in turn boost demand for new technology and provide researchers with incentives to innovate.
- 4.4** SDOs foster development of technologies. Engineers identify alternative avenues to solve a given technological challenge and in cases where there are conflicting technologies where none is evidently superior, SDOs will coordinate on one approach.
- 4.5** Sometimes SDOs also set rules that affect members’ market interactions. For instance, some SDOs require that members disclose patents that are relevant to the standardization process and agree to license patents at reasonable terms and conditions so as to enable a broader adoption of the technology.
- 4.6** In this section, we first discuss the concept of a **market for technology** and the role of IPR in supporting it. We note the long history of technology trading but also sketch some of the emerging economic effects that seem to result from increased use of such markets more recently. Licensing technologies

enables ‘pure ply’ research companies to emerge, potentially making industries more innovative and competitive than they would have been had they been dominated by large, vertically-integrated firms.

- 4.7** We then consider how SDOs enable us of ‘markets for technology’ and the resulting competitive and innovative industry structures. We provide an overview of how actual SDOs operate with their varying structures, membership, rules and processes. We describe the policies of a wide range of SDOs that aim to balance the interests of technology developers and implementers. We discuss various decision making rules of SDOs, their policies regarding IPR disclosure and different forms of licensing rules. Given the great variety of SDOs, it is clear that their policies need to be tailor made.
- 4.8** It appears that policies regarding IPR in SDOs have improved over time in clarity and effectiveness. These organisations design their rules very carefully to ensure participation, wide implementation of the standard, as well as continued innovation. It appears that overall SDOs succeed in preserving incentives of firms to participate, innovate and adopt the standardized technologies. Therefore, it is fundamental that this delicate balance is preserved and not disturbed by uninformed policy interventions that could favour one interest group over others.

Markets for technology

- 4.9** Most innovations ultimately only have value when they are incorporated into a product – usually but not always a physical product – to be manufactured and sold. Selling a product that incorporates an innovation is an obvious way for the innovator to be rewarded for his or her efforts. However, it is not the only way. If the innovation itself can be traded – through technology licensing – then innovators do not also need to be manufacturers. That can have profound effects on industry structure, with possible benefits from increased competition and innovation.
- 4.10** We begin by exploring how the creation of a ‘market for technology’ can be enabled through the use of intellectual property rights (IPRs). Any market for technology will only work effectively if both innovators and implementers have an incentive to take part, a point we later develop when considering the ways in which SDOs seek to provide balanced incentives to both sides. This balance will depend on how IPRs are protected and how payments for licensing technology are set.

⁵⁹ These are sometimes referred to as Standard Setting Organisations (SSOs).

4.11 There is mixed economic evidence on whether patents or other forms of intellectual property rights are essential for technical progress. Many of the most important technological advances have been made without patenting, and studies of changes in patent laws have not conclusively shown that innovation increases as a result.⁶⁰ Studies of the effects of changes in patent law tend to show little or no effect on R&D.⁶¹ The importance of patents varies significantly by industry. A survey of 100 US firms conducted between 1981 and 1983 asked what percentage of commercialised innovations would not have occurred, had patents not been available (Mansfield 1986, cited in Williams 2017). Answers ranged from 65% and 30% in pharmaceuticals and chemicals, respectively, down to zero or nearly so for office equipment, vehicles, rubber and textiles. Surveys also often show senior managers in firms engaged R&D put a lower value on patenting than on secrecy.⁶² However, these surveys are inevitably weighted towards the larger firms who carry out most R&D, while smaller firms might depend more on intellectual property rights and be more likely to produce radical, disruptive innovations. There is evidence that the information-sharing properties of patents assist in rapid *diffusion* of technologies.⁶³

Rewarding innovation indirectly or through a market in technology?

4.12 Industry structure will be fundamentally different if innovators typically produce and sell their own products than if they licence the technology underlying them. In the first case, innovation and production/marketing will be based in vertically-integrated firms, possibly also possessing large market shares downstream to support their R&D function. Licensing of technology allows a more varied industry structure, in which a 'market for technology' emerges, with competition 'upstream' between innovators in research and competition 'downstream' between suppliers of products incorporating innovations.

4.13 Whether firms license or develop their innovations of course will depend on many factors; it is not simply a design choice by policymakers. Licensing is very extensive in some industries, rare in others. IPRs are a necessary but not sufficient condition for such licensing to occur. In almost any industry, some firms will still choose to be vertically integrated rather than license technologies. However, as long as IPRs and payments for the use of technology can be relied upon, the possibility exists for a different industry structure to emerge.

4.14 Some form of enforceable intellectual property rights is essential for a market in technology to develop. Without IPR, an innovator and an implementer cannot easily exchange knowledge and nor can the innovation be publicised without losing value. Vertical integration and secrecy can therefore be expected to prevail if IPR protection is weak.

4.15 Despite the apparent complexity of patent law and economics, one virtue of IPR is its simplicity. Standards for technology are highly complex, so they benefit from modularisation, with specialists developing deep expertise in specific areas. A single firm that sought to create all of the technologies embodied in a mobile telephony standard, for example, would need a vast array of specialist skills and somehow organise them to work together effectively. With tradeable intellectual property rights, users do not need to internalise or even fully understand the technologies they implement, they merely need to license them⁶⁴. Furthermore, innovators do not necessarily need to develop technologies for the entire product, merely a part.

4.16 In this section, we examine the ways in which industries with innovations sold in a 'market for technology' differ from those dominated mainly by vertically-integrated firms in which technology is sold embedded in products. Several industries have developed in this way without SDOs, but the increased prevalence of SDOs today makes the concept relevant across a much wider range of economic activity than ever before.

Early markets for technology

4.17 There is nothing new in this separation between the developers and users of innovative technology, enabled by the commercial use of patent rights. Indeed, some of the most famous inventors in the nineteenth century licensed their technology, rather than marketing products based upon it.

4.18 Lamoreaux and Sokoloff (2013) describe the extensive use of patent licensing in the USA in the nineteenth century. They note, for example, the very different geographic patterns of patenting activity and manufacturing, suggesting that it was not the manufacturing firms that were patenting technology. They also describe the business infrastructure that enabled this secondary market in technology to develop. A key role was played by patent agents, typically lawyers who branched out from merely assisting in filing patents to facilitating markets for technology. Indeed, in many cases, the patent was assigned at least twice, once to a national agent and then to local licensees. There was also increased specialisation, with more innovators holding multiple patents by the late nineteenth century, suggesting that invention itself was a viable career. Furthermore, many inventors had multiple 'assignees' (four, on average) implying that there were indeed licensing into something like a market for technology, not merely operating in a contractual relationship with a single firm.

⁶⁰ There have been several studies comparing international technology exhibitions in the nineteenth century. Moser (2013), for example, notes that only a small share of inventions exhibited were patented, and does not find differences in overall innovation between countries with patent protection and those without. However, there are differences in the sorts of technology exhibited by the two. Khan and Sokoloff (2004) note that the contemporary British reaction was rather different, the Government being sufficiently horrified by the creativity of American inventors to reform their patent law.

⁶¹ Lerner (2009), for example, uses data on foreign firms filing patents in the UK as a measure of overall innovation, finding that it does not change when those firms' domestic patent law was strengthened.

⁶² For example, Levin et al. (1987) found that patents were not the most highly valued means of protecting innovation in any industry in a survey of 650 firms carrying out R&D.

⁶³ For example, Cohen et al. (2002).

⁶⁴ Smith (2007) discusses this point extensively and notes that just as 'physical' property rights define the boundaries of a firm, allowing market exchange to occur, so do IPRs help a modular approach to R&D to emerge.

Box 3.4: Goodyear Tires – without Mr Goodyear

The Goodyear Tire & Rubber Company is one of America's industrial icons, founded in 1898 and still a major player in the global tire industry. It is named after Charles Goodyear, who patented the process for vulcanized rubber in 1844. Yet Charles Goodyear never had any connection with the company named after him, which was founded almost forty years after his death in 1860. As Mossoff (2015) tells the story, Goodyear never manufactured or sold rubber products, despite devoting his life to his process and identifying new uses for vulcanized rubber. He was rather an obsessive in this, for example constructing pavilions entirely made of rubber for the London and Paris world's fairs of the 1850s. Instead, he transferred the rights to his process to others, some of them end-users and some of them patent licensing companies themselves ('non-practicing entities' in today's parlance). Goodyear was a 'pure play' innovator, in the language we use here.

4.19 Over half of the 'great inventors' of the nineteenth century in fact licensed their innovations rather than attempting to manufacture and market the products themselves, according to Khan and Sokoloff (2014), who tracked all of the US inventors mentioned in the *Dictionary of National Biography* and born before 1886.⁶⁵ The most famous inventor in US history, Thomas Edison, made significant use of the secondary market, selling and licensing his patents, particularly in the early part of his career when he is reported as having passed at least twenty of his patented inventions to third parties (Mossoff 2015). He even assigned the patent for his incandescent light bulb to the General Electric Company, although Edison also tried to commercialise the light bulb himself later in his career, as he did his other most notable invention: the phonograph. However, he might have done better to stick to the secondary market, as his performance in these business ventures was "dismal". As his friend Henry Ford noted, Edison was "the world's greatest inventor and the world's worst businessman" (Stross 2007)⁶⁶.

4.20 This secondary market in technology was not unique to the United States, although it was most active there. After Germany brought in its first unified patent law in 1877, about 8% of all issued patents were transferred – rather less than the rate in the US at the time, but about equal to the rate in the US today (Burhop 2010).

Effects of a market in technology: specialised R&D firms in chemicals and semiconductors

4.21 The effects of developing a market for technology on industry structure are best seen in industries that have changed from being based on vertical integration, with the emergence of specialised R&D firms 'upstream'. The chemical processing industry was one of the first large-scale examples and semiconductors provide a more recent example of how important intellectual property rights can be in supporting such a transition.

Specialised engineering firms in the chemicals industry

4.22 In the 1920s, chemical engineers began to consider how to standardise the design of plant for producing different chemicals, by designing generic modules for different operations, that could be combined to produce different chemicals. This led to the concept of chemical engineering developing as a general activity, rather than as a specific design activity for individual plant and processes, leading to the emergence of so-called 'specialised engineering firms' (SEFs). These SEFs became of increasing importance after the Second World War, and by the 1960s it was the rule rather than exception for plant to be designed by SEFs rather than in-house. In the 1960s in the US "nearly three quarters of the major new plants were engineered, procured and constructed by specialist plant contractors" (Freeman 1968, cited in Arora et al. 2004). This industry structure became a global phenomenon, with three quarters of chemical plant constructed world-wide in the 1980s built by the SEFs. They were also increasingly important in R&D, being responsible for about 30% of all chemical process licenses in the 1960s and 1980s (Arora et al. 2004).

4.23 The emergence of the SEFs surely changed the way the chemical industry operates. It seems reasonable to suggest that the SEFs enabled:

- Faster innovation, because of the advantages of specialised chemical process design firms and competition between such firms in R&D;
- More rapid diffusion of such innovation, across the industry and between countries;⁶⁷ and
- A more competitive market structure, downstream for chemical products.

⁶⁵ Lamoreaux et al. (2009) track the continuation of US reliance on smaller specialised laboratories into the twentieth century, finding it ending only with the Great Depression and wartime reorganisation of industry.

⁶⁶ Alexander Graham Bell also licensed or sold the rights to many of his inventions but he developed and sold his most famous invention, the telephone, himself through the Bell Telephone Company. He is said to have offered to sell the patent to Western Union, and been turned down because the asking price of \$100,000 was too high, but this story is disputed (see <http://blog.historyofphonetalking.org/2011/01/the-greatest-bad-business-decision-quotation-that-never-was.html>).

⁶⁷ Making use of the fact that SEFs are more present in some chemical processes than others, Fosfuri et al. (1998) find that investment in less developed countries was highest for those processes with more SEFs operating in developed countries. Moreover, the SEF effect in less developed countries was greatest for domestic-owned firms, rather than multinational enterprises.

4.24 The last two are linked: technology diffusion allows for a more competitive industry structure. In a study of the US chemical industry from the 1950s to 1970s, Lieberman (1989, cited in Arora et al. 2004) found that experience accumulated by incumbents did not deter entry. That is, new entrants appeared to have access to the knowhow that might otherwise be expected to enable established firms to operate at higher efficiency, creating a barrier to entry. Lieberman also noted the indirect effect of this shift, as chemical processes with higher rates of non-producer patenting showed better productivity growth, measured by faster rates of decline in prices.

4.25 In chemical processing, then, the emergence of specialised R&D and design firms helped create a *market for technology* without which the industry as a whole would have a less competitive structure.

The fabless approach to designing semiconductors

4.26 The semiconductor industry, by contrast, illustrates how creating a market for technology through better specification of property rights can enable more competitive markets in R&D.

4.27 The rate of improved performance of semiconductors is one of the most impressive success stories of the twentieth century. It is certainly the most famous, as it is the only such process with a law named after it. Moore's Law reflects the empirical finding that the number of transistors in a dense integrated circuit doubles every 24 months, leading to rapid improvements in processing speed. Remarkably, this has been more or less sustained for 50 years, resulting in a 33 thousand-fold improvement in performance (The Economist Technology Quarterly 2016).

4.28 Semiconductors become faster mainly as a result of improvements in chip design: fitting more components into a given space and improving the connection paths between them (without generating so much heat as to damage the chip). Despite the obvious importance of such design, until 1984, US IP law was rather uncertain as to whether a design could be patented. The Semiconductor Chip Protection Act ("SCPA") Act (1984) remedied this situation (Radomsky 2000).

4.29 The effect on the industry was dramatic. Without strong IP protection, the best way to generate a return on the investment in designing a chip was to make and sell it. The industry was therefore dominated by vertically-integrated firms that designed and manufactured their own chips. However, with rights to a new design assured, it was possible for designers to licence designs to manufacturers for a royalty.

4.30 This brought two completely new business models:

- a. 'Fabless' R&D outfits, with no manufacturing capability, able to concentrate on the design of chips; and
- b. 'Fabs': dedicated 'foundry' manufacturers, able to manufacture chips based on multiple designs, either for marketing themselves or on behalf of others.

4.31 Following this legislative change, a large number of 'fabless' firms entered the industry aggressively while devoting a high share of R&D resources toward the filing of patents. Without protection for chip designs, the products of fabless firms would have been relatively easy for rivals to reverse engineer (Ziedonis 2008).

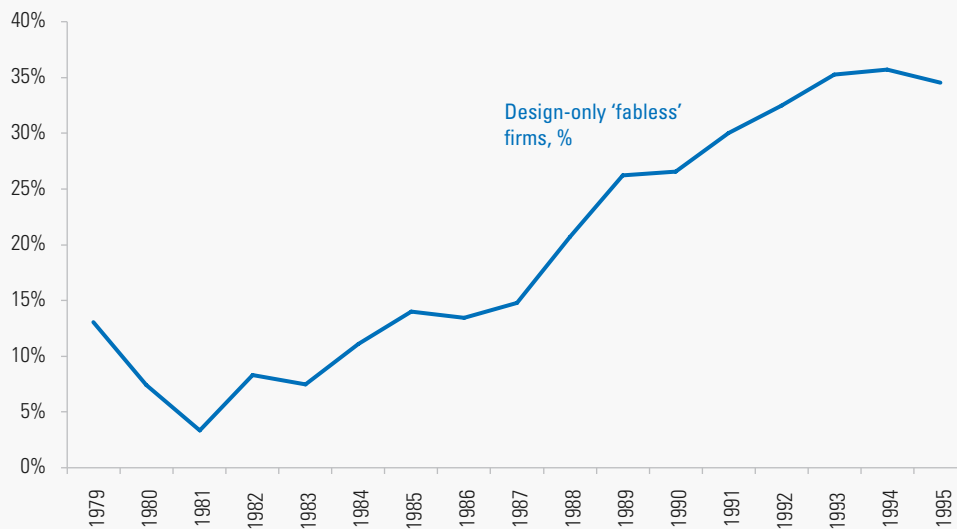
4.32 By 1998 there were over 500 fabless semiconductor design firms, with revenues of over USD 7.8 billion (Macher et al. 1998). In recent years the trend has been for companies to close or sell of their 'foundries'. Companies such as AMD, Texas Instruments, Freescale, Infineon, STMicroelectronics, and NXP have all moved to a fabless model.

4.33 The cost associated with creating and upgrading the manufacturing process has increased, and manufacturing has moved to large 'foundry' companies, such as TSMC, UMC, and Common Platform, that specialize in meeting the needs of their fabless design firm customers.

4.34 Intel is the only PC processor company left with their own 'fab', but even it has begun using external foundries for non-processor semiconductors. Companies like Intel are referred to as Integrated Device Manufacturers (IDMs) (Sperling 2008).

4.35 Between 2005 and 2010, fabless and foundry businesses have grown at 9% and 11% per year respectively, whereas IDMs have grown at 3%. The overall semiconductor industry growth in this period was 4% per year (McKinsey 2011). These fabless firms now carry out most of the design work in the semiconductor business, and are five times as likely to file for patents as the remaining vertically-integrated firms (Hall and Ziedonis 2001). The industry continues to evolve. Liden and Somaya (2000, cited in Arora et al. 2004) discuss the emergence of so-called 'chipless' firms, which do not even design entire chips but rather modules which can be combined by other design firms into chips.

Figure 25: Percentage of design-only 'fabless' firms in Hall and Ziedonis (2001) semiconductor firms study sample, 1979-1995



Source: Adapted by CL from Hall and Ziedonis (2001), Figure 3.

4.36 Without the market for technology, the industry structure would be much more concentrated because of the economics of chip manufacture. Manufacturing semiconductors is a hugely capital-intensive process with very strong economies of scale. Macher et al. (1998) report a USD 1 billion capital cost for a large fab. In an industry in which semiconductors were produced only by vertically-integrated firms, there would obviously be many fewer independent research and design operations. The separation allows for more competition and innovation upstream and the efficient use of economies of scale downstream.

4.37 In short, the ability to license intellectual property has created an R&D specialist layer of the industry that is more innovative and more competitive than would otherwise have been the case.

Economics of markets in technology: modularisation and generic complementary assets

4.38 This can be seen as an application to R&D of Smith's (1776) concept of the division of labour. The ability to trade in a market allows the emergence of specialised producers. For example, farmers might produce their own tools and implements, but in a market economy specialist blacksmiths can emerge, developing and deepening their skills through specialisation and also achieving economies of scale by selling implements to many farmers. However, such division of labour is limited by the extent of the market and the extent of the market will be limited by the availability of property rights. Without a market economy in which property rights are respected, the division of labour in production cannot emerge. Similarly, in R&D, without tradeable property rights in technology, specialist R&D firms cannot emerge.

4.39 A common pattern in the development of markets for technology is the provision of generic technology to replace customised design of individual products. This can appear through the provision of modules: the SEFs created chemical process components to be combined into chemical production lines; the recent 'chipless' firms design modules to be combined into semi-conductor chips. This increased division of labour is particularly evident in the software industry, where modular design is essential because of the scale and complexity of modern software. In early video games, for example, a single team (or even a single programmer) would create the entire game, whereas today the graphics will typically use a third-party 'engine', leaving the game designer to concentrate on the story and characters.

4.40 A related development is the emergence of suppliers of technology used for design. In the biotech industry, for example, the final products of research – new chemicals and drugs – are highly specific, but the 1980s saw the beginnings of firms that concentrated on technology to design and create those products. Often, this was done in alliances and joint ventures with larger (for example pharmaceutical) firms, but increasingly this technology is developed for licensing into a market. Zucker and Darby (1996, cited in Arora et al. 2004) found that nineteen out of twenty-one new biological entities approved by the US FDA by 1994 had been discovered by dedicated biotechnology firms, rather than large pharmaceutical companies.

4.41 The common theme in all of these industries has been specialisation in research and design of technology that can be transferred to a wide range of firms manufacturing and supplying final products. This requires some kind of compatibility – and standardisation.

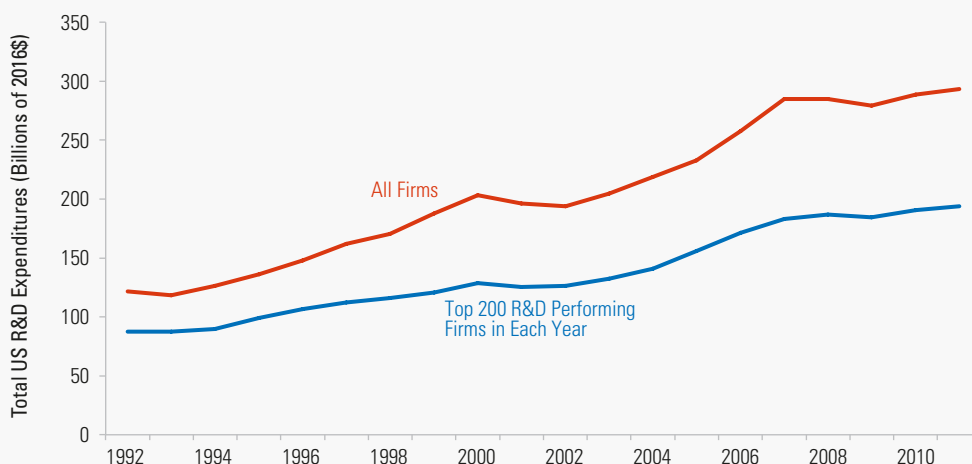
- 4.42** Suppose that this were not the case – imagine, for example, a semiconductor fab that could only make the chips designed by one fabless design firm. Then those two firms would be locked into a relationship of mutual dependence. The fab is dependent on the designer for new products, to keep up with the progress of its rivals. However, given the economies of scale in fabs, it is unlikely that more than one fab would specialise in a given design, so the fabless designer would be equally dependent on the fab (or would be a monopolist in the supply of the design- like a proprietary standard holder).
- 4.43** This is another form of the hold-up problem we discussed in the last chapter and it precisely characterises the conditions facing two firms that are dependent on one another for a continuous stream of new technology, in a fast-moving industry.⁶⁸
- 4.44** This insight has been developed in the business literature by Teece (1986) and formalised in a theoretical economics framework by Aghion and Tirole (1994). Teece (1986) notes that R&D efforts will often have characteristics that are difficult to contract for fully. Outcomes will be uncertain, particularly for those innovations with what Teece (1986) terms ‘weak appropriability’: when a patent cannot fully specify the value, for example because the innovation requires market feedback to perfect. The seller might want to reduce this uncertainty by sharing information about the technology, but this risks the loss of valuable secret information.⁶⁹ The relationship between a developer of technology and potential commercialiser of that technology cannot be contracted for completely, so if assets are specific to that relationship – rather than being generic – the obvious solution is to merge.
- 4.45** However, vertically integrated firms might miss out on the faster and more radical innovation that can arise from specialised R&D firms: because the inventor keeps more of the value of its innovation and because of advantages from specialisation. Aghion and Tirole (1994) develop this framework, balancing the reduction in risk described above, that vertical integration provides, against gains if separate ownership of the R&D provides more effective research. Specifically: the more important is the effort made by the ‘upstream’ R&D firm to the final product, the more valuable it is likely to be for that upstream firm to hold the full rights to the value of that innovation. Therefore, perhaps a little paradoxically, those industries in which innovation is particularly important to the success of commercialised products – such as the high tech industries – are more likely to see vertically-separated structures in which there are specialist R&D producers. Generic technologies, usable by many downstream firms, reduce the risk of this market structure.
- 4.46** Furthermore, owners of technology who do not manufacture the products from that technology *will* also have a strong interest in finding *new uses* for those technologies, making them still more generic. This can help the creation of markets completely different from those for which the technology was first developed.
- 4.47** Firearms manufacture provides an example of this from the nineteenth century. Firearms were among the first products to be standardised, with parts produced according to fixed specifications rather than being customised for each final product. Accordingly, machines that produced such firearm parts could be sold to multiple firearms-makers and a separate industry developed making these machines for manufacturing firearms. Decades later, bicycles were invented and it turned out that the same techniques that could produce gun barrels are also well suited to producing the metal tubes that form the bicycle frame. Accordingly, these same machine-tools makers were able to serve the fast-growing bicycle industry (Rosenberg 1976).
- 4.48** Would they have done so had they merely been the ‘upstream’ divisions of vertically-integrated firearms makers? Most likely not, as the owners and managers of these firms were not familiar with the bicycle market. Thus, the ability to provide generic technical inputs suitable for manufacturing a range of products allows the costs of that technological development to be spread across more products.⁷⁰ Separation between upstream technology and downstream products creates flexibility, to deal with unexpected future developments. For example, Compact Disc technologies were first released in 1980 and were used as a digital solution to music storage. Years later, this standard was repurposed for data storage (Masum et al. 2013).
- 4.49** An industry-based standard is a way to promote generic technologies and is therefore likely to help avoid the ‘hold-up’ problem. Consequently, a more disaggregated industry structure can emerge, with specialised upstream developers of technology and multiple competing downstream producers of final goods.
- 4.50** In his contribution to a twenty-year retrospective on his theory of vertical integration driven by complementary assets, Teece (2006) noted examples of deliberate vertical divestment in technology industries, driven by the benefits that such an industry structure can create. Qualcomm has exited telephone handset manufacture and Texas Instruments exited DRAM manufacture, in both cases to focus and specialise in upstream technology, rewarded mainly through royalties.

68 Nelson and Winter (1982) note that some R&D takes the form of a process, rather than a sequence of specific activities with specific outputs, making it easier to contract by paying developers a salary, in an in-house research unit, than to pay for their work in a market.

69 Lamoureaux and Sokoloff, in their survey of nineteenth century inventors, find that an important reason for inventors to seek employment with a manufacturing firm, rather than to licence their invention, was to avoid having to give away secrets to demonstrate the value of the technology.

70 Bresnahan and Trajtenberg (1995) formalise this intuition in a model, along with other externalities (spill-overs) between different players in the market or markets affected by generic technology.

Figure 26: An increasing share of US R&D takes place outside the top 200 corporations, 1992-2011



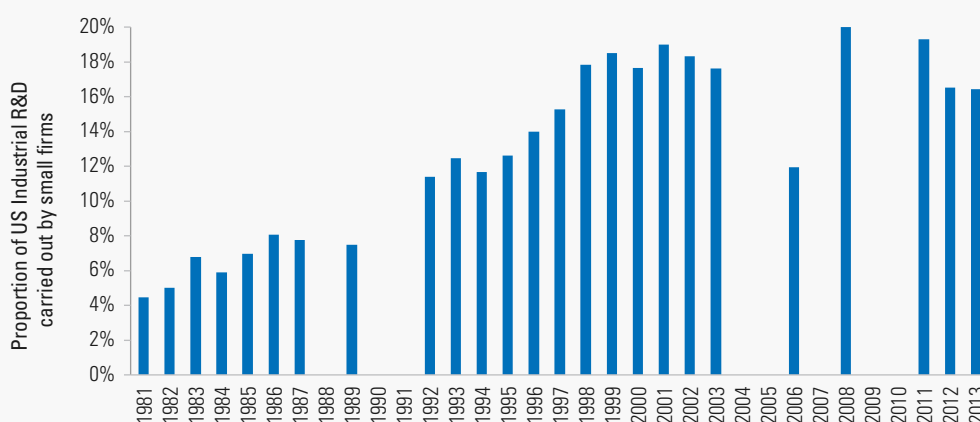
Source: Adapted by CL from Foster et al. (2016), Figure 3.

Effects of a market in technology: smaller, specialist research firms

4.51 Increased use of standards and 'modular' technologies may be creating a more varied, specialised and competitive R&D sector in multiple industries, particularly in the United States. The largest companies have always carried out a disproportionate share of R&D expenditure, perhaps because most forms of R&D both require and help maintain a minimum efficient scale, like advertising.⁷¹ Unlike advertising, however, R&D expenditure is becoming less concentrated, according to researchers working for the US Census Bureau, who conclude "the overall share of innovations by large firms is steadily declining" (Foster et al. 2016; Block and Keller 2009).

4.52 This recent finding confirms an earlier study focused more specifically on how concentration of R&D in the US is developing, which found that mid-sized firms had the fastest-growing R&D budgets between 1976 and 2010 and that specialist R&D firms were responsible for much of the growth (Hirschey et al. 2012). Recent data from the National Science Foundation show a transformation in the importance of small firms for R&D in the United States.

Figure 27: Proportion of US Industrial R&D carried out by small firms, 1981-2013



Notes: Small firms are firms which have less than 500 employees. In 2006, part of the data is suppressed by NSF Surveys of Industrial Research and Development. In years with missing data, no survey was undertaken or the data are missing. A new sample design was introduced in 1991 broadening the coverage; data from 1991 onwards are not directly compatible with earlier years.

Source: NSF Surveys of Industrial Research and Development, available at <<https://www.nsf.gov/statistics/srvyindustry/#tabs-2>>.

71 To adopt the framework formalised by Sutton (1991), who explains industrial concentration as the outcome of such endogenous sunk costs.

4.53 This is a remarkable increase, given the historical domination of corporate R&D by the largest firms and it is likely to be a positive development for both the speed and creativity of innovation in the US. Although larger firms carry out more R&D, there is evidence that smaller firms are more innovative,⁷² particularly more likely to come up with disruptive innovations as Christensen observed.⁷³ Furthermore, smaller specialised firms are likely to be better at their speciality: in this case innovation.⁷⁴ Intellectual property rights are essential for such small, specialist R&D firms to exist (Arora and Merges 2004). Quite apart from the possibility for licensing, patents also provide important collateral for finance⁷⁵ and provide valid signals to the market of future success.⁷⁶

4.54 This might not continue unchecked in all industries. Chesbrough (2003) disputes the notion that this trend will continue toward ever-further specialisation and ‘modularisation’, suggesting this is more likely to be a cyclical relationship. In his framework, an initial ‘integrated’ technology becomes modular, as in the examples above and this is very effective in developing improvements among its components. However, such an industry could run into what Chesbrough and Kusunoki (2001) terms a ‘modularity trap’ in which no one firm has the ability or incentive to undertake a more radical change, advancing the technology overall. For example, Intel needed to integrate forward into the design of the system bus architecture to move on from the original IBM PC’s system bus (Gawer and Cusumano 2002, cited in Chesbrough and Kusunoki 2001).

4.55 However, this will only be true if industries are unable to co-ordinate without vertical integration. As our case studies have demonstrated, Standard Development Organisations can provide such a co-ordinating role. A study on where companies participating in wireless communications standard setting focus their innovation efforts lends support to this theory (Kang and Motohashi 2012).⁷⁷ Vertically-integrated firms that manufacture focus their research on further developing those areas within a standard in which they have manufacturing expertise, whereas specialist R&D non-manufacturers contribute more to upgrading the technology standard itself. In those industries in which SDOs are effective, therefore, there is no obvious reason for the trend towards specialised research to reverse.

4.56 It is hard to prove that this development has increased the rate of innovation and competition, because of the difficulties of opposing a counterfactual to what has been a broad development spanning multiple industries. However, it seems likely that it has done so. There are few principles in economics more widely accepted than that the division of labour and specialisation allowing market-based exchange produces effective results, particularly in those markets are competitive. There is certainly evidence that such processes are generating value: even direct trades of patents result in gains, as innovators less able to exploit their patents transfer them to firms better able to create commercial value. There is scope for more such trade. Arora, Fosfuri and Gambardella (1999) report a British Technology Group (1998) survey of US firms that found companies ignored 35% of their patented technologies (valued at USD115 billion) because they did not fit into their core business operations. Through modelling the effects of patents on the value of firms of different types, Serrano (2011) was able to estimate what value patents would have when held by different firms and thus to measure the gains from trade, which turned out to be about 10% of the value of patents traded.

4.57 The benefits do not arise from a uniform superiority of R&D specialised firms over integrated manufacturing firms in research, but from the *variety* of approaches this creates.

4.58 There may be many reasons for this change in the distribution of technological innovation and the emergence of more specialised R&D firms. The increased importance of SDOs is likely to be one of them because an SDO creates precisely the conditions that enable such firms to thrive. As we have seen, specialised R&D firms are more likely to emerge if their innovations can be licensed for paid use and if their technologies are likely to be applicable to many downstream firms and products. These activities are at the heart of what SDOs do. Furthermore, this model is becoming more common. SDOs are playing a larger role in the world economy both because more industries are using this organisational model but also because more and more industries are using technology from the telecoms industry, for example in ‘internet of things’ applications.

⁷² For example, Arrow (1983) argue that incentives and information flow are more effective in smaller technology firms.

⁷³ Christensen (1997) made ‘disruptive innovation’ widely recognised as a business strategy but, for example, 20 years earlier Jewkes et al (1969) had documented several cases in which outsiders to an industry produce the more radical innovations.

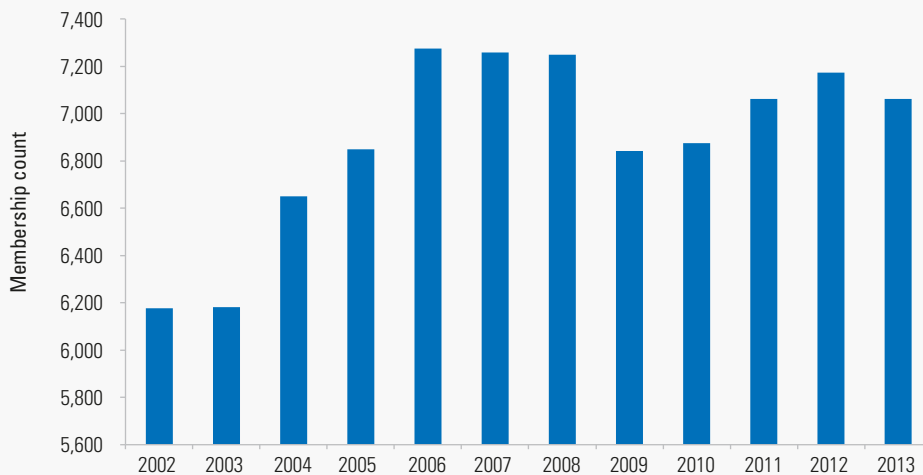
⁷⁴ Rotemberg and Saloner (1984) provide a model in which employees’ compensation is related to the use made of their ideas and such use will be clearer in a firm with a single focus than one that performs many different activities.

⁷⁵ Chava et al (2015) find that firms with frequently-cited patents have lower borrowing costs; Mann (2016) notes both that patents can be used as collateral for borrowing and that firms that do subsequently increase their patenting rate.

⁷⁶ For example, Farre-Mensa et al. (2016) find that a patent grant is a statistically significant predictor of a startup’s later success.

⁷⁷ The authors use reports from the ETSI, 3GPP, and the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT).

Figure 28: Total number of members within sample SDOs



Source: Adapted by CL from Baron and Spulber (2015), Figure 5.

Overview of SDOs

4.59 In this section, we will provide an overview of the major SDOs: their membership, sector, size and role in the standardization process.

Many types of SDOs

4.60 SDOs are voluntary organisations consisting of industry members that develop and disseminate technology standards. The development of standards is conducted primarily by personnel employed by firms active in relevant product markets, with occasional involvement of academic and government participants.

4.61 Standard development organisations are very diverse. Some of them are collaborations on a narrow set of technical specifications and involve only a couple of members, while others have thousands of participants and oversee multiple standardization activities simultaneously. For example, ASTM International, one of the largest SDOs, concurrently develops standards in areas as diverse as electrical wiring, playground equipment, composite materials and nanotechnology (Conteras 2015).

4.62 The European Commission classifies SDOs into three main categories:

- those recognized formally by governmental regulators, e.g. the European Technical Standards Institute (ETSI), the International Standards Organisation (ISO);
- “quasi formal” groups – typically large and well organized, e.g. the Institute of Electrical and Electronics Engineers (IEEE) and the Internet Engineering Task Force (IETF); and
- smaller, privately-organized consortia.⁷⁸

Diverse membership

4.63 SDOs vary greatly in size, and there is a significant movement of members across SDOs over time.

4.64 Baron and Spulber (2015) have studied SDO membership, rules and procedures using a database of SDOs since 1996⁷⁹. They find that the median SDO during the period studied had 114 members. Only five SDOs had membership levels greater than 1,000. Comparable data on SDO membership was available for only 40 of these SDOs over the period from 2002 to 2013 and we illustrate in Figure 28, above, the number of members within this sample.

4.65 In this sample, aggregate SDO membership has fluctuated, but appears to have been broadly stable despite the observed changes in SDO policy. However, at the level of an individual SDO, there have been significant fluctuations in membership over time. Membership of the Cellular Telecommunications Industry Association (CTIA) has declined from over 500 firms in 2001 to less than 300 in 2014. In contrast, membership of WiMAX increased from less than 50 undertakings in 2003 to over 500 in 2007 before declining to less than 100 in 2014.

78 “Standard-Essential Patents”, European Commission Competition Policy Brief, Issue 8. Last accessed 12 June 2017, <http://ec.europa.eu/competition/publications/cpb/2014/008_en.pdf>.

79 The database includes data on quantifiable characteristics of 629,438 standard documents issued by 598 SDOs, institutional membership in a sample of 195 SDOs, and the rules of 36 SDOs on standard-essential patents (SEPs), openness, participation and standard adoption procedures.

4.66 Table 10 shows the participation of the top 10 companies in Baron and Spulber's study.

Table 10: Top 10 SDO member companies

	Total	1998	2003	2008	2013
IBM	109	10	39	57	55
NEC Corporation	100	9	30	57	67
Intel Corporation	97	7	31	51	53
Hewlett-Packard	94	9	38	53	47
Hitachi Ltd	92	10	30	42	63
Fujitsu Limited	89	8	31	50	76
Motorola Solutions	89	11	30	39	40
Samsung Electronics	88	9	27	43	50
Microsoft Corporation	85	8	30	45	46
Nokia	84	7	26	49	39

Source: Adapted by CL from Baron and Spulber (2015), Table 6.

4.67 In practice, many organisations are part of multiple SDOs. For example, IBM Corporation was part of 10 SDOs in 1998, increased to participation in 57 SDOs in 2008, before stabilising at 55 in 2013. IBM Corporation was a part of 109 SDOs between 1998 and 2013 in total.

4.68 Other studies present a consistent picture. In 2003, Updegrove (2003) found that two major computing firms were each involved in more than 150 SDOs.

4.69 SDOs' activity has been gradually reinforced by Chinese firms. For example, Contreras (2014) finds that while participation in Internet standardization by Japanese and Korean firms has

remained steady over the years, participation by Chinese firms has increased from virtually nil in 2003 to a position in 2013, second only to U.S. firms.

Sectors with most SDOs

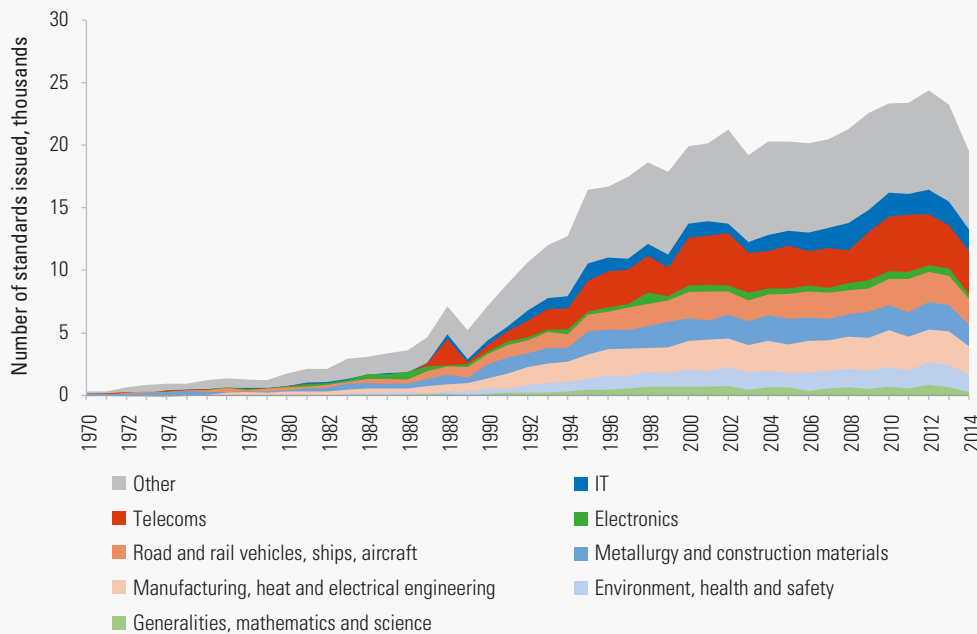
4.70 SDOs are active in a wide range of sectors, with some industries being particularly dependent upon them. Telecoms and electronics are among the most SDO-heavy sectors. A survey by Delimatsis (2015) finds that electronics and telecoms each involve close to 100 SDOs. Table 11 presents the breakdown by sector.

Table 11: SDOs by industry, 2015

Industry	Number of SDOs
Electronics	100
Telecom	89
Multi-Industries	84
Health and Medical	52
Clean Tech and Renewable Energy	40
Manufacturing	35
Power and Smart Grid	30
Consumer Electronics and Content	27
Automotive	23
Digital and Distance Learning	22
Bio IT and Life Sciences	19
Construction	14
Defence	10
Aeronautics	8
Real Estate	5

Source: Adapted by CL from Delimatsis (2015), Table 16.2.

Figure 29: Number of standards issued by technological field



Source: Adapted by CL from Baron and Spulber (2015), Figure 9.

4.71 An IPlytics survey of Standard Essential Patents (SEPs) by Pohlman and Blind (2016) found that most SEPs were declared at ETSI (among those declared at SDOs), representing over 70% of all worldwide SEP declarations. ETSI focuses on communication technologies. SDOs standardizing technologies for media and consumer electronics such as the BluRay Disc Association, the DVD Forum or ISO also constitute a large share of SEP declarations, while SDOs in the computer technology space such as IETS or OASIS have rather small numbers of declared SEPs.

4.72 The largest SDO active in a specific technological area is ETSI, which is active in the field of telecommunications, and has issued 46,303 documents⁸⁰. SDOs such as ITU, SAE (automotive standards) and the ISO/IEC (joint technical standards) have also issued a large number of standards.

4.73 This is reflected in the increasing number of telecommunication standards over the last few years. Figure 29, below, shows the evolution of standards by technological field. While the number of standards issued by SDOs has increased significantly overall, IT and Telecoms standards in particular have grown rapidly in the last two decades.

SDOs generate innovation

4.74 The evidence suggests that participation in SDOs, and similar forms of R&D cooperation, generates innovation. It appears that this happens at the greatest speed when organized through or accompanied by more informal consortia.

Benefits of informal consortia

4.75 Traditionally firms competed in R&D ahead of the working group meetings of SDOs, thereby generating a large volume of patented innovations of which only a fraction would eventually become 'essential'. This formal process generated R&D cost duplications and delays due to vested interests (Farrell and Simcoe 2012).

4.76 For example, in 3GPP and 3GPP2 companies made contributions to their organisations, which were then discussed and refined in working groups, and then potentially approved for discussion and further approval in the technical group.

4.77 Similarly, in many ICT fields, particularly in telecommunications, standards have traditionally been defined cooperatively by governments or industry actors within formal SDOs. These formal SDOs are sometimes perceived to be slow and bureaucratic, particularly when intellectual property rights have become part of the negotiation (Simcoe 2006). For example, the 3G wireless telecom standard contains around 16,000 essential patents and its development took almost a decade (Delcamp and Leiponen 2014).

4.78 Therefore, firms increasingly rely on informal consortia to take the lead in the standard setting process, wherein a group of firms seek to agree on a common design that they will jointly push as a standard. While some of them substitute for the lack of formal SDOs and issue their own standards (e.g., Blu-Ray alliance or W3C for web protocols), most consortia actually accompany formal standardization (Baron et al. 2016).

R&D cooperation and innovation

- 4.79** Historically, collaborative industry organisations have often been considered as a potential threat to competition because of concerns they might lead to collusion (Katz et al. 1990). However, such consortia may be desirable when they reduce coordination problems around innovation. R&D cooperation can mitigate wasteful duplication of effort and increase incentives to invest in R&D by internalizing potential externalities⁸¹.
- 4.80** In fact, studies from the 1980s on R&D consortia, which are in many ways similar to SDOs as far as innovation is concerned, find that R&D investments often create positive knowledge spill overs, which are not accounted for in private investment decisions. By internalising these spill-overs, R&D consortia are able to create socially optimal investments (Kamien et al. 1992).
- 4.81** Moreover these consortia lead to increases in R&D investment. Branstetter and Sakakibara (1998) find that consortium participation among Japanese firms is associated with a 2% increase in R&D expenditure and 4%-8% increase in patenting per dollar spent on R&D (research productivity). Sakakibara (2001) examines a larger sample of Japanese firms and finds that consortium participation is associated with a 9% increase in R&D expenditure.
- 4.82** Participating in consortia also helps firms to access and control strategic knowledge. Leiponen (2008) analyses the 3GPP consortia and finds that participation in technical consortia enhances firms' contributions to new standards, and firms that are central in the network are better able ultimately to influence the standard-setting outcome. Rosenkopf et al. (2001) also find that participation in SDOs helps firms identify potential alliance partners and opportunities for collaboration.
- 4.83** Baron et al. (2010) find that the effects of consortia membership and consortia member share on standard-specific R&D are positive in a broad majority of standards. However, they also suggest that consortia can have a deflating effect in a minority of standards that are characterized by a particularly strong patent race pattern: where consortium members compete to increase their patent applications.

Balancing interests of different participants in SDOs

- 4.84** As we have seen, specialisation, research consortia and SDOs tend to increase innovation, not least by creating opportunities for technology developers and implementers to work together. SDOs provide the forums where this occurs, but the two groups often have different interests. We now, therefore, discuss how SDOs balance the interests of technology developers and implementers to ensure continued innovation and participation.

- 4.85** SDO's governance rules seem to be striking a good balance in preserving the incentives to innovate of the undertakings involved and encouraging them to participate in the development of standards. SDOs have gradually improved the effectiveness of their policies to ensure that one interest group does not dominate others.

Incentives to participate

Increasing patent value

- 4.86** SDOs increase the intrinsic technological values of patents. Most importantly, SDOs generate innovation, which naturally increases the value of patents that are essential to implementation of standards.
- 4.87** From the ex-ante perspective, the prospect of participating in an SDO provides incentives for firms to innovate and to produce valuable patents. From the ex-post perspective, firms' participation in the development of a standard creates value in markets and naturally increases the intrinsic value of patents disclosed as essential to implementation of the standard.
- 4.88** One way of measuring the quality of patents is through citations, i.e. the number of times that a particular SEP is cited as prior art by later patent applications.⁸² Using citations as a measure of technical value⁸³, it is clear that on average, patents that are disclosed as essential to implementation of a standard are more valuable than those that are not in any standard.
- 4.89** The difficulty with this measure lies in distinguishing the extent to which SDOs are defining standards based on those technologies that are already the most valuable, and to what extent the standards themselves confer additional value on standard-essential patents ex post.
- 4.90** For example, Rysman and Simcoe (2008) study patents disclosed to four SDOs - ETSI, IEEE, IETF and ITU – and use citations as a measure of economic and technological innovation. By comparing disclosed patents to a control group of non-disclosed patents, they attempt to isolate the causal effect of an SDO on a patent's value. They find that SDOs tend to identify and endorse more important technologies, while at the same time endorsement by an SDO confers additional value on patents. They observe that SDO patents are cited far more frequently than a set of control patents, and SDO patents receive citations for a much longer period of time. Furthermore, they find a significant correlation between citation and the disclosure of a patent to an SDO. They estimate that the causal effect represents between 20% and 40% of the difference in citations between SDO and non-SDO patents.
- 4.91** Moreover, Layne-Farrar (2008) analyses patenting taking place after the standard has been set, and concludes that essential patents in this group are more valuable – i.e. receive more citations – than average patents.

⁸² See, for example Trajtenberg (1990).

⁸³ This is not ideal, because the number of citations is not a good measure of economic and technological progress. For example, older citations may have more citations and citation policies and citation policies may have changed over time.

- 4.92** Overall, the standardization process seems to increase the intrinsic value of patents by increasing firms' incentives to innovate and through the technology development process.

Increasing firm value

- 4.93** Participation in standard-setting appears to be a market indicator of firm's profitability. Aggarwal et al. (2011) provides empirical evidence of the influence on stock market returns and find that a firm obtained a 4% three-day cumulative risk-adjusted return on stock price by joining a standard-setting initiative, after accounting for time, firm size, and group size. Explicit coordination on standard setting substantially reduces the risk for developers and adopters to be confronted with new technology standards. They also found that an increase in the number of firms in the group decreased the risk-adjusted abnormal return and the market risk of each firm, but increased the idiosyncratic risk (as measured by the variance of firm returns).
- 4.94** Finally, Blind et al. (2011) also find that the ownership of essential patents boosted firms' financial returns, and argue that owning patents may also serve other purposes such as signalling technological competency.
- 4.95** Therefore, in all likelihood, firms have incentives to participate in SDOs because, through various channels, they increase their profitability.
- 4.96** As we will show now, this is only possible because SDOs are governed by carefully designed rules that make sure that their members do not lose out from participation by having to fulfil requirements that are harmful to their business models.

Mechanisms to ensure balance

Openness

- 4.97** SDOs are generally concerned to assure a balanced representation of categories of interest (differently sized firms or consumers, as well as different industries) and to design rules to prevent a single member from dominating standard development.
- 4.98** Different SDOs apply very different voting mechanisms. This seems to reflect the diverse structures of various SDOs and their attempt to balance the interests of the different members involved. Moreover, SDOs typically have multi-stage voting procedures for standards, and usually have a menu of different rules for different standards. In addition, in order to ensure that everyone is heard, approximately half of the SDOs in the Baron and Spulber (2015) sample allow their members to appeal the votes and decisions on standards.
- 4.99** Baron and Spulber (2015) further identify that most SDOs (30 out of the 31) have tiered membership, where voting rights depend on membership tiers, (which in turn may depend on membership fees) or on attendance and participation.
- 4.100** Typically, all members have a vote, but the vote may be weighted. For example, at ETSI, the votes are weighted based on the volume of sales; or may be on a national basis reflecting the weights in the European Council.

- 4.101** The voting percentage required to approve a standard varies across standards:
- 11 out of 31 require a simple majority (i.e. greater than 50%);
 - 5 out of 31 require a unanimous decision (i.e. 100%);
 - 8 out of 31 require a two-thirds majority (i.e. greater than 66%);
 - 3 out of 31 require greater than 71% of the votes; and
 - 4 out of 31 require more than 75% of the votes.
- 4.102** Similarly, Nelson et al. (2005) studied 10 voluntary industry consortia and found that decisions are based on consensus based on membership voting rights, and these voting rights vary by the type of membership. For example, university associate members may be allowed to participate in the technical committee and working groups, but are not allowed to vote.
- 4.103** Almost all SDOs examined in Baron and Spulber (2015) have open membership, i.e. all interested parties can join the SDO subject to specific procedures. This may involve a membership fee, which might be quite onerous for some interested parties. However fourteen SDOs out of 36 also had policies allowing non-members to participate in their meetings and 7 SDOs out of 36 had a specific status of observers that allowed companies to attend meetings, but not take part in the decision making process.

A variety of IPR policies

- 4.104** Products manufactured in accordance with standards normally satisfy the statutory requirements for patent protection. Generally, patents covering these standardized technologies are owned by firms whose employees made inventive contributions to the standard.
- 4.105** Although sometimes the technological contributions are made jointly by several undertakings, it is more often individual firms that submit technical contributions to the standard setting process and own the resulting patents. Generally, any given standard is covered by multiple patents.
- 4.106** There is remarkable diversity among SDOs in how they treat IP rights, perhaps reflecting the very different institutional and sectoral origins of different SDOs. Lemley (2002) has classified IP disclosure and licensing rules in a sample of 43 SDOs. The survey describes IP rules by five categories:
- type of IP covered;
 - disclosure requirements;
 - search requirement;
 - whether the standard can include IP; and
 - licensing provisions such as (RAND or royalty-free).
- 4.107** SDOs often require that their participants disclose patents that are likely to be necessary for the manufacture and use of standard compliant products. This requirement generates databases of SEPs, which are used to estimate patent coverage of SDOs.

4.108 Such disclosures take place on a large scale. For example, Simcoe (2007, cited in Contreras 2015⁸⁴) identifies 1,300 patent disclosures between 1981 and 2004, made at nine telecommunications SDOs. Similarly, Blind et al. (2011) identify around 8,000 disclosures made at eleven large SDOs. Baron and Pohlmann (2015) find more than 200,000 patent disclosures from 19 major SDOs. Importantly, 170,000 of these were disclosed at ETSI alone, while some other SDOs with more than 1000 patent disclosures were Blu-ray, ISO, IEEE, ITU, and DVD Forum.

4.109 It is also possible to track organisations that make most such patent disclosures. Blind et al. (2011) note 292 disclosing organisations, of which most disclosures were done by Qualcomm, InterDigital, Motorola, Siemens, Nokia, and Ericsson. The evidence on disclosure is in line with findings that contributions to SDOs are made by a small number of firms.

4.110 While several SDOs require their members to declare essential patents, they generally do not act as enforcers or evaluate the disclosures reported by their members for essentiality (Gupta and Snyder 2014).

Table 12: Claimed essential patents by firms (six largest firms), February 2011

Claiming firm	Total patents claimed
Nokia	1480
Qualcomm	1284
InterDigital	986
Ericsson	553
Motorola	319
Siemens	196

Source: Adapted by CL from Blind et al. (2011), Table 3-6.

4.111 SDOs also apply a broad range of policies regarding IPR, which reflects the different roles these organisations play in their industries.

4.112 The most common framework under which SEPs are licensed is through the FRAND commitment. A survey by Pohlmann and Blind (2016) for IPlytics found that 68% of all declared SEPs allow licensing under FRAND commitment. Furthermore, 65% of this sample are subject to reciprocity rules such as cross-licensing. Only 9% of declared SEPs are pooled, despite patent pool efficiency in terms of transaction costs and double marginalization effects.

4.113 Licensing rules vary depending on the industry. Patents in the field of audio-visual technologies have the highest share of pooled patents, while patent pooling is yet very uncommon for telecommunication technologies⁸⁵. Digital communication technologies often allow reciprocity licensing and in most cases they state to be prepared to license under FRAND conditions.

4.114 In some SDOs, the rights holder can state that they are not prepared to license essential patents, provided that it did not commit to license and thus did not participate in the standard-setting process. This was the case for only 11% of declared SEPs in the IPlytics sample.

4.115 The range of different approaches to licensing found in Baron and Spulber's survey is illustrated Table 13, below.

Table 13: SDO licensing requirements

Policy description	Number of SDOs	Examples
No licensing requirement specified	1	PCCA
FRAND (or RAND)	9	3GPP, DVB, ETSI, etc.
Menu of licensing options (including FRAND)	23	ANSI, ASTM, TIA, etc.
Royalty-free basis	5	BioAPI, Open Group, etc.

Notes: Based on 38 SDOs in the Baron and Spulber (2015) sample. CL notes that 3GPP and ETSI avoid issues concerning compulsory licensing by allowing members to decline to license their SEPs.

Source: Baron and Spulber (2015).

4.116 Royalty-free SDO licensing policies are not uncommon. In a survey of 251 standards in a typical laptop computer, Biddle et al. (2010) find that 22% were royalty-free, a similar proportion to the five in Baron and Spulber's sample above. Moreover, Contreras (2013) argues that many patent holders that are engaged in development of standards do not actively seek to licence or enforce their SEPs. Their motivation for holding the SEP is largely defensive, i.e. to protect themselves from patent infringement litigation or as bargaining chips in negotiations with other patent holders. Therefore, these SEPs are royalty-free in practice.

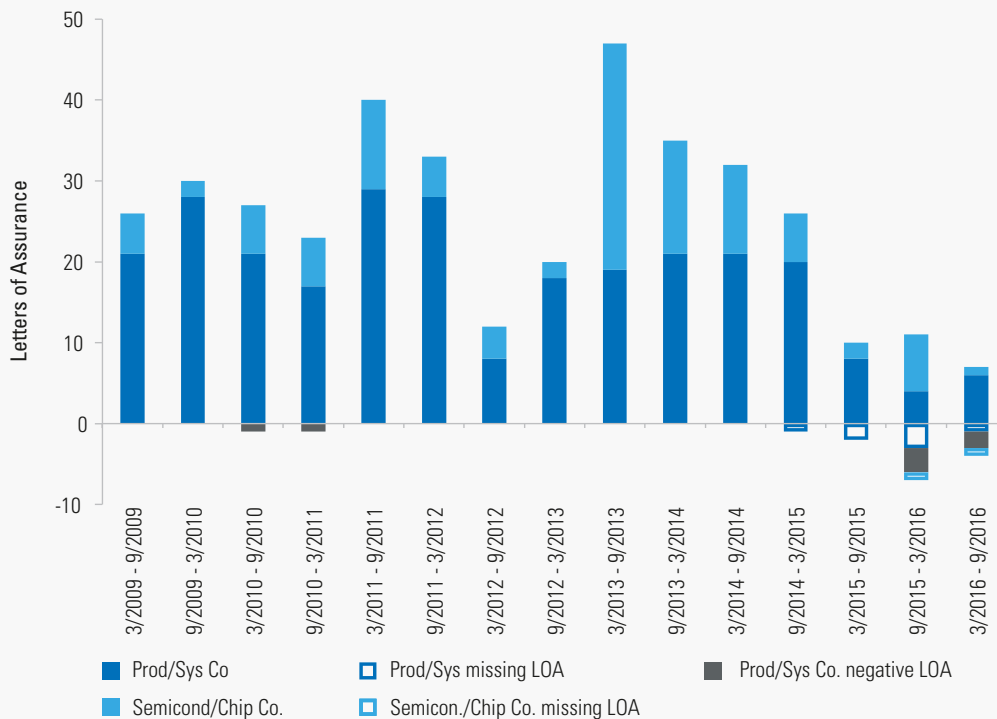
4.117 Contreras (2011) finds that between 2007 and 2010, approximately 59% of all patent disclosures made at IETF were accompanied by a voluntary commitment not to assert patents or to license them on a royalty-free basis. The presence of voluntary royalty-free commitments, such as those at IETF, along with the inactive SEP holders may result in a meaningful number of royalty-free patents in the marketplace (Contreras 2015).

4.118 However, royalty-free licensing may suit some firms – such as vertically—integrated companies that are able to receive a return on their innovation through selling products – but not all. In particular, royalty free licensing may deny patent holders returns on their patent portfolios and discourage the pure research firms from participating in SDOs (Herman 2010).

⁸⁴ All articles referenced in paragraphs 4.108–4.109 are cited in Contreras (2015).

⁸⁵ Pohlmann and Blind (2016)

Figure 30: Decline in non-duplicate licensing Letters of Assurance for IEEE standards by entity type



Source: Adapted by CL from Katznelson (2016).

4.119 The European Commission's Horizontal Guidelines warn that SDOs requiring their members to ex-ante commit to null royalties may actually be restrictive of competition as they may be discriminating against pure innovators whose only source of revenue are royalties, unlike the vertically integrated firms who also profit from sales of downstream products (European Commission 2011).

4.120 Therefore, royalty free solutions, while in some contexts potentially appealing, may actually prevent formation of efficient SDOs and thwart technological progress, by limiting incentives for participation of pure innovators.

IPR policies improving over time

4.121 SDOs regularly update their licensing and disclosure policies as they learn from their activities and mistakes, and because the market contexts in which they are present are dynamic.

4.122 For instance, Bekkers and Updegrave (2012) find that SDOs' IPR policies have improved in their clarity and effectiveness since the 1980s and early 1990s. They use the Rambus case to demonstrate the IPR issues that may emerge due to a lack of clear SDO policies. In their survey, they find that many disputes over SDO's policy in the ICT sector in particular are accepted by businesses as a reasonable in the course of

business. They also argue that SDOs have different needs and their policies need to reflect that.

4.123 Similarly, Tsai and Wright (2015) study SDO policy amendments pertaining to licensing rules at 11 SDOs, and find a gradual reduction in policy ambiguity across their sample.

4.124 The SDO policy amendments seem to concern a very wide range of areas;

- In a study of patent policy amendments at 10 SDOs, Layne-Farrar (2014) finds that these changes had addressed issues of patent ambush and excessive royalty rates.
- Baron and Spulber (2015) find a general strengthening of licencing requirements, but no significant modification to disclosure requirements over the period.
- Contreras and Housley (2008) note that the IETF disclosure policy was amended in response to one of the participants failing to disclose a patent covering an optional portion of a draft IETF standard.

4.125 Overall, these studies appear to find improvements in SDOs' policies over time, covering a wide variety of areas.

Policy changes and participation

- 4.126** It appears that the link between SDO policy and firm participation is determined by the extent to which the SDO depends on the sponsor firms, i.e. firms with patents. Chiao et al (2007) find evidence that SDOs oriented towards a small group of sponsor firms are less likely to demand policy-based concessions from members. In these situations, SDOs need to be particularly careful not to discourage participation of the contributing firms.
- 4.127** Moreover, the impact of the stringency of SDOs' policies on membership depends on the members' needs. Blind and Thumm (2004) survey 149 European firms and find that firms with higher patenting activity are less likely to join collective standardisation efforts because of the disclosure and licencing requirements imposed by the SDOs. However, firms in the ICT sector seem to place a greater value on participating in SDOs.
- 4.128** In 2015, in an attempt to address issues arising from the vagueness of FRAND commitments, IEEE amended its policy which required licensors to offer licences to all applicants, to forego their right to injunction except under limited circumstances; and also recommended a method of calculation of reasonable royalty rates. Katznelson (2016) examines rates of licensing Letters of Assurance at IEEE and finds a sharp (and statistically significant) reduction when changes to patent policy were brought in 2015. Not only did the rate of new LOAs fall, some patent holders actually declined to license under the new terms, on previously-issued LOAs (shown as negative LOAs in the chart below).
- 4.129** There is an active debate around whether such changes will reduce participation in the longer term. An earlier, similar, policy change at VITA, a smaller SDO focused on the defence and avionics sectors, has been found not to have reduced participation (Contreras 2013). Katznelson's findings have been challenged (IPLytics 2017) and further interventions on both sides of the debate are expected. The vigour of the debate shows the importance of the issue and the sensitivity of participants to these rules changes: unsurprising given the importance of standard-setting to the ITC sector and its participants.
- 4.131** Effective co-operation in such processes is only possible if both implementers and innovators gain from the interaction. If this balancing can be achieved, then an effective 'market for technology' can emerge, which allows the creation of an innovative, specialised and competitive upstream R&D industry.
- 4.132** The effect of these is most clearly seen when something changes, such as the policy change in the US that enabled 'fabless' semiconductor designers to emerge, or technological developments that have enabled specialist upstream firms to emerge in the chemicals industry and, more recently, biotechnology.
- 4.133** The institutional arrangements of SDOs vary markedly, reflecting their different industry conditions as well as their different histories. Broadly speaking, however, all seek to bring the industry's expertise together and most quite explicitly do so by attracting both suppliers and consumers of technology. They seem generally to be successful in identifying superior technologies for inclusion in standards.
- 4.134** SDO participation aligns the incentives of its participants to foster greater innovation. They achieve that through a great variety of decision making rules, their policies regarding IPR disclosure and different approaches to licensing. Given important differences among SDOs, and the roles they play in their respective sectors, it is clear that their policies need to be tailored and carefully fine-tuned.
- 4.135** The organisations' rules can change over time and for the most part have done so in a way that successfully eliminates ambiguity, creating clear improvements. This includes policy changes towards IPRs, most of which have benefitted both licensors and licensees. In this context, changes to SDOs licensing rules that disturb the fine balance within SDOs by favouring one of these groups or another could hamper the organisations' ability to attract and maintain participation from both sides of the market.

Conclusions

- 4.130** SDOs now play important roles in a wide range of industries although ICT and telecoms are still the sectors with the most prominent SDOs. As we have noted in this report, this structure enables voluntary participation in open standard-setting, which helps to drive innovation. One of the reasons for this is that voluntary participation in open standard-setting enables more diverse industry structures to emerge, in which specialist research companies can contribute to large sectors without necessarily themselves becoming large producers.

Conclusions

- 5.1** In this report, we have set out the evidence that technical standard-setting matters for economic outcomes. In particular, open standards set through voluntary participation in broad-based industry bodies produce innovative industries, because they provide incentives and opportunities for innovation and also because they enable the development of competitive and diverse industry structures.
- 5.2** This evidence arises from many sources. The performance and success of the mobile telephony industry in recent years is an indication that some things – probably many things – are working well in this industry. There does not appear to be a significant constraint on its growth, or upward pressure on prices or any delay in developing or adopting new technology. It would therefore be surprising if in some way the institutional arrangements for this industry were holding back innovation.
- 5.3** However, a devil’s advocate could argue that this industry would be even more innovative with different arrangements for standard-setting. So, we have examined evidence on how open standards and alternative standard-setting arrangements work. Both proprietary standards and government-imposed standards, although usually better than no standards at all, have their drawbacks. Both can frequently lead to inefficient standards being chosen, for the commercial advantage of a dominant firm in the case of proprietary standards and for political, often protectionist reasons by government. Both of these alternatives are also likely to lead to a less diverse and less competitive market structure than open standards. In particular, they are less likely to create the innovative and competitive ‘market for technology’ in which innovators license technology than would a standard open to all, set through an SDO with voluntary participation by both sides of this exchange.
- 5.4** The reasons for this can be seen by considering economic theories of how and why standard-setting affects investment and innovation incentives. Open standards – with technology licensing - allow innovative firms to contribute technology in a way that is not dependent either upon downstream manufacturing or on dealing with a single powerful counterpart.
- Without such opportunities, we would expect to see the emergence of large, vertically integrated firms and in many cases competition would be less vigorous because economies of scale in manufacturing, or monopolisation of an essential layer in the supply chain, reduce the scope for competitors. Throughout this paper, we have cited economic studies of different standard-setting arrangements, different degrees of openness and different approaches to intellectual property rights that demonstrate the effectiveness of open standards.
- 5.5** If this perspective is right, we would expect to see rather competitive and diverse markets at each level of the mobile telephony supply chain and indeed this is exactly what we see. Downstream, handset markets exhibit significant entry and exit, apps and services are highly competitive and innovative. Upstream, we see the ownership of technology becoming less concentrated in each successive wireless generation. The more diverse ‘ecosystem’ enabled by technology licensing seems even to be showing up in national data as more R&D is being conducted by small firms, at least in the US.
- 5.6** These outcomes depend upon a careful balance being struck between technology producers and users, within the Standard Development Organisations.
- 5.7** We have not in this report engaged at all with the extensive and sophisticated debate about precisely how FRAND rates should be set, the relationship between licensing and competition policy or some of the more detailed questions of SDOs’ governance arrangements. However, we do note that overall, the picture seems fairly clearly to demonstrate that the standard development institutions that supported the 3G, 4G and now 5G transitions performed well. Simply to alter those arrangements because of perceived problems that do not appear to show up in real world outcomes would be perverse.



Bibliography

- Abramson, A. 2002. *The history of television, 1942 to 2000*. McFarland.
- Aggarwal, N., Q. Dai and E. A. Walden. 2011. "The More, the Merrier? How the Number of Partners in a Standard-Setting Initiative Affects Shareholder's Risk and Return". *Management Information Systems Quarterly* 35(2): 445-462.
- Aghion, P. and J. Tirole. 1994. "The Management of Innovation". *The Quarterly Journal of Economics*: 1185-1209.
- Aghion, P., N. Bloom, R. Blundell, R. Griffith and P. Howitt. 2005. "Competition and Innovation: an Inverted-U Relationship". *The Quarterly Journal of Economics* 120(2): 701-728.
- Ala-Fossi, M. 2016. "Why Did TV Bits and Radio Bits Not Fit Together? Digitalization and Divergence of Broadcast Media". In *Media Convergence Handbook-Vol. 1: Journalism, Broadcasting, and Social Media Aspects of Convergence*, edited by A. Lugmayr and C. Dal Zotto, 265-285. Springer.
- Ali-Yrkkö, J., P. Rouvinen, T. Seppälä, et al. 2011. "Who captures value in Global Supply Chains". *Journal of Industry, Competition and Trade* 11: 263-278. doi:10.1007/s10842-011-0107-4
- Andrianaivo, M. and K. Kpodar. 2011. "ICT, financial inclusion, and growth evidence from African countries". IMF Working Paper.
- Angulo, J., J. Calzada, and A. Estruch. 2011. "Selection of standards for digital television: The battle for Latin America". *Telecommunications Policy* 35:773-787.
- Arora, A., A. Fosfuri and A. Gambardella. 1999. "Markets for Technology: The Economics of Innovation and Corporate Strategy". Working Paper 99-17, Business Economics Series 4, February 1999 of the Departamento de Economía de la Empresa, Universidad Carlos III de Madrid.
- Arora, A., Fosfuri, A. and Gambardella, A., 2004. "Markets for technology: The economics of innovation and corporate strategy". MIT press.
- Arrow, K. 1962. "Economic welfare and the allocation of resources for invention". In *The rate and direction of inventive activity: Economic and social factors*. Princeton University Press, 609-626.
- Arrow, K. 1993. "Innovation in Large and Small Firms". *Journal of Small Business Finance* 2(2): 111-124.
- Arthur, W. B. 1989. "Competing Technologies, Increasing Returns, and Lock-In by Historical Events". *Economic Journal* 99: 116-131.
- Athreye, S. and J. Cantwell. 2007. "Creating competition? Globalisation and the emergence of new technology producers". *Research Policy* 36: 209-226.
- Bach, D. 2000. "International cooperation and the logic of networks: Europe and the global system for mobile communications (GSM)". Berkeley Roundtable on the International Economy Working Paper.
- Baldwin, R.E. and R.K. Green. 1988. "The Effects of Protection on Domestic Output". In *Trade Policy Issues and Empirical Analysis*, edited by R.E. Baldwin, 205-232. University of Chicago Press.
- Baldwin, R. 2011. "Trade and Industrialisation After Globalisation's 2nd Unbundling: How Building and Joining a Supply Chain are Different and Why It Matters". NBER Working Paper No. 17716.
- Balto, D. 2013. "Barriers to Competition on the Innovation Superhighway: How the Lack of Antitrust Scrutiny of Patent Pools Deters Competition". <<http://www.dcantitrustlaw.com/patent%20pools%20-5%209%20pdf.pdf>>
- Branstetter, L. and M. Sakakibara. 1998. "Japanese Research Consortia: A Microeconomic Analysis of Industrial Policy". *The Journal of Industrial Economics* 46(2) Inside the Pin-Factory: Empirical Studies Augmented by Manager Interviews: A Symposium: 207-233.
- Barnett, J. 2014. "From Patent Thickets to Patent Networks: The Legal Infrastructure of the Digital Economy". *Jurimetrics* 55: 1-53.
- Baron, J., K. Gupta, and B. Roberts. 2015. "Unpacking 3GPP standards". Searle Center on Law, Regulation and Economic Growth Working Paper.
- Baron, J. and D. F. Spulber. 2015. "Technology Standards and Standards Organizations: Introduction to the Searle Center Database". *Innovation Economics Working Papers*. <http://www.law.northwestern.edu/research-faculty/searlecenter/innovationeconomics/documents/Baron_Spulber_Searle%20Center_Database.pdf>.
- Baron, J. and T. C. Pohlmann. 2010. "Essential Patents and Coordination Mechanisms: The Effects of Patent Pools and Industry Consortia on the Interplay between Patents and Technological Standards". <<http://dx.doi.org/10.2139/ssrn.1655660>>.
- Baron, J., T. Pohlmann and K. Blind. 2016. "Essential patents and standard dynamics". *Research Policy* 45(9): 1762-1773.
- Baseman, K. C., F. R. Warren-Boulton, and G. A. Woroch. 1995. "Microsoft Plays Hardball: The Use of Exclusionary Pricing and Technical Incompatibility to Maintain Monopoly Power in Markets for Operating System Software." *Antitrust Bulletin* 40(2): 265-315.
- BCG. 2015. "The Mobile Revolution: How Mobile Technologies Drive a Trillion-Dollar Impact". *BCG Perspectives*. <https://www.bcgperspectives.com/content/articles/telecommunications_technology_business_transformation_mobile_revolution/>.

- Beck, T. 2016. "Financial Inclusion – measuring progress and progress in measuring". <https://www.imf.org/external/np/seminars/eng/2016/statsforum/pdf/beck_paper.pdf>.
- Bekkers, R., G. Duysters, and B. Verspagen. 2002. "Intellectual property rights, strategic technology agreements and market structure: The case of GSM". *Research Policy* 31(7):1141-1161.
- Bekkers, R. and J. West. 2009. "The limits to IPR standardization policies as evidenced by strategic patenting in UMTS". *Telecommunications Policy* 33(1):80-97.
- Bekkers, R., R. Bongard and A. Nuvolari. 2011. "An empirical study on the determinants of essential patent claims in compatibility standards". *Research Policy* 40(7): 1001-1015.
- Bekkers, R. and A. S. Updegrove, 2012. "A study of IPR policies and practices of a representative group of Standards Setting Organizations Worldwide". <<https://ssrn.com/abstract=2333445>>
- Bernhofen, D. M., Z. El-Sahli and R. Kneller. 2016. "Estimating the effects of the container revolution on world trade". *Journal of International Economics* 98: 36–50.
- Bertschek, I. and T. Niebel. 2016. "Mobile and more productive? Firm-level evidence on the productivity effects of mobile internet use". *Telecommunications Policy* 40(9): 888-898.
- Bessen, J. 2003. "Technology and Learning by Factory Workers: The Stretch-Out at Lowell, 1842". *The Journal of Economic History* 63(1): 33-64. doi:10.1017/S0022050703001724
- Bessen, J. 2015. *Learning by Doing: The real connection between innovation, wages and wealth*. Yale University Press.
- Biddle, B., A. White and S. Woods. 2010. "How Many Standards in a Laptop? (And Other Empirical Questions)". <<https://ssrn.com/abstract=1619440>>
- Blind, K. and N. Thumm. 2004. "Interrelation between patenting and standardisation strategies: empirical evidence and policy implications". *Research Policy* 33(10): 1583-1598.
- Blind, K. and A. Jungmittag. 2005. "Trade and the impact of innovations and standards: the case of Germany and the UK". *Applied Economics* 37(12): 1385-1398.
- Blind, K., R. N. A. Bekkers, Y. Dietrich, E. J. Iversen, F. Köhler, B. Müller and J. Verweijen. 2011. "Study on the interplay between standards and intellectual property rights (IPRs)". Final Report Tender No ENTR/09/015.
- Blind, K. 2015. "The Influence of Standardization on Innovation and Economic Growth: State-of-the-art for Research and Policy". ICES 2015 Conference, hosted by Korean Standards Association.
- Block, F. and M. R. Keller. 2009. "Where do innovations come from? Transformations in the US economy, 1970–2006". *Socio-Economic Review* 7(3): 459-483. doi: 10.1093/ser/mwp013
- Blodget, H. 2013. "In Case You Don't Appreciate How Fast The 'Windows Monopoly' Is Getting Destroyed...". *Business Insider*. <<http://www.businessinsider.com/windows-monopoly-is-getting-destroyed-2013-7?IR=T>>
- Boudreau, K. 2008. "Opening the Platform vs. Opening the Complementary Good? The Effect on Product Innovation in Handheld Computing". <<https://ssrn.com/abstract=1251167>>.
- Boudreau, K. 2011. "Let a Thousand Flowers Bloom? An Early Look at Large Numbers of Software 'Apps' Developers and Patterns of Innovation". <<https://ssrn.com/abstract=1826702>>.
- Bower, J.L. and C. M. Christensen. 1995. "Disruptive technologies: catching the wave". *Harvard Business Review* 73(1): 43-53.
- Boylaud, O. and G. Nicoletti. 2000. Regulation, market structure and performance in telecommunications. OECD Economics Department Working Paper. doi: 10.1787/601531871521.
- Bresnahan, T. F. and S. Greenstein. 1999. "Technological competition and the structure of the computer industry". *The Journal of Industrial Economics* 47(1): 1-40.
- Bresnahan, T.F. and Trajtenberg, M., 1995. "General purpose technologies 'Engines of growth'?" *Journal of Econometrics* 65(1): 83-108.
- Brown, A. and R. G. Picard, Eds. 2005. *Digital terrestrial television in Europe*. Lawrence Erlbaum Associates, 313-315.
- Brusoni, S. and N. Corrocher. 2006. "The development and commercial success of SMS: standard committees as engine of knowledge-based entrepreneurship". European Commission Sixth Framework Programme (2002-2006).
- Burger, R. A., G. Iacovoni, C. Reader, X. Fu, X. Yang, and W. Hui. 2007. "A survey of digital TV standards China". Second International Conference on Communications and Networking in China: 687-696. IEEE.
- Burhop, C. 2010. "The transfer of patents in Imperial Germany". *The Journal of Economic History* 70(4): 921-939.
- Burton, F. N. and F. H. Saelens. 1987. "Trade Barriers and Japanese Foreign Direct Investment in the Colour Television Industry". *Managerial and Decision Economics* 8:285-293.
- Business Insider, 2013. "Microsoft's Biggest Problem in One Chart". <<http://www.businessinsider.com/microsofts-biggest-problem-in-one-chart-2013-9?IR=T>>
- Byrne, D. M. and C. A. Corrado. 2015. "Prices for Communications Equipment: Rewriting the Record". Finance and Economics Discussion Series 2015-069. Washington: Board of Governors of the Federal Reserve System. <http://dx.doi.org/10.17016/FEDS.2015.069>
- Cabral, L. 2009. "Setting the Standard: Two Generations of Wireless Telecom" Class Note for Stern School of Business, New York University. <<http://luiscabral.net/economics/teaching/wireless.pdf>>.
- Casadesus-Masanell, R. and D. B. Yoffie. 2007. "Wintel: Cooperation and conflict". *Management Science* 53(4): 584-598.
- Cavaggioli, F., A. de Marco, F. Rogo, and G. Scellato. 2015. "Patenting strategies and characteristics of declared inventions in the long term evolution standard". *R&D Management*.
- CEBR. 2015. "The Economic Contribution of Standards to the UK Economy". <<https://www.bsigroup.com/LocalFiles/en-GB/standards/BSI-standards-research-report-The-Economic-Contribution-of-Standards-to-the-UK-Economy-UK-EN.pdf>>

- Chava, S., Nanda, V. and Xiao, S.C., 2015. Lending to innovative firms. *The Review of Corporate Finance Studies*.
- Chesbrough, H. (2003) 'Towards a dynamics of modularity: a cyclical model of technical advance', in A. Prencipe, A. Davies and H. Hobday (Eds.) *The Business of Systems Integration*, Oxford: Oxford University Press.
- Chesbrough H. W. and K. Kusunoki. 2001: "The Modularity Trap: Innovation, Technology Phase Shifts and the Resulting Limits of Virtual Organizations". In *Managing Industrial Knowledge: Creation, Transfer and Utilization*, edited by I. Nonaka and D. J. Teece. SAGE Publications.
- Chiao, B., J. Lerner and J. Tirole. 2007. "The rules of standard setting organizations: an empirical analysis". *The RAND Journal of Economics* 38(4): 905-930.
- Christensen, C. 1997. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business Review Press.
- Cisco, 2017. "The Zettabyte Era: Trends and Analysis". <<http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html>>
- Clougherty, J. and M. Grajek. 2008. "The impact of ISO 9000 diffusion on trade and FDI: A new institutional analysis". *Journal of International Business Studies* 39(4): 613-633.
- Cohen, W.M., A. Goto, A. Nagata, R.R. Nelson and J.P. Walsh. 2002. "R&D spillovers, patents and the incentives to innovate in Japan and the United States". *Research Policy* 31(8-9): 1349-1367.
- Computer World. 2017. <<http://www.computerworld.com/article/2593382/networking/networking-packet-switched-vs-circuit-switched-networks.html>>.
- Contreras, J.L. and R. Housley. 2008. "IP Squared: Internet Standards and Intellectual Property". *IEEE Internet Computing* 12(6).
- Contreras, J.L. 2011. "An Empirical Study of the Effects of Ex Ante Licensing Disclosure Policies on the Development of Voluntary Technical Standards". National Institute of Standards and Technology, U.S. Department of Commerce. Contract No. SB134110SEI033.
- Contreras, J. L. 2013. "Fixing Frand: A Pseudo-Pool Approach to Standards-Based Patent Licensing". *Antitrust Law Journal* 79(1): 47-97.
- Contreras, J. L. 2014. "Divergent Patterns of Engagement in Internet Standardization: Japan, Korea and China". *Telecommunications Policy* 38: 916-934.
- Contreras, J. L. 2015. "Patents, Technical Standards and Standards-Setting Organizations: A Survey of the Empirical, Legal and Economics Literature". <<https://ssrn.com/abstract=2641569>>
- Copeland, A. and A. H. Shapiro. 2010. "The impact of competition on technology adoption: An apples-to-PCs analysis". Staff Report, Federal Reserve Bank of New York, No. 462.
- Crane, R. J. 1979. *The Politics of the International Standards: France and the Color TV War*. Praeger.
- Crockett, R. O. 1998. "How Motorola Lost Its Way: The inside saga of warring factions and strategic blunders". *Bloomberg*. <<https://www.bloomberg.com/news/articles/1998-05-03/how-motorola-lost-its-way>>
- Czubala, W., B. Shepherd and J. S. Wilson. 2007. "Help or Hindrance? The Impact of Harmonized Standards on African Exports". Policy Research Working Paper; No. 4400. World Bank, Washington, DC.
- David, P. A. 1985. "Clio and the economics of QWERTY". *American Economic Review* 75.
- David, P. A. and S. Greenstein. 1990. "The Economics of Compatibility Standards: An Introduction to Recent Research". *Economics of Innovation and New Technology* 1: 3-41.
- Dediu, H. 2012. "The rise and fall of personal computing". <<http://www.asymco.com/2012/01/17/the-rise-and-fall-of-personal-computing/>>.
- DeGusta, M. 2012. "Are Smart Phones Spreading Faster than Any Technology in Human History?" <<https://www.technologyreview.com/s/427787/are-smart-phones-spreading-faster-than-any-technology-in-human-history/>>.
- Delcamp, H. and A. Leiponen. 2014. "Innovating standards through informal consortia: The case of wireless telecommunications". *International Journal of Industrial Organization* 36: 36-47.
- Delimatsis, P. 2015. *The law, economics and politics of international standardisation* (Vol. 21). Cambridge University Press.
- Deloitte, GSMA and Cisco (2012). What is the impact of mobile telephony on economic growth? A report for GSM Association. <<https://www.gsma.com/publicpolicy/wp-content/uploads/2012/11/gsma-deloitte-impact-mobile-telephony-economic-growth.pdf>>
- Deloitte. 2014. Value of Connectivity: Economic and Social Benefits of Expanding Internet Access. <www2.deloitte.com/content/dam/Deloitte/ie/Documents/TechnologyMediaCommunications/2014_uk_tmt_value_of_connectivity_deloitte_ireland.pdf>.
- DigiTAG - The Digital Terrestrial Television Action Group. 2014. "Roadmap for the evolution of DTT – A bright future for TV". <http://www.digitag.org/wp-content/uploads/2015/01/0694-Roadmap-Report_web-2.pdf>.
- Economides, N. and F. Flyer. 1997. "Compatibility and Market Structure for Network Goods". NYU Stern School of Business Discussion Paper No. 98-02. <<https://ssrn.com/abstract=81268>>.
- Economides, N. and A. Skrzypacz. 2003. "Standards Coalitions Formation and Market Structure in Network Industries". NYU Stern School of Business Working Paper.
- Elen, R. 2014. "The 'Color Wars'". <<http://www.screenonline.org.uk/tv/technology/technology6.html>>.
- Ernst, D. 2016. "Standard-Essential Patents within Global Networks - An Emerging Economies Perspective". <<https://ssrn.com/abstract=2873198>>.
- European Commission. 1987. Commission of the European Communities, Towards a dynamic European economy: Green Paper on the development of the common market for telecommunications services and equipment COM (87) 290 (Brussels: CEC, 30 June 1987).
- European Commission (2011). Guidelines on the applicability of Article 101 of the Treaty on the Functioning of the European Union to horizontal co-operation agreements (Text with EEA relevance) (2011/C 11/01).

- European Council. 1987. Council of Ministers, Council Recommendation of 25 June 1987 on the coordinated introduction of pan-European cellular digital land-based mobile communications in the Community 87/371/EEC (Brussels: European Community, 25 June 1987).
- Evans, D. S., A. Hagiu, and R. Schmalensee. 2008. *Invisible engines: how software platforms drive innovation and transform industries*. MIT press.
- Farre-Mensa, J., Hegde, D. and Ljungqvist, A., 2016. "The bright side of patents" (No. w21959). National Bureau of Economic Research.
- Farrell, J. and P. Klemperer. 2007. "Coordination and Lock-In: Competition with Switching Costs and Network Effects". In *Handbook of Industrial Organization, Volume 3*, edited by M. Armstrong and R. Porter, 1967-2072.
- Farrell, J. and G. Saloner. 1985. "Standardization, Compatibility, and Innovation". *The RAND Journal of Economics* 16(1): 70-83.
- Farrell, J. and G. Saloner. 1986. "Installed Base and Compatibility: Innovation, Product Preannouncements, and Predation". *American Economic Review* 76(5): 940-55.
- Farrell, J. and G. Saloner. 1988. "Coordination Through Committees and Markets". *The RAND Journal of Economics* 19(2): 235-252.
- Farrell, J. and G. Saloner. 1992. "Converters, Compatibility, and the Control of Interfaces". *The Journal of Industrial Economics* 40(1): 9-35.
- Farrell, J. and T. Simcoe. 2012. "Choosing the rules for consensus standardization". *The RAND Journal of Economics* 43(2): 235-252. doi: 10.1111/j.1756-2171.2012.00164.x
- Fickers, A. 2002. "'Politique de la grandeur' versus 'Made in Germany', Politische Kulturgeschichte der Technik am Beispiel der PAL-SECAM –Kontroverse". Dissertation, University Aachen.
- Fickers, A. 2010. "The Techno-politics of Colour: Britain and the European Struggle for a Colour Television Standard". *Journal of British Cinema and Television* 7(1):95-114.
- Foster, L., C. Grim and N. J. Zolas. 2016. "A Portrait of Firms that Invest in R&D". US Census Bureau Center for Economic Studies Paper No. CES-WP-16-41. <<https://ssrn.com/abstract=2845982>>
- Fridenson, P. 1991. "Selling the Innovation: French and German Color TV Devices in the 1960s". *Business and Economic History* Second session 20:62-68.
- Funk, J. 1998. "Competition between regional standards and the success and failure of firms in the world-wide mobile communication market". *Telecommunications Policy* 22(4/5): 419-441.
- Gaillard, I. 2007. "The CCIR, the standards and the TV sets' market in France (1948-1985)". European Business History Association. <<http://www.ebha.org/ebha2007/pdf/Gaillard.pdf>>
- Galetovic, A. and K. Gupta. 2016. "Royalty Stacking and Standard Essential Patents: Theory and Evidence from the World Wireless Industry". Hoover IP2 Working Paper 15012.
- Galetovic, A., S. Haber and R. Levine. 2015, "An empirical examination of patent hold-up", *Journal of Competition Law and Economics* 11(3): 549-578. doi:10.1093/joclec/nhv024.
- Galetovic, A., S. Haber, and L. Zaretski. 2016. "A New Dataset on Mobile Phone Patent Royalties". Working Paper No. 16011. <<http://hooverip2.org/wp-content/uploads/ip2-wp16011-paper.pdf>>
- Gallagher, S. and S. H. Park. 2002. "Innovation and Competition in Standard-Based Industries: A Historical Analysis of the U.S. Home Video Game Market". *IEEE*.
- Gandal, N. 2001. "Quantifying the Trade Impact of Compatibility Standards and Barriers: An Industrial Organization Perspective". In *Quantifying the Impact of Technical Barriers to Trade: Can it be done?*, edited by K. E. Maskus and J. S. Wilson, 136-154. University of Michigan Press.
- Gandal, N. 2002. "Compatibility, standardization, and network effects: Some policy implications". *Oxford Review of Economic Policy* 18(1): 80-91.
- Gandal, N., D. Salant and L. Waverman. 2003. "Standards in wireless telephone networks". *Telecommunications Policy* 27(5): 325-332.
- Gawer, A. and R. Henderson. 2007. "Platform Owner Entry and Innovation in Complementary Markets: Evidence from Intel". *Journal of Economics and Management Strategy* 16(1): 1-34.
- Giachetti, C. 2013. *Competitive Dynamics in the Mobile Phone Industry*. Palgrave Macmillan.
- Goleniewski, L. 2001. *Telecommunications Essentials: The Complete Global Source for Communications Fundamentals, Data Networking and the Internet, and Next-Generation Networks*. Chapter 2. Addison-Wesley Professional.
- Gonzalez Sempere, J. 2001. "An Overview of the GSM System". Communications Division, Department of Electronic and Electrical Engineering, University of Strathclyde.
- Grant, G. 2000. *Managing Telecommunications and Networking Technologies in the 21st Century: Issues and Trends*. Chapter on "Global Competition and Cooperation in Standardisation". IDEA Group.
- Grimme, K. 2002. *Digital television standardization and strategies*. Artech House, Inc.
- GSM Arena. 2017. "GSM technology celebrates 20 years of calls". <http://www.gsmarena.com/gsm_technology_celebrates_20_years_of_calls__happy_birthday-news-2843.php>.
- GSMA. 2014. "European Mobile Network Operators - a regulatory assessment". <http://www.gsma.com/publicpolicy/wp-content/uploads/2014/12/European_mobile_network_operator_mergers-A_regulatory_assessment-WEB_FINAL.pdf>.
- GSMA. 2015. "State of the Industry Report: Mobile Money". <https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2016/04/SOTIR_2015.pdf>.
- GSMA. 2016. "The Mobile Economy". <<http://www.gsma.com/mobileeconomy/>>.
- Guerrero, D. 2014. "Deep-sea hinterlands: Some empirical evidence of the spatial impact of containerization". *Journal of Transport Geography* 35: 84-94.
- Gupta, K. and M. Snyder. 2014. "Smart Phone Litigation and Standard Essential Patents". Hoover IP2 Working Paper 14006.

- Gupta, K. 2015. "Technology Standards and Competition in the Mobile Wireless Industry". *Geo. Mason L. Rev.* 22(4): 865-896.
- Hall, B. H. and R. H. Ziedonis. 2001. "The patent paradox revisited: an empirical study of patenting in the US semiconductor industry, 1979-1995". *RAND Journal of Economics* 32(1): 101-128.
- Haimowitz, J. and J. Warren. 2007. "Economic Value of Standardization". SSC. <https://www.scc.ca/sites/default/files/migrated_files/DLFE-342.pdf>
- Herman, M. K. 2010. "Negotiating Standards-Related Pa to IPR standardization policies as evidenced by strategic patenting in UMTS". *Telecommunications Policy* 33(1): 80-97.
- Hirschey, M., H. Skiba and M. B. Wintoki. 2012. "The size, concentration and evolution of corporate R&D spending in U.S. firms from 1976 to 2010: Evidence and implications". *Journal of Corporate Finance* 18(3): 496-518.
- i-Runway, 2012. "Patent & Landscape Analysis of 4G-LTE technology". <<http://www.i-runway.com/images/pdf/iRunway%20-%20Patent%20&%20Landscape%20Analysis%20of%204G-LTE.pdf>>.
- i-Runway, 2013. "2G and 3G Mobile Communication". <<http://www.i-runway.com/images/pdf/iRunway%20-%202G%20and%203G%20Mobile%20Communication.pdf>>.
- IPLYtics, 2017. "IEEE remains very active after patent policy change". <<http://www.iptytics.com/general/ieee-active-patent-policy-change/>>
- ITU. 2005. "Cellular Standards for the Third Generation". <[http://www.itu.int/osg/spu/ni/3G/technology/#Cellular Standards for the Third Generation](http://www.itu.int/osg/spu/ni/3G/technology/#Cellular%20Standards%20for%20the%20Third%20Generation)>.
- Jho, W. 2007. "Global political economy of technology standardization: A case of the Korean mobile telecommunications market". *Telecommunications Policy*, 31(2):124-138.
- Jewkes, J., D. Sawers and R. Stillerman. 1969. *The sources of innovation*. Macmillan.
- Kang, B. and K. Motohashi. 2012. "Determinants of Essential Intellectual Property Rights for Wireless Communications Standards: Manufacturing firms vs. non-manufacturing patentees". RIETI Discussion Paper Series 12-E-042.
- Karamchedu, R. 2009. "Does China Have the Best Digital Television Standard on the Planet?". *IEEE Spectrum*. <<http://spectrum.ieee.org/consumer-electronics/standards/does-china-have-the-best-digital-television-standard-on-the-planet>>.
- Katz, M. L. and C. Shapiro. 1985. "Network Externalities, Competition, and Compatibility". *The American Economic Review* 75(3): 424-440.
- Katz, M. L. and C. Shapiro. 1986. "Technology Adoption in the Presence of Network Externalities". *Journal of Political Economy* 94(4): 822-841.
- Katznelson, R.D. 2016. "The IEEE controversial policy on Standard Essential Patents – the empirical record since adoption". Symposium on Antitrust, Standard Essential Patents, and the Fallacy of the Anticommons Tragedy, Berkeley, CA. <<http://bit.ly/IEEE-LOAs>>.
- Khan, B.Z. and Sokoloff, K.L., 2004. "Institutions and Democratic Invention in 19th-Century America: Evidence from "Great Inventors"" 1790-1930. *The American Economic Review* 94(2): 395-401.
- Koenig, S. 2016. "Global Technology Market Update". Presentation at CES 2016, Slide 22/31.
- Koski, H. and Kretschmer, T., 2009. "The role of product innovation on the diffusion of mobile telephony" (No. 1200). ETLA Discussion Papers, The Research Institute of the Finnish Economy (ETLA).
- Kshetri, N., 2005. "Diffusion pattern of Linux: An assessment on major technology dimensions". *First Monday* 10(8). <<http://firstmonday.org/article/view/1263/1183>>.
- Lamoreaux, N. R. and K. L. Sokoloff. 1999. "Inventors, Firms, and the Market for Technology in the Late Nineteenth and Early Twentieth Centuries". In *Learning by Doing in Firms, Markets, and Nations*, edited by N. R. Lamoreaux, D. M. G. Raff and P. Temin, 19-57. The University of Chicago Press.
- Lamoreaux, N. R., K. L. Sokoloff and D. Sutthiphisal. 2009. "The Reorganization of Inventive Activity in the United States during the Early Twentieth Century". NBER Working Paper 15440.
- Lamoreaux, N. R., K. L. Sokoloff and D. Sutthiphisal. 2013. "Patent Alchemy: The Market for Technology in US History". *Business History Review* 87: 3–38. doi:10.1017/S0007680513000123
- Layne-Farrar, A. 2008. "Innovative or Indefensible? An Empirical Assessment of Patenting within Standard Setting". <<https://ssrn.com/abstract=1275968>>
- Layne-Farrar, A. 2014. "Proactive or reactive? An empirical assessment of IPR policy revisions in the wake of antitrust actions". *The Antitrust Bulletin* 59(2): 373-429.
- Layne-Farrar, A., G. Llobet and J. Padilla. 2014. "Payments and Participation: The Incentives to Join Cooperative Standard Setting Efforts". *Journal of Economics and Management Strategy* 23(1): 24-49.
- Lee, K. E. 1996. "Cooperative Standard Setting: The Road to Compatibility or Deadlock? The NAFTA's Transformation of the Telecommunications Industry". *Federal Communications Law Journal* 48(3): 487-509.
- Lee, S. H., J. Levendis, and L. Gutierrez. 2012. "Telecommunications and economic growth: An empirical analysis of sub-Saharan Africa". *Applied Economics* 44(4): 461-469.
- Lemley, M. A. 2002. "Intellectual Property Rights and Standard-Setting Organizations". *California Law Review* 90(6): 1889-1980.
- Lerner, J. 2009. "The empirical impact of intellectual property rights on innovation: Puzzles and clues". *The American Economic Review* 99(2): 343-348.
- Levin, R. C., A. K. Klevorick, R. R. Nelson, S. G. Winter, R. Gilbert and Z. Griliches. 1987. "Appropriating the Returns from Industrial Research and Development". *Brookings Papers on Economic Activity* 1987(3) Special Issue on Microeconomics: 783-831.
- Levinson, M. 2008. *The box: how the shipping container made the world smaller and the world economy bigger*. Princeton University Press.

- Liebowitz, S. J. and S. E. Margolis. 1994. "Network Externalities: An Uncommon Tragedy." *Journal of Economic Perspectives*, 8(2): 133-150.
- Link, A. N. and G. Tassey. 1988. "Standards and the Diffusion of Advanced Technologies". *Evaluation and Program Planning*. 11: 97-102.
- Linux Foundation. 2014. "2014 Enterprise End User Trends Report. Fourth Annual Survey of Enterprise Linux Users." December 2014. <http://www.foxt.com/wp-content/uploads/2015/08/lf_end_user_report_1214-1.pdf>
- Macher, J.T., Mowery, D.C. and Hodges, D.A., 1998. Reversal of fortune? The recovery of the US semiconductor industry. *California Management Review* 41(1):107-136.
- Mallinson, K. 2015. "Don't Fix What Isn't Broken: The Extraordinary Record of Innovation and Success in the Cellular Industry under Exiting Licensing Practices". Geo. Mason L. Rev.
- Mallinson, K. 2016. "The Role of Licensing in Trade, Investment, and Technology Transfer". Presentation at the USPTO-CPIP Licensing Conference. <<http://www.wisefharbor.com/wp-content/uploads/2016/12/Amended-WiseHarbor-Mallinson-licensing-trade-investment-June-2016.pdf>>
- Mann, W. 2016. "Creditor rights and innovation: Evidence from patent collateral". Working Paper. <<https://ssrn.com/abstract=2356015>>
- Masum, H., R. Lackman and K. Bartleson. 2013. "Developing global health technology standards: what can other industries teach us?" *Globalization and Health* 9(1): 49.
- McGrath, R. 2013. "The pace of Technology Adoption is Speeding Up". <<https://hbr.org/2013/11/the-pace-of-technology-adoption-is-speeding-up>>.
- McKinsey. 2011. "The evolution of business models in a disrupted value chain". *McKinsey on Semiconductors*. http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/semiconductors/pdfs/mosc_1_business_models.ashx
- Miotti, H. 2009. "Impact Économique de la Normalisation: Changement Technologique, Normes et Croissance en France". Afnor. <<http://normalisation.afnor.org/wp-content/uploads/2016/06/Etude-ImpactEcoNormFr2009.pdf>>
- Moenius, J. 2006. "Do national standards hinder or promote trade in electrical products?" In *International Standardization as a Strategic Tool: Commended Papers from the IEC Centenary Challenge*. IEC.
- Mossoff, A. 2015. "Patent Licensing and Secondary Markets in the Nineteenth Century". *Geo. Mason L. Rev.* 22(4): 959-971.
- Nelson, M. L., M. J. Shaw and W. Qualls. 2005. "Interorganizational System Standards Development in Vertical Industries". *Electronic Markets* 15(4): 378-392.
- Nelson, R.R. and Winter, S.G., 1982. The Schumpeterian tradeoff revisited. *The American Economic Review* 72(1):114-132.
- New Scientist. 1981. "Taiwanese threat to European TV makers". *New Scientist* 89(1236): 56.
- New York Times. 1982. "France curbs Japan imports". <<http://www.nytimes.com/1982/02/18/business/france-curbs-japan-imports.html>>.
- OECD. 2013. *Interconnected Economies: Benefiting from Global Value Chains*. <http://www.oecd-ilibrary.org/science-and-technology/interconnected-economies_9789264189560-en>
- OECD. 2015. Roundtable on Competition Issues in Liner Shipping. <<http://www.oecd.org/daf/competition/competition-issues-in-liner-shipping.htm>>
- Ofcom. 2004. "Communications Market Report 2004". <<http://webarchive.nationalarchives.gov.uk/20160702162827/http://stakeholders.ofcom.org.uk/market-data-research/market-data/communications-market-reports/cmpdf/>>
- Ofcom. 2016. "Communications Market Report 2016". <<https://www.ofcom.org.uk/research-and-data/cmr/cmr16/international>>.
- Ohashi, H. 2003. "The Role of Network Effects in the US VCR Market, 1978–1986". *Journal of Economics & Management Strategy* 12(4): 447–494.
- OHG. 2000. "Open Letter to: ARIB, TTC, ETSI, TIA, TTA, T1, CWTS, 3GPP, 3GPP2". <http://www.3gpp2.org/Public_html/News/OHGLetter.cfm>
- Ortt, J. R. and T. M. Egyedi. 2014. "The Effect of Pre-Existing Standards and Regulations on the Development and Diffusion of Radically New Innovations". *International Journal of IT Standards and Standardization Research* 12(1): 17-37.
- Padilla, J. and G. Llobet. 2017. "The Inverse Cournot Effect in Royalty Negotiations with Complementary Patents". Hoover IP2, The Law and Economics of Patent Systems.
- Paleologos, J. M. and M. L. Polemis. 2013. "What drives investment in the telecommunications sector? Some lessons from the OECD countries". *Economic Modelling* 31: 49-57.
- Pohlmann, T. and K. Blind. 2016. "Landscaping study on Standard Essential Patents (SEPs)". IPlitics, for the European Commission.
- Puffert, D. J. 2000. "The standardization of track gauge on North American railways 1830 - 1890". *Journal of Economic History* 60(4): 933-960.
- Puffert, D. J. 2002. "Path Dependence in Spatial Networks: The Standardization of Railway Track Gauge". *Explorations in Economic History* 39(3): 282-314.
- Qiang, C, Rossotto, C.M., and Kimura, K. 2009. "Economic impacts of broadband." *Information and communications for development 2009: Extending reach and increasing impact* 3: 35-50.
- Radomsky, L. 2000. "Sixteen Years after the Passage of the U.S. Semiconductor Chip Protection Act: Is International Protection Working". *Berkeley Technology Law Journal* 15(3): 1049-1094.
- Raghvendra, R. 2006. "After 14 yrs, Rlys revives single-gauge plan to cut losses, 'unify' country". <<http://archive.indianexpress.com/news/after-14-yrs-rlys-revives-singlegauge-plan-to-cut-losses--unify--country/16413/>>
- Research and Markets. 2016. «China Digital TV Forecasts». <http://www.researchandmarkets.com/research/9mprxv/china_digital_tv>.

- Risk and Policy Analysts. 2014. "Study on the Impact of the MoU on Harmonisation of Chargers for Mobile Telephones and to Assess Possible Future Options". Framework Service contract ENTR/2008/006/Lot 1.
- Rosenberg, N. 1963. "Technological Change in the Machine Tool Industry, 1840-1910". *The Journal of Economic History* 23(4): 414-443.
- Rotemberg, J.J. and Saloner, G., 1984. "A supergame-theoretic model of business cycles and price wars during booms". https://dspace.mit.edu/bitstream/handle/1721.1/49114/supergametheoret00rote.pdf?sequence=1&origin=publication_detail
- Russell, A. L. 2007. "The American System: A Schumpeterian History of Standardization". Progress & Freedom Foundation Progress on Point Paper No. 14.4. <http://dx.doi.org/10.2139/ssrn.975259>
- Rysman, M. and T. Simcoe. 2008. "Patents and the Performance of Voluntary Standard-Setting Organizations". *Management Science* 54(11): 1920-1934.
- Sakakibara, M. 2001. "The Diversity of R&D Consortia and Firm Behavior: Evidence from Japanese Data". *The Journal of Industrial Economics* 49(2): 181-196.
- Scherer, F.M. and D. Ross, 1990. "Industrial Market Structure and Economic Performance". University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship. <<https://ssrn.com/abstract=1496716>>
- Schofield, H. 2012. "Minitel: The rise and fall of the France-wide web". BBC. <<http://www.bbc.co.uk/news/magazine-18610692>>
- Seck, M. D. and D. D. Evans. 2004. "Major U.S. Cities Using National Standard Fire Hydrants, One Century After the Great Baltimore Fire". NISTIR 7158.
- Serrano, C. J. 2011. "Estimating the Gains from Trade in the Market for Innovation: Evidence from the Transfer of Patents". NBER Working Paper No. 17304.
- Shapiro, C. and H. R. Varian. 1999. "The Art of Standards Wars". *California Management Review* 41(2):8-32.
- Shelanski, H. A. 2000. "Competition and Deployment of New Technology in U.S. Telecommunications". *University of Chicago Legal Forum* 2000(5): 85-118.
- Silberschatz, A., P. B. Galvin and G. Gagne. 1998. *Operating system concepts*. Vol. 4. Reading: Addison-Wesley.
- Simcoe, T. 2006. "Open Standards and Intellectual Property Rights". In *Open Innovation: Researching a New Paradigm*, edited by H. Chesbrough, W. Vanhaverbeke and J. West. O.U.P.
- Slack, B. 1990. "Intermodal transportation in North America and the development of inland load centres". *Professional Geographer* 42(1): 72-83.
- Smith, A. 1776. *An Inquiry into the Nature and Causes of the Wealth of Nations*.
- Smith, H. E. 2007. "Intellectual Property as Property: Delineating Entitlements in Information". *Yale Law Journal* 116: 1742-1822.
- Sperling, E. 2008. "AMD's 'Fab'ulous Deal". <http://www.forbes.com/2008/10/10/cio-amd-fabs-tech-cio-cx_es_1013amd.html>.
- Sridhar, K. S and V. Sridhar. 2008. "Telecommunications infrastructure and economic growth: Evidence from developing countries". Working Paper.
- Stallings, W., & Paul, G. K., 1998. "Operating systems: internals and design principles" (Vol. 3). Upper Saddle River, NJ: Prentice Hall.
- Stross, R. E. 2007. *The Wizard of Menlo Park: How Thomas Alva Edison Invented the Modern World*. Crown Publishers.
- Sutton, J. 1991. *Sunk costs and market structure: Price competition, advertising, and the evolution of concentration*. MIT Press.
- Swann, P., P. Temple and M. Shurmer. 1996. "Standards and Trade Performance: the UK Experience". *The Economic Journal* 106(438): 1297-1313.
- Takahashi, T. and F. Namiki. 2003. "Three attempts at "de-Wintelization": Japan's TRON project, the US government's suits against Wintel, and the entry of Java and Linux." *Research Policy* 32(9): 1589-1606.
- Tan, Z. 2001. "Comparison of Wireless Standards-Setting - United States Versus Europe" Working Paper. <<https://pdfs.semanticscholar.org/4eb2/17bbeb67ad99a73cfe6b29518bdf7447b02.pdf>>.
- Tanenbaum, A. S., & Bos, H. 2014. "Modern operating systems". Prentice Hall Press; Figure 11-1 on p. 858.
- Teece, D.J., 1986. "Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy". *Research policy*, 15(6), pp.285-305.
- Teece, D. J. 2006. "Reflections on "Profiting from Innovation"". *Research Policy* 35(8): 1131-1146.
- The Economist. 2016. "Cloud chronicles". <<https://www.economist.com/news/business/21705849-how-open-source-software-and-cloud-computing-have-set-up-it-industry>>.
- The Economist Technology Quarterly. 2016. "After Moore's Law: Double, double, toil and trouble". Q1. <<http://www.economist.com/technology-quarterly/2016-03-12/after-moores-law>>.
- The Verge. 2012. "Research, no motion. How the Blackberry CEOs lost an empire". <<http://www.theverge.com/2012/2/21/2789676/rim-blackberry-mike-lazaridis-jim-balsillie-lost-empire#section-link-title5>>.
- The Verge. 2015. "Windows 10 and Skylake processors were 'designed together,' says Intel's Kirk Skaugen". <<https://www.theverge.com/2015/9/1/9238379/intel-skylake-launch-ifa-2015-kirk-skaugen-interview>>.
- Tirole, J. 1986. "Procurement and renegotiation". *Journal of Political Economy* 94(2): 235-259.
- Trajtenberg, M. 1990. "A Penny for Your Quotes: Patent Citations and the Value of Innovations". *The RAND Journal of Economics* 21(1): 172-187.
- Tsai, J. and J. D. Wright. 2015. "Standard Setting, Intellectual Property Rights, and the Role of Antitrust in Regulating Incomplete Contracts". *Antitrust Law Journal* 80(1): 157-188.
- UK PC magazine. 2013. "'CDMA vs. GSM: What's the Difference". <<http://uk.pcmag.com/cell-phone-service-providers-products/11593/news/cdma-vs-gsm-whats-the-difference>>.

- Updegrove, A. 2003. "Major Standards Players Tell How They Evaluate Standard Setting Organizations". *Consortium Standards Bulletin*.
- Van de Kaa, G and M. J. Greeven, 2016. "Mobile telecommunication standardization in Japan, China, the United States, and Europe: a comparison of regulatory and industrial regimes". *Telecommunication Systems* 65(1):181–192.
- Vanessa, C. 1999. "Operators Propose 3G Compromise". *Total Telecom*.
- Vodafone annual report. 2014. <https://www.vodafone.com/content/annualreport/annual_report14/downloads/market_overview.pdf>.
- von Hippel, E. 1988. *The Sources of Innovation*. Oxford University Press.
- Waverman, L., M. Meschi, and M. Fuss. 2005. "The impact of telecoms on economic growth in developing countries". *The Vodafone policy paper series* 2(03):10-24.
- Williams, H. L. 2017. "How Do Patents Affect Research Investments?" NBER Working Paper No. 23088. doi: 10.3386/w23088
- Williamson, O. 1975. *Markets and Hierarchies: Analysis and Antitrust Implications*. Free Press, New York.
- World Bank. 1999. "Competition in Mobile Telecoms". <<http://siteresources.worldbank.org/EXTFINANCIALSECTOR/Resources/282884-1303327122200/184rosso.pdf>>.
- Wu, Y., S. Hirakawa, U. H. Reimers, and J. Whitaker. 2006. "Overview of digital television development worldwide". *Proceedings of the IEEE* 94(1):8-21.
- Yam, M. 2007. "Sony Releases Report on Blu-ray vs HD DVD". <<http://www.dailytech.com/Sony+Releases+Report+on+Bluray+vs+HD+DVD/article6841.htm>>
- Yasuoka, K. and M. Yasuoka. 2011. "On the Prehistory of QWERTY". *ZINBUN* 42: 161-174. <http://repository.kulib.kyoto-u.ac.jp/dspace/bitstream/2433/139379/1/42_161.pdf>
- Yoo, Y., K. Lyytinen and H. Yang. 2005. "The role of standards in innovation and diffusion of broadband mobile services: The case of South Korea". *The Journal of Strategic Information Systems* 14(3): 323-353.
- Ziedonis, R.H., 2008. "On the apparent failure of patents: A response to Bessen and Meurer". *The Academy of Management Perspectives* 22(4): 21-29.



