THE BATTLE BETWEEN STANDARDS: TCP/IP VS OSI VICTORY THROUGH PATH DEPENDENCY OR BY QUALITY?

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Between the end of the 1970s and 1994 a fierce competition existed between two possible standards, TCP/IP and OSI, to solve the problem of interoperability of computer networks. Around 1994 it became evident that TCP/IP and not OSI had become the dominant standard. This article specifically deals with the question whether the current dominance of the TCP/IP standard is the result of third degree path dependency or of choices based on assessments of it being technical-economically superior to the OSI standard and protocols.

Mid 1990s it turned out that TCP/IP had become the dominant standard protocol on the Internet rather than the OSI standard proposed by the International Standard Organization (ISO). The development of TCP/IP was a follow-up of the development of the ARPANET, a project started in the 1960s under auspices of the US Defense Advanced Research Project Agency (DARPA) for connecting computers at several US research centers and universities. The initial TCP/IP concept was developed in 1973, by Robert Kahn and Vint Cerf, to enable communication between different types of (computer) networks (Norberg and O'Neill, 1996: 183-185). OSI has been under development by international committees under auspices of ISO since the end of the 1970s. OSI has long been promoted and supported by Governments of European countries.

Why did TCP/IP win out in the competition with OSI? It should be emphasized that it was a real competition, if not battle, because TCP/IP and OSI claimed to be a solution to the same problem, notably the inter-operability of different (types) of computer networks (Egyedi, 1996: 228-232; Norberg and O'Neill, 1996: 183-185; Hafner and Lyon, 1996: 246-251). Their histories, however, differ. TCP/IP, as a standard, was derived *ex post*, as a by-product of a functioning system; OSI provided an *ex ante* reference frame to guide standards activities (Egyedi, 1996: 231).Several authors have discussed the various factors that might have influenced the adoption of TCP/IP rather than OSI (Egyedi, 1996; Tanenbaum, 1996; Bruins, 1993; Drake, 1993). This article will treat the question of dominance from a more limited perspective. This perspective is related to the question whether possible processes of path dependency and lock-in in the development and adoption of technology might result in the dominance of an inferior technology (see next section). Simply put, did TCP/IP become dominant basically because TCP/IP had superior technical-economic qualities compared to the OSI-standard, or was it because it had already been entrenched before OSI presented itself on the market?

Dominance through Path Dependency Versus Victory by Quality

Why do we have the specific technologies we have for fulfilling certain functions or carrying out specific tasks? This question is particularly intriguing when alternative technologies were developed and available to achieve the same ends. Current technology is a product of the past. But why is one technology rather than another dominant? Is it the result of (historical) contingency or technical-economical superiority? One such 'dominance by contingency' may be rooted in what has been called network externalities (suggesting a kind of market failure[2] (Liebowitz and Margolis [1999: 18, 68]). This, for instance, could happen in case of 'network technologies', where the benefits for the customer increase when more people are connected to the technology (as is the case for telephony). Standardization is vital to such technologies, enabling the interaction between different customers or for exchanging software. For instance, different video standards inhibited the use of Betamax-video tapes on a Video Home System (VHS) recorder and vice-versa. Thus, when the competition

[1] We acknowledge the constructive comments of three anonymous referees on a previous version of this article.

[2] Because of this negative connotation Liebowitz and Margolis prefer to use the term "network effects", which sounds more neutral than "network externalities".

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starts with one of the (network) technologies having already more customers, such a technology might become dominant, not so much for its technical superiority, but because interaction with an ever wider range of customers becomes possible. This is a self-reinforcing effect which may even cause members of the competing technology to switch to this faster growing network technology. It might also impede customers of the dominant technology to switch to an emerging technology of much higher quality, just because this technology, by being late, lacks the network effect benefits of which the dominant technology has already taken advantage. The sketched course of events may thus cause a 'lock-in', preventing higher quality products to enter the market successfully.

Another example is the competition between the word processors WordPerfect and Microsoft Word, each using its own standard. Word processors are not used merely for 'autarkic' purposes like making and printing one's own text. Their benefit is substantially increased through the possibility of exchanging digital documents between persons and organizations. Whereas in the second half of the 1980s WordPerfect's quality was considered to be higher than that of Microsoft Word, and WordPerfect was (next to WordStar) the leading word processor, MS-word won out in the 1990s (Liebowitz and Margolis, 1999: 180-194). At first sight this course of events seems to contradict the above sketched path dependency (and accompanying lock-in) through network effects. Liebowitz and Margolis (from now on abbreviated as L&M), however, argue that this turn-over coincided with the change from disk operating system MS-DOS to Windows, where the new MS-Word for Windows was (not surprisingly?) quicker and better to adapt to the new Operating System environment than WordPerfect was able to transform from its Disk Operating System (DOS) version to a Windows compatible program. Indeed, L&M use this as an example for the winning power of quality that, in their view, on the market will always defeat the inferior technology, thus diminishing the relevance of 'lock-in', if existing at all.

Here we are at the heart of a scientific (and political? – see Lewin, 2001) controversy, that is, whether path dependency and lock-in, resulting into the entrenchment of an inferior technology, is more than a theoretical possibility, and actually occurs, or that market processes will always allow (or force) the qualitatively better products to survive, if not to become dominant. The most outspoken exponents of the opposite views are Paul David, well-known for his claim of the occurrence of path-dependency regarding the QWERTY typewriter keyboard (where QWERTY are the first six letters on the keyboard) [David, 1985; 1986] and L&M, contesting this and other claims. L&M support their position by a number of empirical examples, in which the dominant technology always appears to be qualitatively superior (or at least not inferior) to the unsuccessful competing technologies. An extensive review and analysis of this debate has been given by Lewin (2001).

Broadly, path dependency refers to specific technological trajectories generated by economic, technical, and institutional forces (Garud and Karnøe, 2001: 4). L&M don't deny the existence of path dependency and certainly not of network effects. They agree that "history matters". What they do contest is that these phenomena may lead to economic inefficiencies and to inferior products for the consumers. They think that much of the, in their view, erroneous claims made in the path dependency literature as to the dominance of inferior technologies and accompanying economic inefficiencies is rooted in both a sloppy use of the concept of path dependency and the lack of sound empirical data. Therefore, they distinguish three types of path dependency (L&M, 1999: 52-56). A minimal form of path dependency simply refers to durability of decisions made, like buying a house. Even if one has correctly predicted all relevant aspects (income, family size, interest rates, etc.) for the future, the house may still not be always of the desirable size over time (first a little too large, then somewhat too small), but this might have been calculated in when buying the house. This is what L&M call *first degree path dependency.* "Path dependency here does no harm; it is simply a consequence of durability". A *second degree path dependency* occurs when the available information at the time of decision making is imperfect. Then it is possible that decisions, efficient in view of the information available at the time, turn out to be inefficient in retrospect, in light of new information, or by new events. Here the inferiority of a chosen path is unknowable at the time the choice was made. Therefore, according to L&M, "[T]his dependence is not [...] inefficient in any meaningful sense, given the assumed limitations in knowledge." ((L&M, 1999: 54). These two types of path dependency "are extremely common" according to L&M. It is the *third degree path dependency* on which they focus and which applies to the claims of Davis regarding the QWERTY keyboard, and to other claims of technological trajectories leading to the application of inferior technology. In this type of path dependency decisions have been made, while a better alternative was available and while the existence of this alternative was known. Such inefficiencies therefore could have been avoided. "For an inefficiency to be economically relevant there must be some better alternative that is feasible in light of the information that we have at the time we are making a decision." (L&M, 1999: 54). L&M have researched several competing technologies and claim to have found *no* empirical evidence supporting the presence of *third degree path dependency.* In addition to the 'classic' example of the QWERTY keyboard, these include the competition between the VHS and Beta standards in video recording, the competition between different spreadsheets, as well as the battle between various word processors.

This expose now allows us to put our research question more specifically as the question whether the dominance of the TCP/IP standard is the result of third degree path dependency or of choices based on assessments of it being technical-economically superior to the OSI standard and protocols. Framed differently, will this case provide counter-evidence to L&M's position or rather support it? It should be clear that the purpose of this article is not to fully explain all of the dynamics of the battle between the two standards and its outcome, though the article will briefly provide some historical background.

Methodology

One crucial element in L&M's case studies is what quality judgments on the competing technologies were available at the time when choices were made by customers. For, if in spite of available superior technological-economic quality judgments for one technology, most customers chose in favor of the competing 'inferior' technology this might hint at third degree path dependency, and thus, in L&M's terms, at 'market failure'. We will follow L&M's method, by using primarily the quality assessments of experts writing (mainly) for scientific-technical magazines (L&M, 1999: 151, 238). As to the question of market share of the network protocol standards TCP/IP and OSI we will primarily look for either the number of networks or the number of countries using a particular standard, that is TCP/IP or OSI, which seems to be a more suitable measure than, for instance, the number of hosts (computers) connected to the Internet.

Brief Histories of Internet, TCP/IP and OSI[3]

To give context for a more specific comparison of quality assessments of TCP/IP and OSI, we first sketch brief histories of Internet and TCP/IP and OSI developments.

Internet and TCP/IP

In the 1960s, under auspices of the US Defense Advanced Research Project Agency (DARPA), a project was started for connecting computers at several US research centers and universities. By the end of the 1960s, this resulted in the creation of the 'wide-area' network ARPANET, based on a switch (that is, a small 'connection-computer') called Interface Message Processor (IMP). ARPANET turned out to be the earliest forerunner of what later became the Internet. Because of a clear need for a basic computer-communication protocol, the development of a Network Control Protocol (NCP) was started in 1969. In the next years NCP was gradually extended and improved. In 1975, ARPANET itself, mainly used by scientists and engineers, already included more than 100 nodes. In particular the "killer application" of e-mail, released in 1972, caused an explosive growth of traffic on the ARPANET (Mowery and Simcoe, 2002).

ARPANET had been designed without the notion of sending messages to other networks. In 1973, again under auspices of DARPA, Robert Kahn and Vinton Cerf started work on the development of a protocol for interconnecting different packet switching networks so that computers ('hosts') located in different networks could communicate to each other (Norberg and O'Neill, 1996). The system of connected networks was called 'Internet' and the resulting communication protocols became known as TCP/IP, called after the two main underlying protocols, that is, the Transmission Control Protocol (TCP) and the Internet Protocol (IP). The specifications of these protocols were put in the public domain by a publication in the IEEE (Institute of Electrical and Electronic Engineers) Transactions on Communications in 1974. At the same time a new e-mail protocol – Simple Mail Transfer Protocol (SMTP) – was developed that substantially eased the communication with alternative networks, like BITNET and USENET. Since then, the TCP/IP protocols have been extended and further developed, mainly through proposals of the research community: so-called RFCs (Requests For Comment)[4]. In 1981 TCP/IP became the *de facto* protocol of the Internet.

TCP/IP's popularity much increased when, by 1983, it was built in into the UNIX operating system (in particular the Berkeley UNIX version implemented by SUN-Microsystems) which was widely used by universities and research institutes (Hafner and Lyon, 1996: 250; see also box 4, below). Its use further mushroomed through the wide use by universities and research institutes of Ethernet, a local area network

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[3] Used sources: Piscitello and Lyman (1993), Tanenbaum (1997), Casad and Willsey (1998), Peterson and Davie (2000), Egyedi, (1994), Norberg and O'Neill, (1996), Mowery and Simcoe (2002), Cerf et al. (2000).

[4] RFCs are on-line technical documents to be consulted and commented by anyone in order to obtain consensus on a proposed standard.

(LAN) sold by Xerox (and subsequently by3Com) as a commercial product since 1980 (Hafner and Lyon, 1996: 250-251).

In 1983 ARPANET switched from the NCP to TCP/IP communication protocols, implying that not only local networks but also the main *inter*net adopted the TCP/IP as the official standard (Tanenbaum, 1996).

In the US, in the meantime, the National Science Foundation (NSF) deployed a network connecting, among others, five supercomputer centers. NSF played an important role in strengthening the position of TCP/IP, as Mowery and Simcoe (2002) have pointed out: "In 1985, the NSF mandated that any university receiving NSF funding for an Internet connection must use TCP/IP on its network, NSFNET, and must provide access to all 'qualified users'." In subsequent years, NSF continuously and substantially increased the speed of its network 'backbones', causing many institutes to switch from a connection with ARPANET to NSFNET. As a consequence ARPANET was closed in 1989, and its users and hosts transferred to NSFNET.

Internet in Europe

In Europe some regional networks were established in the early 1980s, like the research networks European Unix Network (EUNet) and the European Academic and Research Network (EARN), using respectively the Unix to Unix Copy Protocol and the Network Job Entry protocol. The growth of these networks lagged far behind ARPANET. By the end of the 1980s operators of these networks suggested to switch to TCP/IP. Though Europe often was considered to be a stronghold for OSI, in 1989, the Résaux IP Européenne (RIPE) was created to co-ordinate the organization of Internet in Europe. But, by that time, networks from a large number of European countries, including France, Sweden, Norway, Germany, Italy and the Netherlands were already connected to the NSFNET.

OSI (Open Systems Interconnection)

The 1970s, that is, the early years of computer networks, showed a variety of (business) network architectures, like Systems Network Architecture (SNA) from IBM, Digital Network Architecture (DNA) from DEC and Distributed Systems Architecture from Honeywell (MacKinnon et al., 1990). These networks were technically so distinct that no mutual communication was allowed. In 1977, in view of the growing (need of) data exchange and the accompanying need for an independent network architecture, the International Standards Organization (ISO) started, a project for developing a framework and a set of standards for connecting computers of different types and network architectures. It may be considered as the start of the 'OSI-movement'. Subsequently, this initiative was transferred to Sub Committee 16 (SC16) of the ISO-Technical Committee TC97 that had responsibility for data-processing standardization. The main technical input to SC16 came from the European Computer Manufacturers Association (ECMA), the International Telegraph and Telephone Consultative Committee (CCITT)[5] and the Institute of Electrical and Electronics Engineers (IEEE).

A close collaboration arose between ISO and the CCITT, leading to the joint development of ISO-OSI standards and CCITT recommendations. In 1984 the first version of the Open System Interconnection Reference Model (OSI-RM) was published , designated as *ISO 7498* by ISO and as *X.200* by CCITT. The core of the model is a seven-layered protocol stack, aimed for building 'future-proof' networks, that can mutually communicate (see figure 1). This model and its related OSI-protocols entered into what has been called a 'holy war' with the TCP/IP protocols (Egyedi, 1996).

Because of an increasing overlap in standardization activities for information and for communication technology, ISO and the International Electrotechnical Commission (IEC), established in 1985 the ISO/IEC Joint Technical Committee 1 (JTC1) to co-ordinate their activities for developing joint ICT standards. In the meantime the SC16 activities were redistributed over two sub-committees, notably SC6, responsible for the lower OSI layers and SC21 for the upper layers. Additional sub-committees were developing standards for specific information and communication technology (ICT) themes, like SC18 for the Message Handling System (MHS or X.400) and the Open Document Architecture (ODA) standards.

After the introduction of the first version of OSI-RM in 1984 three additional modules were developed, that is, for Management Framework (X.700), issued in 1992, Security Architecture (X.800), issued in 1989, and for Naming and Addressing (X.650), issued in 1996. Moreover, the original 'connection-oriented' model was extended to include a connectionless[6] model for data transmission. The resulting version was published in 1994 as ISO/IEC 7498-1.

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[5] CCITT is one of the advisory committees of the International Telecommunication Union (ITU). In 1993 it was replaced by the newly created Telecommunication Standardization Sector (ITU-T).

[6] A connectionless service requires no *direct* link, in contrast to a connection-oriented service (compare the post and telephony system)

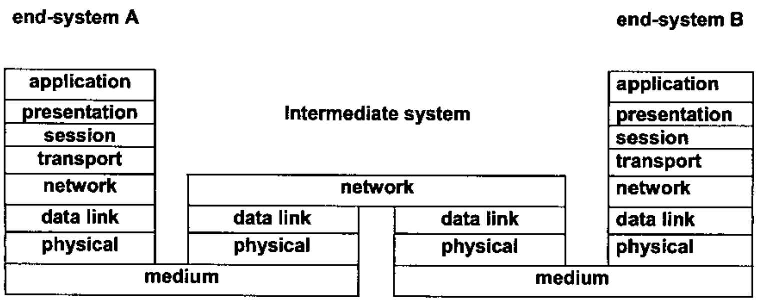

Figure 1. *Protocol stack of the ISO-OSI Reference Model* (Source: Sinderen et al. (1999)

The United States, being the main driving force for developing computer networks, not only led the development of Internet TCP/IP but also supplied the related products. The rest of the world was mainly following. Against this backdrop European governments and the European Union viewed the development of OSI as an opportunity for strengthening their position on the computer and telecom market, for instance by funding research projects aimed at the development and deployment of OSI-based products. According to this policy US made products, like TCP/IP, were ignored, and sometimes even labeled as technically limited and inferior. This policy was further supported by guidelines issued by a number of governments to buy and use only OSI based products. Such guidelines were collected in, for instance, the European Procurement Handbook for Open Systems (EPHOS) for members of the European Union and the Government Open Systems Interconnection Profile (GOSIP) for a variety of other countries (Jurg and Zegwaart, 1995; Egyedi, 1996). Even the government of the United States, the cradle of TCP/IP, issued a GOSIP, to facilitate the integration of OSI-products in government deployed systems, for fear of missing possible useful OSI components. In practice, however, these GOSIPs had little effect.

Quality Assessments of TCP/IP and OSI through the Years

In this section we review the quality assessments of the two competing standards, positioning these assessments within the histories of the previous section. It should be emphasized that, next to considering the 'ideal' architectural models and protocols, these assessments in particular pertain to the real and concrete implementations of the standards and protocols. The impact of the way of implementing a standard on its quality may be illustrated by McConnell's observation (in 1988) regarding OSI: "Efficient implementation has not been addressed at all. The higher layers for interworking have to interact extensively with the local operating system as they carry out OSI functions. Again the choice of implementation strategies may result in excessive costs and performance degradation." (McConnell, 1988: 30). See also box 5 and 6.

Critique and support

When OSI presented itself, it soon came under attack from proponents of TCP/IP. Main arguments against OSI were its technical complexity, its merely theoretical existence and the fact that it had never been tested in practice (Egyedi, 1994). By contrast, it was argued, TCP/IP was rooted in experience, and, indeed, a number of networks using TCP/IP operated perfectly (Piscitello and Chapin, 1993). However, other voices were raised as well, questioning the presumed superiority of TCP/IP, pointing, for instance, at the age of TCP/IP and the little number of adaptations made over the years (see box 1). Such voices were no reason for ARPANET or NSF to reconsider their positions towards TCP/IP. Whereas operating on a TCP/IP network, once connected, might cause little problems, establishing such a connection appeared to be not as unproblematic as was often suggested (see box 2). Nevertheless, when ARPANET closed down in 1989, most regional networks in the US were somehow connected to NSFNET. As we saw, even networks in Europe, the presumed stronghold of OSI, drifted towards TCP/IP rather than to OSI, at the end of the 1980s (see also box 3).

Box 1
For one, TCP/IP is getting a little long in the tooth. The essential services and mechanisms found in all five of the TCP/IP protocols have not changed in over 15 years.
While TCP is functionally as powerful as its ISO cousin (the OSI Class 4 transport protocol) and IP is almost as functionally rich as its ISO cousin (the OSI connectionless network protocol), the application-level programs for file transfer (FTP), electronic mail (SMTP), and remote terminal access (Telnet) are years behind their ISO/CCITT cousins-File Transfer, Access, and Management (FTAM), electronic mail (X.400), and Virtual Terminal Protocol VTP) -- in depth and breadth of features. Secondly, the TCP/IP suite is essentially a static offering. All of the OSI-related protocols are undergoing evolution in response to changes in user demands and to technical progress. New areas not addressed by TCP/IP, such as document interchange and transaction processing, are being pursued in the standards bodies. All of these new developments are designed to be integrated into OSI hosts. In contrast, there are no planned enhancements or additions to the DOD standards.
(William Stallings, *Data Communications*, May 1988)

Box 2
But not all is rosy in TCP/IP land, as several frustrated users have discovered. The different implementations of the protocol can pose serious compatibility problems by the very nature of TCP/IP.
(...) agrees that there are often problems with broader TCP/IP implementations, particularly with Telnet. Often client programs using the Telnet virtual terminal utility for transmitting are not compatible with receivers' Telnet server programs. More headaches. Other problem areas, says Newman are ICMP (...) and some implementations created for use on DEC machines.
Still another interoperability problem arose with connections to Netbios.
(Paulina Borsook, *Data Communications*, August 1987)

Box 3
Despite proclamations that conformance with the seven-layer OSI reference model is inevitable, the renegade TCP/IP continues to thrive. TCP/IP, the homegrown Department of Defence protocol set, has emerged as a de facto standard in both US government and academic networks. And now TCP/IP is even gaining commercial acceptance in Europe, where it was thought most networkers were dedicated to OSI.
(Paulina Borsook, *Data Communications*, May 1987).

This movement towards TCP/IP got much support from, among others, the European Network users (EUNET) because of TCP/IP's current capabilities, which were still lacking with OSI (see box 4).

Box 4
Support is also growing for TCP/IP services, widely used by the Unix community "The users here don't ask whether it's OSI. They just bang on the door saying they want to use this graphics program," says Daniel Karrenberg executive officer of the European network (Eunet). "The [only usable] open protocol suite at the moment is TCP/IP"
Although OSI will come, it currently lacks key offerings like graphics, remote file access, and network management. "It's totally irrational to make the international R&D community wait for international standards," Karrenberg adds.
User demand for TCP/IP support over EUnet is soaring following trials in France, West Germany, Britain, The Netherlands, and Scandinavia.
Besides being cheap, it only requires a Unix operating system and a modem, and basically says Karrenberg, "everyone wants it."
Users have forced the developers of the Netherlands Surfnet X.25 research network to permit the use of TCP/IP services.
Similarly OSI-only rules are being quietly broken by TCP/IP enthusiasts using Britain's Janet X 25 research network, according to one source who asked not to be identified.
(Peter Heywood, *Data Communications*, October 1989)

OSI protocols often a compromise

Whereas the OSI reference model itself is analytically transparent, this is often not true for the OSI protocols constructed. The latter are often the result of compromises between different business and country interests represented in ISO and its subcommittees. One example is the inclusion of the X.25 standard into the OSI protocols. X.25 (in full: ITU-T X.25 Recommendations of ISO 8202) is a standard for getting access to public data networks and had been developed by CCITT before the OSI-RM had been completed. X.25 was subsequently included into OSI to give in to the demand (in this case mainly from CCITT) that existing standards should be incorporated into OSI. But actually this standard is not limited to only one layer. It rather supports services some of which belong to the data-link layer and others to the network layer. It was predominantly the national Public Telecom Operators (PTOs) that offered X.25 services. Various European research networks have used X.25, as did the banks for electronic banking. For the new multi-media applications, X.25 was not suitable, however, because of the much larger bandwidth required.

Transport layer protocols

Likewise, in 1979, ISO and CCITT independently worked on a standard for application in the transport layer. To co-ordinate their activities an ISO working group was established consisting of predominantly members of CCITT and ECMA. Due to conflicting interests it was hard to find one single solution, in spite of all efforts (see box 5).

> ***Box 5***
> *In an effort to bring together diverging views on how OSI standards should be implemented the ISO has invented a new type of norm, called International Standardisation Profile or ISP. (...) It was necessary to do this because OSI standards cater to such a wide range of options-opening almost limitless possibilities for different implementations.(...)*
> *Citing the difference in Class 4 proposals from the United States and Europe, Van den Beld admits that ISO's initiative won't be able to patch over all of the embedded regional preferences. In such cases admits Van den Beld, "we might have to publish two ISPs."*
> (Peter Heywood, *Data Communications*, August 1987)

Finally, and unfortunately, the result became a compromise of five solutions, notably transport classes TP0 till TP4, each class performing part of the task. For instance, error recovery mechanisms in class TP1 and multiplexing in TP2 (Egyedi, 1996: 188).This caused a complicated way of 'internetworking' (see box 6).

> ***Box 6***
> ***OSI compatibility.*** *Will the different versions of the OSI protocol stack permit internetworking? "If we limit the discussion to the protocols themselves, then I think there would be some tweaking necessary," (...) the options available under each layer make internetworking difficult to achieve the first time out.*
> *As the ISO continues to develop OSI protocols, the number and variety of available options also grow. Citing the transport layer as an example, Rosenthal notes that there are "myriad options" within the five available classes of transport service.*
> (Robert Rosenberg, *Data Communications*, May 1987)

To alleviate these problems, methods were developed to allow a kind of 'negotiations' between the different protocol parts. However, the existence of a number of different protocol segments prevented the transport layer to become a solid base for the upper layers (Egyedi, 1996: 190). It also caused problems for testing the protocols in the transport layer (see box 7).

> ***Box 7***
> *Conformance testing notwithstanding, OSI protocols embody so many discrete functions that it's impractical to test the conformance of every permutation. To guarantee the conformance of an OSI transport-layer protocol, for instance, one would have to put it through 100 million different test scenarios.*
> (Peter Heywood, *Data Communications*, March 1987)

Moreover, the OSI protocols of the transport and network layers appeared to be too slow to accommodate future networks. The slowness of OSI protocols appeared to be a rather general feature caused by their complexity and size (a lot of overhead) and became one reason why OSI was associated with inferior technology. This bad image was even reinforced because some functionalities were taken out of the model to lower the costs, which, in its turn, hampered smooth co-operation with different OSI implementations and systems of slightly different configuration (see box 8).

> ***Box 8***
> *To cut down on the costs, some OSI-implementations leave out functionalities that were intended to be part of standard-conform products. For example, there are implementations of File Transfer, Access & Management (FTAM-OSI) that make it impossible to update the same file from different locations - a functionality which is incorporated in the standard. These OSI-implementations are cheaper, but imply a loss of functionality. Such OSI-implementations weigh down the market for OSI-products.*
> (Egyedi, 1994).

Session layer protocols
Conflicting interests also played a role in protocol standardization for the *session layer* (for realizing joint sessions between different machines, such as timesharing or file transfer). CCITT and ECMA followed their own course, developing mainly those parts that were important for their own members. CCITT focused on solutions relevant for Public Telecom Operators(PTOs), ECMA on those most fit for the computer branch. Moreover, no consensus could be reached in the OSI working group dealing with this theme because of conflicting interests of the participating countries. Thus, similar to the case of the transport layer, no single solution could be reached for the session layer, implying that different applications had to use different parts of the session layer (Egyedi, 1996: 190-191).

Application layer protocols
The assessments of the protocols for OSI's application layer show a more mixed picture. CCITT was the first organization that, independently from ISO, developed an e-mail standard, called X.400, which it approved in 1984, whereas ISO was still working on its own standard, called MOTIS (Message Oriented Text Interchange System). In 1986, ISO and CCITT decided to co-operate, and in 1988 a revised version of X.400 was issued by both organizations. Still, again because of conflicting interests, no agreement could be reached on all points. In such cases both solutions were adopted. Thereafter, in 1992, a revised and much improved version of X.400 was issued.

The FTAM protocol (File Transfer, Access and Management) of the application layer was assessed to be superior to the File Transfer Protocol (FTP) of the Internet Protocol Suite (IPS) (see box 9). However, when it came to implementation of actual protocols, FTAM had to give way to FTP.

Box 9
The ISO has produced recommendations for communications protocols that perform tasks in each of the OSI layers. These ISO protocols offer further modularity relative to the current DARPA protocol suite due to their more rigidly defined, layered structure, and offer additional capabilities in the higher layers. The FTAM protocol defined by ISO, for example, provides a significant increase in function over that provided by FTP.
(David Retz, *Data Communications*, November 1987)

Directory services.
The OSI model uses so-called *directory services* for linking Internet users and addresses. Already since the 1970s different networks actually use their own directory services. In order to realize a global and universal addressing system, both IPS and ISO started developing a new directory standard. In the mid 1980s, however, ISO and CCITT joined forces in order to issue a joint directory standard, called X.500 directory service (that is, a database on user information). The first versions were heavily criticized (see box 10), after which a much more extended and improved version was issued in 1992. The directory services from X.500 are now used on the Internet as well.

Box 10
"X.500 has holes" (...). Technically, X.500 is considered as difficult as X.400, the first standard to arise from the applications layer of the OSI model, which has taken seven years to solidify."They had to scale back their initial targets. They just did not have enough time and manpower, (...)".
(Paul Ken, *Data Communications*, November 1987)

Costs
A striking feature is the difference in price of the protocols themselves (apart from implementing them). Whereas TCP/IP standards can be freely downloaded, a relatively large amount has to be paid for each OSI standard[7] (see box 11).

Box 11
I've got some advice for anyone interested in obtaining documentation for the Open Systems Interconnection: Bring your checkbook, it's not cheap!
The high price of information on OSI is in sharp contrast to TCP/IP, where documents cost pennies per page. Cheap documentation, in turn, means that large numbers of students and professionals can buy and learn the standard.
The big difference between TCP/IP and OSI is that the latter is copyrighted by the International Organization for Standardization (ISO), while TCP/IP documentation is in the public domain.

[7] For instance, the price of ISO/IEC-RM (ISO/IEC 7498-1) issued in 1994, is € 100 (as of April 2003).

ISO has produced vital, useful standards, yet by pricing OSI documentation out of the reach of so many potential users, the ISO and ANSI are demonstrating that they're remarkably shortsighted.

(Carl Malamud, *Data Communications*, June 1990)

If, by now the reader may have got the impression that TCP/IP was assessed to be technically superior to OSI in all respects, it is time to correct this image. Firstly, Internet's security status was rather vulnerable (see boxes 12 and 13), and, until 1994 little attention was paid to security issues.

Box 12
Commercial use of Internet is at present (1994, red.) slowed down by lack of provisions for network security. Some measures are available to compensate lack of security. However, these security measures imply expenses and often lessen the useability of Internet. Another threshold for commercial Internet use, is the lack of network control and the lack of guarantees for transmission of critical messages. The reliability of Internet is lower than is normally the case for corporate networks.

(Egyedi, T.M. *Grey fora of standardisation: a comparison of JTC1 and Internet*, November 1994)

Box 13
Government has invested significantly in OSI security initiatives. Implementations of the security features in OSI products, although slow initially, are starting to be available. In the Internet, the IETF now considers security to be its most important area of work, and significant work is underway to define standards for security, and to add security to all major network protocols. With respect to the security situation in the operational Internet, the infrastructure is highly vulnerable to a variety of threats. Most fundamental routing protocols and elements are largely unprotected. Directory services, particularly the Domain Name System, are similarly unprotected.

(Mills, Mulvenna and Nielsen. *Report of the Federal Internetworking Requirements Panel*. 31 May 1994)

Another critique of TCP/IP concerns the addressing and routing problems in the Internet around 1994, caused by its explosive growth (related to the application of the World Wide Web), which threatened to overwhelm the IP addressing room and routing capacity (see box 14). By contrast OSI's internetworking protocol CNLP (Connectionless Network Protocol), that is, the counterpart of IP, does not face this problem.

Box 14
The IPS is currently facing the routing and addressing problem in the Internet. The tremendous growth of the Internet combined with the limitations of the 32bit IP address have resulted in problems that threaten the viability of the existing infrastructure. The problem is two fold. First there is a simple problem of address depletion. IP is simply running out of code-points from which to assign network addresses.
(...) The second critical problem is that of an explosion of routing information within highly connected backbone networks. The lack of ability to encode additional levels into the IP routing hierarchy results in IP addresses being treated as flat identifiers for the purpose of routing.

(NIST *Functional Comparison of the Internet Protocol Suite and the OSI Protocol Suite*, February 1994)

Market shares of TCP/IP and OSI

This section looks at the market development over the years in more detail (anyhow as far as data are available).

By 1994 the fierce competition between TCP/IP and OSI ended, when TCP/IP had firmly established its market dominance over OSI and governments abandoned their 'OSI-only' stance (Egyedi, 1996: 240). Still, in the early years of OSI, when many analysts welcomed the OSI initiative as a promising universal solution for the interoperability problems of computer networks (see box 15), it was not evident that OSI would lose out to TCP/IP (see also boxes 1 and 2).

Box 15
OSI is becoming the dominant force in the arena of networking environments. Its dominance sometimes masks the fact that it is incomplete and has several flaws, but it appears to be a factor that those in the field must come to grips with (12)

The OSI standards appear to be the major force determining the next stage of internetworking and interoperation products (29).

(McConnell, J. *Internetworking computer systems: interconnecting networks and systems*, 1988)

The growth of Internet and increasing use of TCP/IP in the United States has already been sketched in the historical section. After ARPANET and NSFNET were interconnected this growth became tremendous. Not only regional networks in the US became connected, but also networks from Canada, Europe and Australia. In 1990, Internet comprised of 3000 networks and 200 thousand computers. In 1994 there were already several backbones, hundreds of regional networks, tens of thousands of Local Area Networks, millions of hosts and several tens of millions of users.

Until the early 1990s Internet was mainly used by universities and governmental and industrial research institutes. The emergence of World Wide Web (WWW), initially with its browser Mosaic (1993), caused many millions of users to join the Internet. Within one year the number of WWW servers increased from 100 to 700. Figure 2 indicates the growth of the number of networks using TCP/IP.

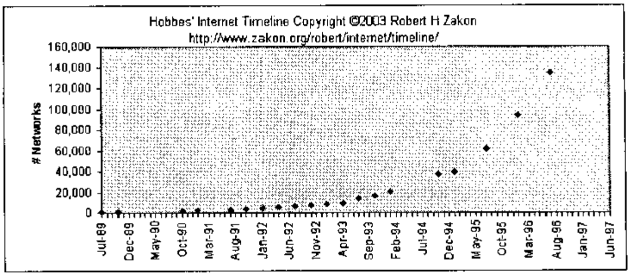

Figure 2. *Number of Internet Networks world wide from July 1989 – August 1996*

It is not so easy to trace the extent to which OSI based products are used. For one, because there are only relatively few and scattered data available (with experts, in the literature, or on Internet), but also because one cannot always unequivocally define a product as being OSI based. For instance, the X.25 standard was developed in the 1970s by CCITT and used in many countries, years before the first initiatives for OSI were taken At a later stage, however, it was incorporated into the OSI protocol suite (see above, subsection *OSI protocols often a compromise*). In such cases, this study will consider these products as being OSI based.

One of the few sources providing data on the spread of OSI is Hobbes Internet Timeline (Zakon, 2003), which shows that the number of countries using OSI increased from 25 to 31 in the period of April 1992 till January 1993, after which the growth stagnated[8]. At the same time the number of countries connected to the Internet kept rapidly increasing (see figure 3). A similar image appears from the work of Larry Landweber (1992, 1994) on network connections in various countries. The rapid growth of Internet, compared to other network types, as well as the switching of networks to the Internet, becomes particularly evident when comparing his pictures of 1992 and 1994 (see figures 4 and 5). Another source (Pinsky, 1992) shows the growing market dominance of the Internet Protocol Suite over OSI in networks used by Multinational Companies (see table 1) around 1990. The traffic share of OSI based products amounts to 2 percent in 1989 and an estimated 4 percent in 1991, whereas these numbers for TCP/IP products are respectively 15 and 18 percent.

[8] At least until 1994. No data are provided for subsequent years.

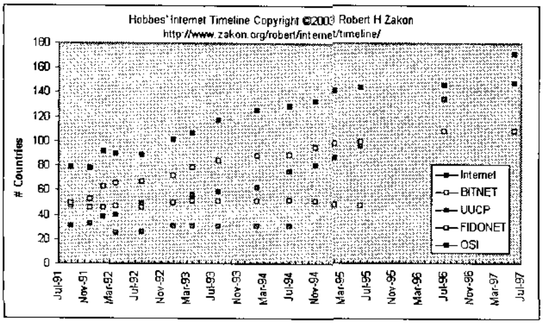

Figure 3. *World-wide growth of Networks from July 1991 – July 1997*

	Current	In Two Years
OSI	2	4
Bisynchronous	4	3
SNA LU6.2	5	7
DECNet	10	8
Asynchronous	8	6
IPX	15	16
TCP/IP	15	23
SNA SDLC/HDCC	33	28

Table 1. *Percentage of Traffic on Protocol, Based on a Survey of 400 Multinational Companies (Source: Business Research Group, of Newton, Massachusetts, as quoted in Pinsky, 1992)*

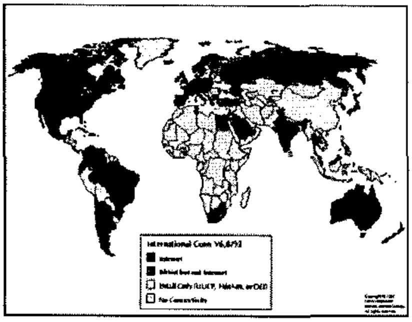

Figure 4. *Worldwide International connectivity in August 1992. (Source: Landweber, 1992)*

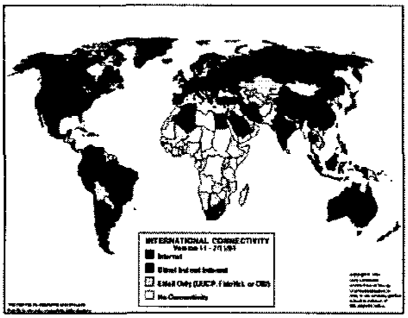

Figure 5. *Worldwide International connectivity in August 1994 (Source: Landweber, 1994)*

The image of a fast growing use of TCP/IP and a stagnating use of OSI, that emerges from the few data available, is confirmed by observations in reports and magazines (see box 16 and 17).

Box 16
'The Internet's core protocol, IP, operates in 62 countries. Look at some market figures which compare the sales of Internet and OSI products in Europe. All this despite well intentioned government interference in free-market economics (e.g. GOSIP). The question isn't Europe versus the United States. The question is political solutions versus engineering solutions.'
(Marshall Rose, 1993, *quoted in: Zegwaart & Jurg, 1994)*

Box 17
Further it seems as if producers lack the will to provide OSI-products. For example, the share of OSI based LAN traffic is very limited (...). In market terms the X.400-based electronic message system is the only successful OSI-product.
(Egyedi, T.M. *Grey fora of standardisation: a comparison of JTC1 and Internet,* November 1994)

The conclusion from this is that by 1994 TCP/IP had won out over OSI, in spite of support for the development of the OSI standard and OSI based products from, in particular, European governments. The victory is most evident from the fact that, in 1994, these governments relinquished their 'OSI-only' stance (Egyedi, 1996: 240). Though initially OSI was assessed as promising, it had not lived up to its promises, at least not in a timely manner, as is apparent from boxes 18 and 19.

Box 18
"Back in 1988, OSI was touted as the Cadillac of open protocols, whereas TCP/IP was the mid-sized economy car," says Bill Biagi, director of information technology at the Corporation for Open Systems International. "But OSI Products have been slow in coming, whereas TCP/IP has evolved and added new capabilities."

(Donne Pinsky, *Communication Week*, 1989)

Box 19
Although OSI has the limelight, developing an OSI specification takes far too long. The time needed to win approval for a specification and then to develop a product that conforms to it is often measured in years. And OSI specifications are still far from complete. Only the bottom five layers have been formally adopted as ISO standards. The remaining layers are still entwined in a time-consuming approval process.
A lot of work remains to be done in the specification of OSI-based services. Areas such as security and network management have received belated attention from standards committees, and they lag far behind the seven-layer protocols developed for computer communications. These lacks will hamper the creation of truly effective OSI operation. No architecture can claim to be complete without addressing the full range of issues and problems that arise in an open environment of different computers.
The long delays in creating standards engender problems that come back to haunt users in the future.

(John McConnel, *Data Communications*, June 1988)

Indeed, according to an observation by the US National Institute of Standards and Technology (NIST), OSI was confronted with an increasingly entrenched Internet, based on TCP/IP (see box 20).

Box 20
The entrenchment of Internet is of fundamental importance to NIST because it impacts longstanding strategic policy calling for a federal information infrastructure whose foundation is the OSI protocol suite. This strategic stance is becoming increasingly tenuous as the Internet grows while OSI standards and products continue to struggle through an agonizingly long gestation period. If OSI products, with competitive prices, had been widely available before the Internet Protocol Suite (IPS) became so solidly entrenched, the situation would, perhaps, be quite different.

(NIST, *Functional Comparison of the Internet Protocol Suite and the OSI Protocol Suite*, February 1994)

This doesn't mean that OSI has disappeared from the scene. From 1990 on the official standardization organizations, like ISO, started to recognize the usefulness of the TCP/IP protocol stack. To avoid a future situation of two distinct standards, co-operation was sought and from 1994 on the collaboration between the Internet Society (ISOC)[9] and JTC1/ SC6 has been formalized. In this way TCP/IP can profit from the long term strategies of OSI. Nevertheless, ISOC continues to develop new products without integrating the comprehensive OSI protocols. Its choice for co-operation was more politically than technologically inspired and primarily aimed for easier acceptance of Internet in the GOSIP programs. But, as Egyedi (1994) has observed, since governments have abandoned their OSI-only policy the need for convergence is less pressing for ISOC.

Path Dependency and Technical-Economic Quality

The empirical material collected above now allows us to answer our research question whether the dominance of the TCP/IP standard is the result of *third degree path dependency* or of choices in accordance with assessments of technical-economic superiority.

Preliminary conclusions

When the OSI movement entered the scene by the end of the 1970s and the OSI-reference model was issued in 1984, the assessments in the literature were positive, not to say enthusiastic, in particular because of the model's long term perspectives for a systematic development of interoperability standards for internetworking. However, when it came to specific protocols it turned out that these were rather complex, containing many compromises, in particular related to lengthy negotiations between a great number of interests represented in the OSI standardization committees. Moreover TCP/IP products were readily available whereas one had to wait long, too long according to comments from analysts, for OSI products. Furthermore, when it came to actual implementations of OSI protocols, these were carried out in great variety, often resulting in new incompatibilities. All this made analysts then turn against OSI. Still, on some points OSI-protocols scored better, in particular as to network security. This, however, was no predominant issue at the time and has been

[9] ISOC was created in 1991 to co-ordinate the TCP/IP policy on the Internet. ISOC is an open organisation in principle accessible to anyone.

valued higher only more recently, that is, after Internet has become an important medium in business and governmental interactions and communication. Table 2 summarizes the technical-economic quality comparisons.

From this it is clear that, at the time one had to choose *and could choose* between network standards and protocols, both the technical and economic quality assessments, in many respects, favored TCP/IP, the standard that actually became dominant. In that respect, the current case supports the Liebowitz and Margolis (L&M) position that qualitative superior products will win out. It does not provide evidence of *third degree path dependency*. At the same time it neither proves that path dependency, network effects and lock-in have *not* occurred. Indeed, it may have, but if so, it did not cause damage in the sense of market or economic inefficiencies that were remedial. Let us have a closer look at these issues.

If there was no third degree path dependency in the TCP/IP trajectory, what about *second degree path dependency*? Certainly, there was no perfect information on all issues when decisions in favor of TCP/IP were made, but it turned out that even in retrospect these decisions were considered to be the right ones. So there was also no matter of second degree path dependency. Moreover, when problems occurred at a later stage, solutions often could be found by extending and transforming relevant protocols. A case in point is the lack of space of the Internet addressing system that emerged in 1994 due to an explosive growth of Internet. This may now be solved by replacing IP version 4 (Ipv4) by IPv6, which implementation is underway since about 2000.

Thus, at most *first degree dependence* may have occurred. That is, though one might have foreseen some future disadvantages of TCP/IP, for instance regarding its relatively low security, this was accepted as being of less importance at the time.

Pro TCP/IP & contra OSI protocols	**Pro OSI & contra TCP/IP protocols**
Technical	
OSI (too) complex – TCP/IP straight forward	OSI's security is considerably better than TCP/IP's security
OSI protocols are slow	Overload of TCP/IP's addressing and routing system
OSI has a great number of possible implementations (due to its comprehensiveness) leading to compatibility problems	OSI protocols were, in principle, more oriented towards long-term future interoperability
Leaving out different parts in OSI implementations (related to its comprehensiveness and costs) causes compatibility problems	
Economic	
TCP/IP standards were for free - OSI standards were relatively expensive	Development and procurement of OSI products were supported by European governments (until 1994)
TCP/IP protocols were available on time - OSI protocols often not	OSI presumed to be a solution for the long term
Availability of wide-spread technical expertise on TCP/IP (due to extensive deployment, i.e. large 'installed base')	
Other	
TCP/IP had proven itself	OSI was often more like a promise
Software makers viewed OSI-protocols as a creation by telecom-operators and the European Union, (image as a bureaucratic product).	

Table 2. *Technical-economic assessment comparison between TCP/IP and OSI*

Discussion of methodology

The focus of this article is on L&M's position that, though theoretically possible, *in practice* no third degree path dependency occurs in an open market situation[10], which would result in the societal embedding of an inferior technology. L&M emphasize that the qualification of 'superiority' includes both technical and economical features (L&M, 199: 238). Superior products or standards, then, are defined as those that the (well informed) consumers, would prefer if they could choose between alternatives. This implies that 'quality' is not a purely intrinsic aspect of a technology, but includes technological features as well as user needs and preferences. One should be watchful using this definition in a sloppy way, because it may easily end up in a circularity regarding the proposition that superior products will prevail on the market. For instance, it may lead to the

[10] One may argue that before the deregulation of the telecom sector in Europe, the condition of an open market was not fulfilled. However, because the national PTT's supported there own and CCITT standards (e.g X.25 rather than IP) this would have counteracted, rather than supported TCP/IP becoming dominant.

conclusion that prevailing products are superior because, apparently, the consumers have chosen this technology rather than another. In case of technologies with network effects, however, the choice of a consumer may strongly have been influenced by the fact that other consumers were already using this technology, which may substantially increase its value to the newcomer. Therefore, it is essential that such network effects are excluded from the definition of technical-economic superiority. Accordingly, L&M define "a standard A to be superior if, for all consumers and *any given market share* the net value of A is higher than the net value of B when B *has the same market share.*" (L&M, 1999: 107; emphasis added). As to computer software quality, L&M argue that assessments by expert reviewers in professional and scientific-technical magazines probably do represent the best information available to consumers and that such experts' judgments will correspond with subsequent experiences by the consumers (L&M, 1999: 238). In our case study we have used this method. Based on scattered statements from network operators, our impression is that L&M's assumption, to a large extent, holds for our case as well. Still, network effects may not always have been filtered out in reviewers' judgments, for instance when they weigh market share or lack of immediate availability in their judgments (see, box 4). Actually, to get more insight in the motives of network managers and operators[11] for choosing TCP/IP rather than OSI standards, our research should preferably be supplemented with interviews, where possible, (with the caveat for distortion of the interviewee's memory of the actual reasons). It might provide more insight into the role of 'quality' (as defined above) in decision making.

Discussion of results

Possibly more interesting than the supposed dichotomy, whether third degree path dependency has occurred or that TCP/IP's dominance is rooted in its higher quality, is the notion that (software) standards often are not static but continuously evolving and improving. In due time, competing standards often incorporate valuable features of each other. For instance, sometimes, when an OSI protocol had clear advantages, these were imported and used on the Internet, as was the case with the X.500 directory services from OSI and CCITT and with the Lightweight Directory Access Protocol (LDAP - an application based on X.500 for dealing with large amounts of user information in an easy way). Therefore, the choice *pro* TCP/IP did not always imply an absolute choice *contra* OSI protocols. Such practices diminish the quality gap on aspects where OSI had better solutions, and substantially dissolve the dichotomy mentioned above.[12] In this way, the dynamic and evolutionary nature of standards may reduce the quality differences between competing standards, thus softening the practical impact of past choices.

The question whether a *lock-in* situation has arisen with respect to TCP/IP is hard to answer. Whereas sticking to the Internet Protocol Suite, but adopting specific technology parts from the competitor may be viewed as a kind of path dependency in the original technological trajectory, it certainly is no prove of lock-in. A lock-in situation implies that the transaction costs of switching to a better alternative would be prohibitively high (Lewin, 2001: 82-83). However, when no better alternative exists, as is the case with TCP/IP according to the reviewers' assessments, such a lock-in is at most latent, and certainly causes no harm. That is, it is irrelevant from the perspective of economic inefficiency.

A clear case showing that network effects not necessarily cause lock-in, is the switch of the Dutch University network SURFNET[13], from the X.25 protocol to TCP/IP (see also box 4). Indeed, the world wide existence of X.25 networks (later becoming part of OSI, see a previous section) implied certain network effects. These network effects, however, did not cause the Dutch SURFNET to stick to this standard of lower quality and prevent it from switching to TCP/IP, in 1992. Another example of the absence of lock-in is the switch of ARPANET from NCP protocols to TCP/IP, in 1983. When TCP/IP entered the scene and was considered qualitatively superior to NCP, which had been operational already for many years, possible network effects of NCP might have prevented ARPANET's switch to TCP/IP. However, it did not, showing that there was no lock-

[11] Regarding network standards, it is mainly the network managers, rather than the end users, who decide on adopting a certain standard. Still, in a competitive market, such decisions have to be to their clients' satisfaction.

[12] Likewise, in the competition between two Dutch banking chipcard standards (around 1995), the 'Chipknip' (of the banks) soon incorporated the same multifunctionality features that gave competing Postbank's 'Chipper' its initial superior quality, thus reducing the quality gap (De Vries and Hendrikse, 2001).

[13] Because of increasing demand by SURFNET (Samenwerkende Universitaire Rekencentrum Faciliteiten network) users for Internet services around 1989, and the opening up of the US Internet to European users, SURFNET made a connection to Internet in 1989. By lack of an Internet backbone SURFNET transported IP-traffic via X.25 (that is, IP-over-X.25). When SURFNET was upgraded to higher capacity networks, it incorporated also an IP-backbone, in 1992, next to the existing X.25 backbone. To counter the "OSI-only" policy of (European) governments at the time, SURFNET even issued a pamphlet (in English) to prove, by hard research data, that 'native IP' was nearly five times faster than the IP-over-X.25 construction (see: '*10 jaar SURFnet*' by the SURFNET organization).

in to NCP, though the transition from NCP to TCP/IP did require a major effort[14]. The choice for TCP/IP, however, may have been reinforced because other networks, in particular the growing NSFNET, gravitated towards the TCP/IP standard.

Finally, TCP/IP's market dominance doesn't mean that all OSI-protocols have been pushed from the market. Apart from the shift towards co-operation since 1994 and the application of specific OSI protocols (like X.500/LDAP) on the Internet, a number of OSI (or OSI related) products are also used in relation to some application niches, as is illustrated by the continued use of X.25 networks for electronic banking, Videotext, and Electronic Data Interchange (EDI) in business (though X.25 may work together with IP). The existence of such niche applications does not necessarily undermine L&M's position that quality will always win on the market. It may turn out that for those *specific* applications, the 'generally inferior' alternative technology still proves to be the best solution. Indeed, in that case, such niche applications would still support L&M's position. X.25 might then be replaced only when a clearly better alternative is offered. Only if X.25 would be assessed as being inferior (to an available alternative) for these niche applications as well, these continued applications might provide evidence for 'lock-in' of those 'inferior' products.

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[14] The transition of the ARPANET host protocol from NCP to TCP/IP as of January 1, 1983 was a "flag-day" style transition, requiring all hosts to convert simultaneously or be left having to communicate via rather ad-hoc mechanisms. This transition was carefully planned within the community over several years before it actually took place and went surprisingly smoothly (but resulted in a distribution of buttons saying "I survived the TCP/IP transition"). TCP/IP was adopted as a defense standard three years earlier, in 1980. The transition of ARPANET from NCP to TCP/IP permitted it to be split up (for security reasons) into a MILNET supporting operational requirements and an ARPANET supporting research needs. (see: http://www.isoc.org/internet/history/brief.shtml)

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