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The long wave of the Internet

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1. Introduction

The Internet technology has radically transformed the computer and communication world, with revolutionary effects on economic and social systems at a global level. Its invention is the result of a collective research effort performed by computer scientists and telecommunications, electrical, software and computer engineers tied together in a sort of loosely coupled community, nurtured by US federal and military research programs. Indeed, between the 1960s and the 1980s a series of key information technologies' innovations have occurred, mainly in the United States of America. Although apparently belonging to different research communities, they appear to have been all relevantly correlated in the development of the Internet. In fact, we can trace a *fil rouge* of cross-fertilization effects across the invention of the fundamental building blocks of the technology, such as the TCP/IP protocol at the Defense Advanced Research Projects Agency (DARPA), the Unix operative system and the C programming language developed at Bell Laboratories, the Ethernet technology at Xerox PARC, and personal computers.

In a diachronic perspective, the evolution of the Internet can be read in two different respects. One restrictively follows its progress as a data transportation networking technology; the other more widely focuses on the multiple applications that have been developed with time on the groundwork laid by its open architectural design.

Within the first approach, the main stages of the Internet's historical path are the invention and first application of the packet switching transmission method in the 1960s, the creation of the TCP/IP protocol suite in the early 1970s, the expansion and privatization of the physical infrastructure of the network across the 1980s and 1990s, the development of independent institutions for its governance (such as the Internet Configuration Control Board, born in 1979 within the DARPA agency and later merged into the Internet Society in 1992), the rise and fall of Internet Service Providers starting from the end of 1980s, the takeover of transport technology by large telecommunications companies and the parallel rise of voice over Internet Protocol (VoIP) in the 1990s, the market differentiation between "backbone" transport and "last mile" providers, and the convergence of telephone, media and data communication systems onto the same network ("network convergence"). Such a trajectory has been consistently characterized by almost continuous unit cost decreases and transport speed increases in time.

The second interpretation follows the commoditization trajectory of the Internet transport services, together with the explosion of applications on the Internet, starting from the email (1971), web browsers, portals and search engines in the 1990s all the way through the social web and, even more recently, edge computing devices, the Internet of Things (IoT) and blockchains (2010s).

These two perspectives can be heuristically fruitful for understanding the historical evolution of the technology, and we will exploit both in the following discussion.

Several contributions have already provided in-depth analyses of the social and economic impacts of the Internet and historical accounts of its development. In this work we will, first, systematically recollect and reframe these contributions from the technological, business and economic history of the Internet into the interpretive framework provided by the evolutionary theories of technical change. More specifically, we will show how the Internet as we know it is the outcome of the evolutionary processes followed by multiple technological innovations both in its transport infrastructure and in the applications grown out of it. Then, we will focus on a selection of such innovations, and illustrate with case-specific evidence that they can be understood and analyzed within the conceptual lenses of *technological paradigms* and *technological trajectories*, while, at the same time, the whole technology system generated by the Internet can be interpreted in the 'macro-technological' framework of *techno-economic paradigms*.

The paper is organized as follows. In the next section, we recall the concepts of technological paradigms, technological trajectories and techno-economic paradigms. Section 3 traces the history of the Internet from the 1960s to the late 2010s, following the abovementioned perspectives on its transport infrastructures and its applications. The historical overview is complemented in Section 4 by mapping the key milestones of the Internet to their core patents, extracted from the United States Patent and Trademark Office (USPTO) database and other sources. Section 5 draws some interpretations on the evolution of the Internet technology, applying the theoretical categories of technological paradigms and trajectories to its specific case. Section 6 concludes.

2. Technological Paradigms, Technological Trajectories and Techno-economic Paradigms: an Overview

The terms "technological paradigm" and "technological trajectory" have been first applied in the theoretical discourse on technical change at the beginning of the 1980s, with the aim of providing a systematic framework for understanding the emergence of technological innovation, the regularities in the accumulation and evolution of technical knowledge, and the sources of variation among different technological fields and different eras of technical progress. The most seminal authoritative exposition of the concepts is Giovanni Dosi's paper "Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change" published on Research Policy in 1982, together with the extensive treatment and application to the semiconductor industry expounded in Dosi (1984). Their intellectual genesis stems from the adaptation to the technological domain of the category of "scientific paradigm" formulated by Kuhn's (1962) *Structure of Scientific Revolutions* for conceptualizing the ways in which scientific theories are born, evolve and eventually get substituted by newer theories.

Following the reappraisals and definitions contained in Dosi and Nelson (2010) and Dosi and Nelson (2016) – from which we draw extensively in the following exposition – a technological paradigm can be defined as a *model* and a *pattern* of solution of *selected* technological problems, comprising "*specific knowledge bases building on selected chemical or physical principles, problem-solving procedures, search heuristics and often also some 'dominant design' of the artefacts produced on grounds of the paradigm itself*" (Dosi and Nelson, 2016, p.1). On the other hand, technological trajectories "*map the relatively ordered patterns of advance in the techno-economic characteristics of products and in the efficiencies in inputs use*" (Dosi and Nelson, 2016, p.1), and represent the pattern of "normal" problem solving activity (i.e. of technical "progress") on the ground of a technological paradigm.

Since the key purpose of technological paradigms resides in the solution of technological problems, it is useful to also provide a definition of the nature of a technology. According to Dosi and Nelson (2010:55), in very general terms a technology can be defined as "*a human designed means for achieving a particular end*"; such means can be represented or embodied by specific pieces of knowledge, recipes and routines, or artifacts, and "technological problems" address the ways in which they can be successfully devised and applied. This notion of a technology's nature and scope underlies the features of technological paradigms, which can be summarized as follows. A paradigm:

(a.) embodies an *outlook*, a definition of the relevant techno-economic problems to be addressed and the *patterns of enquiry* in order to address them.

(b.) entails *specific patterns of solution to selected techno-economic problems*, based on highly selected principles derived from natural sciences.

(c.) involves specific rules for the acquisition of new knowledge aimed at the solution of the abovementioned techno-economic problems, together with specific *heuristics of search*, that shape the modes of innovation and the organizational forms of the firms producing the technology.

(d.) is often (but not always) linked with the emergence of a *dominant design* in the configuration of the specific artifacts or processes at the core of the paradigm.

These features orient the efforts to advance a technology along distinct *technological trajectories*, in which progress proceeds over significant periods of time in certain relatively invariant directions defined by improvements in specific performance measures or characteristics of artefacts and production processes.

Technological trajectories possess two main properties: first, as already stated, they shape and confine the generation of variety within the paradigm from which they originate; second, and relatedly, they work as *uncertainty-reducing representations* for the communities working on it; indeed, since they select the relevant dimensions of improvement of the technology, they allow to project the likely directions towards which it will move in the future, in terms of characteristics and performances. Of course, while they facilitate the *representation* of the possible future, they neither mechanically reveal the proper way to reach the desired improvements (the object of *procedural uncertainty*), nor they can reduce the *substantive* uncertainty related to the future states of the world, both intrinsic challenges of innovative activities.

A practical distinction between two different kinds of technological innovations – "normal" technical progress as opposed to "radical innovations" - can further clarify the meaning of paradigms and trajectories. More specifically, the first category applies to those improvements that occur *within* a given technological paradigm and *along* its technological trajectory; on the other hand, *radical innovations* are those that discontinuously entail a *change* from a previous technological paradigm towards a novel one, characterized by its own new technological trajectory.

Each paradigm has its own technology-specific characteristics, for which the main differentiating features can be attributed to (i) the *technological opportunities* they can seize, that is the nature of the underlying knowledge bases from which they draw and their sources (e.g. scientific research vs. operating experience and learning by doing), and (ii) the *appropriability conditions* of the improvements they generate along their trajectory, that is the extent to which the firms operating within the paradigm can extract economic benefit from innovating.

Notwithstanding the specificity of technological paradigms, their related trajectories often share some common features, mainly (i) a trend towards *mechanization* and/or *automation* of production activities, and (ii) the presence of *learning effects*, empirically described by *learning curves* most commonly denoted by statistical power laws of falling unit costs or increasing productivity following cumulated production.

The framework provided by technological paradigms and trajectories has helped in overcoming the longstanding debate between "demand-pull" and "technology-push" theories of innovation. "Demand-pull" theories – who assumed demand signals coming from the market (such as consumer's needs and desires) to be the "prime movers" of technological innovation – were based on an incorrect understanding of the nature and endogenous dynamics of knowledge, and neglected the empirical evidence refuting such a unidirectionality. On the other hand, "technology-push" theories – maintaining a primary role of the technological supply side for the origination of innovations – did not take into account the importance of signals from the demand side (e.g. market profitability of the innovation, or users' demand for specific improvements) in shaping the direction and evolution of technologies. Technological paradigms emerge, instead, from the "*interplay between scientific advances, economic factors, institutional variables, and unsolved difficulties on established technological paths*" (Dosi 1982: 147). In this respect, innovation is mainly motivated by technological opportunities (opened, for example, by novel scientific advances), whereas economic forces, together with other other institutional and social factors, operate as *selective devices* that determine whether the technology gets established in a market, and influence the rate and direction of its improvement.

The successful establishment and evolution of a new technological paradigm subsequently shape the structure and dynamics of the industry in which it operates. Two broad phases can be recognized. The first one, following the introduction of a new paradigm, is characterized by *Schumpeterian competition*, the process "*through which heterogeneous firms compete on the basis of the products and services they offer and get selected, with some firms growing, some declining, some going out of business, and some new ones always entering on the belief that they can be successful in this competition. Such processes of competition and selection are continuously fuelled by the activities of innovation, adaptation, and imitation by incumbent firms and by entrants.*" (Dosi and Nelson, 2010, p. 96). If, after this creative, "embryonic" stage, the paradigm successfully establishes and reaches maturity, it becomes the standard of the industry, and a second phase of *maturity*, characterized by an oligopolistic structure, ensues, in which less performing firms exit the market and the industry consolidates around a smaller set of major firms each with a larger market share, who drive the "normal", incremental development of the paradigm along its trajectory.

The notions of technological paradigms and trajectories so far illustrated apply well to the study of technologies in a 'micro' perspective, i.e. by taking them as individual, highly specific sets of techniques building on specific knowledge bases to solve specific technological problems. In order to study the Internet as a revolutionary technology *system*, involving several technologies, industries and market segments, it is instead fruitful to introduce the notions of *technological revolutions* and *techno-economic paradigms*, coined by Freeman and Perez (1988). In Perez (2010)'s words, *technological revolutions* can be defined as "a set of interrelated radical breakthroughs, forming a major constellation of interdependent technologies" with two specific features that distinguish them from a random collection of technology systems: (i) "<t>he strong interconnectedness and interdependence of the participating systems in their technologies and markets", and (ii) "<t>he capacity to transform profoundly the rest of the economy (and eventually society)". These revolutions unfold their effects across the entire industrial structure, within which each sector involved can be classified in three different categories: (i) "the *motive branches*, which produce the cheap inputs with pervasive applicability"; (ii) "the *carrier branches*, which are the most visible and active users of the inputs and represent the paradigmatic products of the revolution, carrying the 'word' about the new opportunities: computers, software and mobile phones today, automobiles and electrical appliances in the fourth, steel steam ships in the third, iron steam engines in the second and textile machinery in the first." ; and (iii) "the *infrastructures*, which are part of the revolution in terms of technology and whose impact is felt in shaping and extending the market boundaries for all industries:

internet today, roads and electricity in the fourth, the world transport network in the third (transcontinental railways and steamship routes and ports), national railways in the second and canals in the first." (Perez 2010). *Techno-economic paradigms* identify instead "a best practice model for the most effective ways of using the new technologies within and beyond the new industries. While the new sectors expand to become the engines of growth for a long period, the techno-economic paradigm that results from their use guides a vast re-organisation and a widespread rise in productivity across pre-existing industries." (Perez, 2010)

The overview here presented serves as the theoretical benchmark upon which investigating the nature of the Internet as a techno-economic paradigm, and of its main milestones as a chain of interrelated micro-technological paradigms, asking, for example:

(a.) Which are the scientific knowledge bases from which the Internet has developed?
(b.) What role have the communities of scientists - and the public institutions that hosted them - played in its development?
(c.) Which are the sets of routines and recipes and the search heuristics of the companies that have driven its introduction?
(d.) What has been the lifecycle of the industrial sectors most closely linked to its emergence and development?
(e.) What have been the appropriability strategies put in place by winning companies in the building up of the technology, and what has been their relationships with a strong open source community substantially contributing to its development in the same period?
(f.) How did demand side factors – such as users' explicit requirements, relative prices, market regulation etc. –influence its growth and evolution?

Such a large set of questions represent a whole research agenda, whose breadth cannot be fully covered in the present work. We will limit therefore at putting to test the suitability of the concepts just presented for our study by providing overarching historical evidence, together with more case-specific illustrations for a sample of the Internet's major technological milestones and applications.

3. The development of the Internet Technology

Before reconstructing the history of the Internet technology, it is first useful to introduce a brief description in layman's terms of how the contemporary Internet works, together with some terminology that we will recurrently find in the following exposition.

3.1 How the Internet works: a brief resume

The Internet is essentially a system of *interconnected computer networks* that uses a specific set of rules and standards (the *TCP/IP protocol suite*) to communicate between networks and devices therein contained, and allow to access, share, send and receive information in multiple forms.

In order to better grasp its workings, we can try to follow the "journey" of a typical Internet operation, such as the sending of an e-mail message. In terms of physical infrastructure, the route between the e-mail sender and the email-receiver's devices can be seen as being composed by three fundamental interconnected blocks:

1. The *last mile* of the Internet, that refers to the technologies managed by the so-called *Internet Service Providers*, private organizations who provide connection services to and from the users' devices, such as in homes or offices.

2. The *hubs* or *Internet exchange points*, the locations in which different Internet Service Providers, each operating and overlooking their networks, and individually providing Internet to their clients as final users, connect with each other.

3. The Internet *backbone*, that makes up the large, high-speed, high-volume physical infrastructure of optical fiber trunk lines that cover large distances across countries and continents.

The e-mail journey starts in the *last mile*, once the "Send" button on the sender's device has been clicked. The sender's device then takes the email content and cuts it up in *packets*. These packets are the fundamental unit of transportation across the Internet: indeed, the technological novelty upon which the Internet was built is exactly an information transmission method called *packet switching*. Each packet has a *header* with some additional information – such as where it is from and where it is going, together with a set of rules governing the way in which it travels across the Internet and eventually, together with all the other packets, makes up the full message once it reaches its destination. All these rules go under the name of the TCP/IP protocol, that is the *Transmission Control Protocol/Internet Protocol*. We will illustrate its principles and major components in the second part of this section.

In order to be sent, the content of the e-mail message is transformed in binary information – made by zeros and ones – which can be easily transmitted through various mediums. For example, if the e-mail is sent from a cell phone connected to a Wi-Fi, the cell phone produces sequences of radio waves with two different frequencies, one for the zeros, and another for the ones, and transmits them to the Wi-Fi router.

The router then receives the radio waves and transforms the same binary information in laser light pulses (or, alternatively, pulses of electricity) which, again, "codify" the sequences of binary information, and transmit them through optical fiber cables (or, alternatively, copper wires) towards other routers. The *Internet Service Provider* (ISP) manages this transmission and overlooks each packet's route through the wires from the user's router to its next intermediate destination, which is an *Internet exchange point*. An *Internet exchange point* is a physical location in which different networks, managed by different ISPs, connect with each other. Through the Internet exchange point(s), the e-mail message eventually passes from the sender's network, to her e-mail server's network, then to the receiver's e-mail server's network, and finally to the receiver's device network, from which the e-mail message will be accessed and read. If the sender and the receiver, or their respective e-mail servers, happen to reside in very distant locations, the journey of the e-mail packets will almost certainly pass from the Internet *backbone*, the third, core physical block of the Internet. The Internet backbone is made of a set of fiberglass cables capable of transporting high volumes of data at the highest attainable speed. These cables cover major routes across countries and continents, and connect the latter by means of submarine cables laid on the bed of oceans and seas.

The TCP/IP Protocol

The TCP/IP (*Transmission Control Protocol/Internet Protocol*) is a suite of communication protocols that identify how data travelling across the Internet should be broken down in packets, properly addressed, transmitted, routed and eventually received at destination. Its first formulation has been developed in 1973 by Vinton Cerf and Robert E. Kahn at the DARPA Information Processing Technology Office, to address the need for a common protocol to ensure the network communication of different computers with different operative systems; it is named after the two most important of the protocols it includes: the TCP, which defines how applications create communication channels and manages how a message is broken down to be transmitted and reassembled at destination; and the IP, which defines how to address and route each packet to ensure it reaches the right destination. The TCP/IP suite is designed for network reliability – i.e. to ensure that a message arrives at its destination even if one or more nodes in the network break down - and auto-recovery from failure. Moreover, it can be used by network administrators to establish connectivity with little central management.

The functionality of TCP/IP divides into four layers:

1. the *application layer*, which provides applications with standardized data exchange. These protocols include, for example, the HTTP (HyperText Transfer Protocol), FTP (File Transfer Protocol), SMTP (Simple Mail Transfer Protocol), and SNMP (Simple Network Management Protocol) protocols;
2. the *transport layer*, which maintains end-to-end communications across the network with the TCP protocol;

3. the *network layer*, which manages packets and connects networks to transport the packets across the network boundaries, using IP and Internet Control Message Protocol;
4. the *physical layer*, which comprises protocols that only operate on a link, the component that connects nodes or hosts in the network.

TCP/IP is non-proprietary and easily modified. It is compatible with all operating systems, hardware, and networks, and it is highly scalable.

3.2 A technological history of the Internet

Now that we have clear the most basic functioning of the Internet, we are well equipped to understand its technological history. Following and expanding from Naughton (2016), the historical evolution of the Internet can be periodized in two distinct phases:

- The first era of *non-commercial Internet* (1956-1995), comprising
  - The "pre-history" (1956-1966);
  - The birth and establishment of ARPANET (1967-1972);
  - The "internetwork" based on the newly designed TCP/IP protocol suite (1973-1983);
  - The gradual transition from a military and research network to a "civilian" network (1983-1995);
- The second era of *commercial Internet* (1995-nowadays), comprising:
  - The first Internet Boom (1995-2000)
  - Web 2.0: the invention and diffusion of the Portal and Social Internet Technologies (2000-2008)
  - Web 3.0: the invention and diffusion of Mobile and Semantic Web Technologies (2008-2015)
  - The contemporary developments (2015-nowadays)

Due to its multi-layered nature, such an evolution can be better understood within the lenses of its three fundamental aspects: (i) its properly *technological* evolution, (ii) the operations and management aspect, and (iii) the commercialization aspect. Let us therefore trace a chronological overview of the major events regarding them.

The Internet's evolution: a timeline

The Internet's "pre-historic" phase revolves around the theorization of the fundamental technological novelty that underlies it – i.e., the *packet switching method*.

Before its invention and application, the most efficient way to transmit information between two locations made use of the *circuit switching method*, typical, for example, of telephone communications. With this method, the two locations had to first establish a unique connection on a telephone line, a dedicated channel for the duration of communications, along which information – transmitted in the form of electric pulses – would flow continuously. Packet switching differs from circuit switching in two fundamental respects: (i) first, the information to be transmitted does not flow continuously, but – as we already mentioned in the previous section - is divided in "packets" of binary information, that are put back together at the final destination; (ii) second, and relatedly, the packets need not travel along a unique route between the sender and the receiver, but each of them can arrive at destination following the most efficient route along the multiple paths connecting the two locations. Furthermore, since the packets contain additional information on their origin, destination, and on the sequencing of the message, they do not need to arrive in sequence.

What spurred interest in the invention of a new information transmission method? Here, three institutions come into play: the Rand Corporation (USA), the Advanced Research Project Agency (ARPA) at the United States Department of Defense, and the National Physics Laboratory in the UK.

The Rand Corporation had been established in 1948 as a consultancy think tank for the United States Armed Forces (USAF), and has later become known for its contribution to the management of nuclear arms confrontation with the Soviet Union in the Cold War, more specifically for the doctrine of nuclear deterrence by mutual assured destruction. During the 1950s it built up an environment in which talented researchers could work in relative autonomy and, at the same time, contribute to relevant policy decisions for the US government. In that period, the quality and resilience of the internal military communications system had become one of the main concerns of the defense system; the issue was addressed by Paul Baran, a computer scientist that had joined Rand in 1959. Indeed, as Abbate (1999) recalls, Baran (1990:11) later wrote that

> "Both the US and USSR were building hair-trigger nuclear ballistic missile systems […]. If the strategic weapons command and control systems could be more survivable, then the country's retaliatory capability could better allow it to withstand an attack and still function; a more stable position. But this was not a wholly feasible concept, because long-distance communications networks at that time were extremely vulnerable and not able to survive attack. That was the issue. Here, a most dangerous situation was created by the lack of a survivable communication system."

To address the problem of survivability, Baran developed the concept of "*distributed communications*", a precursor of packet switching theory, exposed in the 1960 RAND paper "*Reliable Digital Communications Using Unreliable Network Repeater Nodes*" (Baran, 1960). In his view,

> “<p>acket switching offered a variety of benefits. [He] was determined to use small, inexpensive computers for his system, rather than the huge ones he had seen in other message switching systems […]. The use of fixed-size packets rather than variable-size messages could simplify the design of the switching node. Another advantage for the military was that breaking messages into packets and sending them along different routes to their destination would make it harder for spies to eavesdrop on a conversation. But the biggest potential reward was efficient and flexible transmission of data. ‘Most importantly,’ [he] wrote (Baran, 1964, p. 6), ‘standardized data blocks permit many simultaneous users, each with widely different bandwidth requirements[,] to economically share a broad-band network made up of varied data rate links.’ In other words, packet switching allowed a more efficient form of multiplexing (sharing of a single communication channel by many users).” (Abbate 1999: 19).

In the same period, the need for a more efficient communications method had arisen also in the United Kingdom. There, it was not motivated by military concerns, but was framed instead in the “white heat” context of catching up projects - formulated in 1963 by the then Labour Party leader, and later Prime Minister, Harold Wilson – with the aim of filling the perceived technological gap between the US and the UK. In such a climate, a novel communications system could serve as a way to allow resource sharing between large, expensive computing devices. Donald Davies, a computer science research at the National Physical Laboratories, theorized to this purpose the “packet switching” method around 1965, a few years later than, and independently from, Baran’s contributions: “Like Baran, Davies saw that packet-switching would allow many users to share a communications link efficiently . But he wanted that efficiency for a different purpose. Packet switching, in his view, would be the communications equivalent of time sharing: it would maximize access to a scarce resource in order to provide affordable interactive computing” (Abbate, 1999:19).

Finally, the ARPA (later DARPA) agency was the “blue-skies” research branch of the United States Department of Defense (DoD). Set up in 1958, in strategic response to the 1957 Soviet Union’s successful launch of the Sputnik, it was devoted to the funding of long-term, advanced research projects in collaboration with universities across the United States. To this purpose, it had funded the purchase and operation of at least a dozen (Naughton, 2016) of expensive mainframe computers to be located in the partner universities. However, as Naughton (2016) recalls,

> “<t>he problem was that these machines were incompatible with one another, and therefore could not function as shared resources for the community of ARPA-funded researchers across the US (Hafner and Lyon 1996, 41). From this came the idea, and the funding, for a network that would enable these valuable resources to be shared. ARPANET (Advanced Research Projects Agency Network) was the result.”

So, while the whole ARPA agenda was established with the purpose of providing long-term ideas and solutions for the Pentagon, the main motivation that kick-started the project was that of resource sharing, more than the direct concern with survivable military communications that had inspired Paul Baran at Rand.

Out of these three institutions, only ARPA eventually engaged substantially with the development of the computer network that later become the Internet, leveraging on funding from the DoD. In what follows, we will pinpoint the major events that have shaped its birth and later consolidation.

The "pre-history" (1956-1966)

1960

- Paul Baran, working at Rand Corporation, publishes "*Reliable Digital Communications Systems Using Unreliable Network Repeater Nodes*" in which he formalizes the concept of "distributed communications"

1961-4

- Leonard Kleinrock, a computer science graduate student at the Massachusetts Institute of Technology (MIT), publishes theoretical contributions on packet switching.

c. 1965

- Donald Davies theorizes packet switching at National Physical Laboratories (UK).

1965

- With ARPA funding, Lawrence Roberts (MIT) and Thomas Merrill try to connect the TX-2 computer in Massachusetts to the Q-32 in California with a low speed dial-up telephone line, creating the first wide-area computer network ever built (Leiner et al., 2004). The attempt works, but it also shows the inefficiency of circuit switching on telephone lines for machine networking, therefore spurring further interest for packet switching.

1966

- Lawrence Roberts joins ARPA to develop the computer network concept, and puts together his plan for the "ARPANET", published in 1967.

The birth and establishment of ARPANET (1967-1972)

1968

- Bolt Beranek and Newman (BBN), a private firm, wins ARPA contract to develop and build the hardware interface for the ARPANET project. The main problem to be addressed is that of communication between different mainframe computers: BBN solves it by building a "sub-net" of identical minicomputers called Interface Message Processors (IMPs), each connected to each other, and linked to a single mainframe "host" at their opposite end.

1969

- The first four nodes of the ARPANET are established and successfully communicate with each other through leased telephone lines. They are located at UCLA's Network Measurement Center, at the Stanford Research Institute (SRI), at the University of California-Santa Barbara and University of Utah.

1970

- "The Network Working Group (NWG) at DARPA, working under S. Crocker finished the initial ARPANET Host-to-Host protocol, called the *Network Control Protocol* (NCP). As the ARPANET sites completed implementing NCP during the period 1971-1972, the network users finally could begin to develop applications" (Leiner et al., 2004). The Network Control Protocol is the first set of rules governing packet switching communications within the ARPANET.

1971

- ARPANET connects 23 nodes.

1972:

- BBN's Ray Tomlinson introduces network *email*, the first fundamental application of the Internet.
- The Internetworking Working Group (INWG) forms to address the need for establishing standard protocols of networking between machines.

The "internetwork" based on the newly designed TCP/IP protocol suite (1973-1983)

While these initial developments at DARPA for the first time put into practice the theoretical novelty of packet switching, the features that will later allow the Internet to obtain its name are still not there, as the ARPANET, with the NCP protocol, allows communications to flow in packets *within* itself, a unique network, and there has still not been an attempt to connect different networks one with each other (*inter-*connect). The opportunity comes soon indeed. At the University of Hawaii a group of researchers had developed ALOHANET, a packet-switched network that operated using *radio* signals instead of electric signals through telephone lines (as ARPANET did). ARPA decides to work on this prototype and creates the PRNET radio network in the San Francisco area. The feasibility of packet-switched communications through *satellite* is also put to test, with the creation of the network called SATNET, also known as Atlantic Packet Satellite Network, developed by BBN to allow communications between ARPA computers in the US and the NORSAR (Norwegian Seismic Array) center in Norway, a strategic US-Norway base established to monitor seismic signs of Soviet nuclear testing. Therefore, as Naughton (2016) recalls,

> "ARPA found itself running three separate 'experimental' networks – ARPANET, PRNET, and SATNET – all of which used packet switching technology, but in different ways. An obvious next step was to see whether a method for 'internetworking' them, so that they functioned as an apparently seamless whole, could be developed. A key challenge for the designers of the new system was to find a way of transitioning from a unitary network like ARPANET to something that could incorporate a variety of different networks that were owned and operated by independent organisations and entities. From a technical point of view, there were various ways of achieving this goal. One was to allow networks wishing to join the new 'internetwork' to retain their existing protocols and simply construct 'gateway' computers that would translate those into a common set of conventions. The other was to require that all candidate networks adopted a new set of protocols, which would become the lingua franca of the new overarching network (Abbate 1999, 128)".

Eventually, the "internetworking" challenge will be won by exploring and adopting the second solution, with the design of the TCP/IP protocol suite, starting in 1972 with the first discussions, officially published in 1974, and established as official host protocol for the whole ARPA in 1983, and later for the NSF-funded NSFNET.

1972

- The emergence of PRNET makes evident the limitations of the NCP host protocol first developed to allow packet switching communication throughout the latter, and stimulates discussions over an "open-architecture" design for computer networks, that will end up with the creation of TCP/IP. As Leiner et al. (2004) recall,

  > "The idea of open-architecture networking was first introduced by Kahn shortly after having arrived at DARPA in 1972. This work was originally part of the packet radio program, but subsequently became a separate program in its own right. At the time, the program was called "Internetting". Key to making the packet radio system work was a reliable end-end protocol that could maintain effective communication in the face of jamming and other radio interference, or withstand intermittent blackout such as caused by being in a tunnel or blocked by the local terrain. Kahn first contemplated developing a protocol local only to the packet radio network, since that would avoid having to deal with the multitude of different operating systems, and continuing to use NCP.
  >
  > However, NCP did not have the ability to address networks (and machines) further downstream than a destination IMP on the ARPANET and thus some change to NCP would also be required. […] NCP relied on ARPANET to provide end-to-end reliability. If any packets were lost, the protocol (and presumably any applications it supported) would come to a grinding halt. In this model NCP had no end-end host error control, since the ARPANET was to be the only network in existence and it would be so reliable that no error control would be required on the part of the hosts."

1973

- First inter-continental network connection is realized: University College of London (UK) and Royal Radar Establishment (Oslo, Norway) connect to ARPANET.
- Thirty institutions are connected to ARPANET.

1974

- Telenet, the first commercial Internet Service Provider, is established.
- Vinton Cerf and Bob Kahn, working within the DARPA Information Processing Technology Office, develop the Transmission Control Protocol.
- "In addition to DARPA, The National Science Foundation (NSF) is actively supporting computing and networking at almost 120 universities. The largest NSF installation is at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. There, scientists use a home-built 'remote job entry' system to connect to NCAR's CDC 7600 from major universities" (Wang and Ledley, 2012).

1979

- By the beginning of 1979, more than 200 computers in dozens of institutions have been connected.
- The Internet Configuration Control Board, ICCB is established by Winton Cerf at DARPA to oversee the standardization of TCP/IP.

1981

- The Computer Science Network (CSNET) begins operation in the United States, with three-year funding (up to 1984) from the National Science Foundation. Its aim is to connect computer science departments at academic and research institutions not directly related to ARPANET. It will play a fundamental role in spreading awareness and interest about the Internet, and contributing to the shift of the Internet from military project to civilian utility.

1982

- The EUnet network (an abbreviation for European UNIX Network) is established. It is the first international UUCP connections under the auspices of the EUUG (European UNIX Users Group). In the 1990s it evolved to the fully commercial entity EUnet International Ltd.

1983

- On January 1, the networks of DARPA transition from the NCP host protocol to the TCP/IP. The protocol suite is also adopted by the Department of Defense, that mandates that all their computer systems would use the TCP/IP for long-range communications.
- Paul Mockapetris creates the Domain Name System (DNS). The DNS addressed the increasing number of computers connected to ARPANET and associated to each IP address a name within a domain (such as .edu, .gov, .com, etc.). As described in *Computer Mail Meeting Notes*,

  > "it was initially the need for a real-world solution to the complexity of email relaying that triggered the development of the domain concept. RFC 805 outlines many of the basic principles of the eventual domain name system, including the need for top level domains to provide a starting point for delegation of queries, the need for second level domains to be unique - and therefore the requirement for a registrar type of administration, and the recognition that distribution of individual name servers responsible for each domain would provide administration and maintenance advantages."[1]

- The Defense Communications Agency decides to split the network into a public 'ARPANET' for civilian research use and a classified 'MILNET' for military purposes, with only 45 hosts remaining on the ARPANET.
- MCI Mail service is launched on September 23 in Washington, D.C. MCI Mail is the first *commercial* email service to use the internet. The service will be officially decommissioned by MCI in 2003.

The gradual transition from a military and research network to a "civilian" network (1983-1995)

Retrospectively, the year 1983 represented a sort of watershed for the history of the Internet in two fundamental respects: (i) first, the separation between ARPANET and MILNET within DARPA allowed ARPANET to grow focusing only on civilian research purposes, neatly separating its trajectory from that of the military; (ii) second, the ARPA efforts to disseminate TCP/IP as the standard protocol for internetworking proved useful for the later explosion of the Internet. As Naughton (2016) recalls, "ARPA funded various operators to create TCP implementations for various operating systems (notably Unix10) and launched a $20m fund to help computer manufacturers implement TCP/IP software on their machines (Abbate 1999, 143). So by 1990, TCP/IP was available for most computers, at least in the US market."

1985

- The National Science Foundation, building on the CSNET experience, establishes the NSFNET, a network of networks connecting academic users across the United States, funding it with 5 million dollars per year. While the ARPANET connected only departments and institutions working for DARPA projects, the new NSFNET expanded the access to the *whole* academic community.

1986

[1] See https://tools.ietf.org/html/rfc805

- The NSF builds the backbone network of NSFNET, to interconnect four NSF-funded regional supercomputer centers and the National Center for Atmospheric Research (NCAR). The "Appropriate Use Policy" enforced by the NSF limits traffic over the backbone to *non-commercial use*, hampering the commercial exploitation of the Internet. Later, the NSFNET continued to grow and provide connectivity between both NSF-funded and non-NSF regional networks, eventually providing the original backbone of the modern Internet in the United States.

1987

- Between the beginning of 1986 and the end of 1987 the number of networks grows from 2,000 to nearly 30,000. In early 1987 the number of hosts passes 10,000 and by year-end there have been over 1,000 RFCs issued. In 1989 The number of hosts increases from 80,000 in January to 130,000 in July to over 160,000 in November. Australia, Germany, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, and the United Kingdom join the Internet.

1989

- The NSFNET, originally comprising 56-kbps links, is upgraded to T1 (1.544 Mbps) links. The migration to a higher quality network was supervised by a consortium comprising Merit (a Michigan state regional network), IBM, and MCI.
- Tim Berners-Lee, a computer scientist working at Geneva's CERN, publishes a project called "Information Management: a Proposal" in which he envisions the creation of a "world wide web" based on hypertext pages.

1990:

- The ARPANET project is officially decommissioned and replaced by a new Defense Research Internet (DRI) for unclassified military information that would make use of NSFNET. Networks that were connected to ARPANET migrate towards the NSFNET backbone too. In twenty years, 'the net' has grown from the original 4 to over 300,000 hosts.
- Following Berners Lee's 1989 project, the development of the first Internet *browser* of history, WorldWideWeb, together with the first *web server* (*httpd*) is launched at CERN and will be concluded in 1991. A *browser* is a software interface that allows users to access information on the web, while the *web server* has the purpose of storing, processing and delivering web pages to the users. As Naughton (2016) recalls,

  > "The Web was the creation of a single individual – the physicist and computer scientist Tim Berners-Lee, who was employed in the late 1980s and early 1990s at CERN […]. The

underlying idea was to develop a way of publishing, locating, and retrieving documents stored on Internet servers across the world, something that would be useful for a large international laboratory like CERN, which had large numbers of visiting physicists and a perennial problem with document control. Berners-Lee's idea was to take an established technology called 'hypertext' – software which created documents with extensive cross-referencing between related sections of text and associated graphics (Naughton 1999, 220) – and make it work across the Internet. In a remarkable burst of creativity at the end of 1990, Berners-Lee created a working prototype of what he dubbed the 'WorldWideWeb', in three months (Berners-Lee 2000, 30–32)."

By October of the same year, Berners Lee, using a Lisp Computer, had written the three fundamental technologies that remain the foundation of today's web:

- HTML: *HyperText Markup Language*. The markup (formatting) language for the web.
- URI: *Uniform Resource Identifier*. A kind of "address" that is unique and used to identify each resource on the web. It is also commonly called a URL.
- HTTP: *Hypertext Transfer Protocol*. A protocol which allows for the retrieval of linked resources from across the web.

By the end of 1990, the first web page is served on the open internet.

1991

- The 'High Performance Computing Act', sponsored by Al Gore, is issued from the US Senate. The National Research and Education Network, or NREN initiative, is created. The purpose of the act is expressed in its third section:[2]

"*The purpose of this act is to help ensure the continued leadership by the United States and high-performance computing and its applications by:*

A. Expanding Federal support for research, development, and application of high performance computing in order to:

1. Establish a high-capacity and high-speed National Research and Education Network;

2. Expand the number of researchers, educators, and students with training in high-performance computing and access to high-performance computing resources;

3. Promote the further development of an information infrastructure of databases, services, access mechanisms, and research facilities available for use throughout the network"

This legislation permits an upgrade in the National Science Foundation's Internet backbone to T3 status speed (45 Megabytes), together with a substantial increase in the number of hosts and networks connected.

[2] Accessed from: https://www.congress.gov/bill/102nd-congress/senate-bill/272/text

- Advanced Network & Services, Inc. (ANS), a non-profit company formed by IBM and MCI, is responsible for managing the NSFNET and supervising the transition to T3 status speed. During this period, the NSF also funds several regional Internet service providers (ISPs) to provide local connection points for educational institutions and NSF-funded sites. Moreover, it lifts the Acceptable Use Policy which previously restricted commercial use of the backbone. Interchanges with PSINET and UUNET are formed.
- Total traffic exceeds 1 trillion bytes. The number of hosts exceed 600,000, connected over nearly 5,000 networks in more than 100 countries.

1992

- The number of networks exceeds 7,500. The number of computers connected passes 1,000,000.
- The MBONE (short for *Multicast Backbone*) for the first time carries audio and video.
- The browser lands in the USA. Building on Berners-Lee hypertext proposal, in the summer of 1992 Marc Andreesen and Eric Bina – two programmers at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana–Champaign – begin working on the development of Mosaic, a *browser* they will release in 1993. Although not the first browser, it will become the one that first popularized the World Wide Web and the Internet, due to two important features: (i) the addition of *graphics* to otherwise only text-based pages, and (ii) the adaptation of the software from Unix computers – used in academia – to Microsoft Windows operative systems (Reid 1997), increasingly accessible and widespread within the general public. It is written in C and best suited for Unix systems, but later adapted for Windows.

1993

- The number of computers connected to NSFNET grows from 2,000 in 1985 to more than 2 million in 1993.

1994

- Inspired by Mosaic, the Netscape browser is launched, becoming the first widely successful commercial browser.
- In June, Netscape develops the Internet *cookies,*[3] included in the version 0.9 Beta of Mosaic Netscape. The first actual use of cookies (out of the labs) was made for checking whether visitors to the Netscape Web site had already visited the site. Lou Montulli, the developer, will apply for a patent for the cookie technology in 1995, and US patent 5774670 will be granted in 1998. Support for cookies will be integrated in Internet Explorer in Version 2, released in October 1995.

[3] See in Google Patents "*Persistent client state in a hypertext transfer protocol, based-client server system*" https://patents.google.com/patent/US5774670A/en.

- Two Stanford students start Yahoo!, a manually constructed "table of contents" for Web sites.

1995-2000: First Internet boom.

Along with a substantial growth in the use and adoption of the Internet, this period was characterized by the massive entry of Internet-related companies in the market around which massive speculation in financial markets ensued, until 2000, when the 'dot-com' or 'New Economy' bubble bursted. The Internet boom run in parallel with the expansion of the Internet Service Provider sector and then by the Browser sector.

1995

- Spyglass, Inc. had previously licensed the technology and trademarks from NCSA for developing their own web browser but never used any of the NCSA Mosaic source code. In 1995, Microsoft licenses Spyglass Mosaic for US$2 million. Then, it modifies it and releases it under the new name of Internet Explorer.
- The Netscape IPO triggers speculative interest around the Internet, inaugurating the Internet commercial boom who will characterize the following five years.
- The original NSFNET backbone is decommissioned, following the implementation of a 1994 NSF plan "to allow Internet service to be taken over by commercial companies known as 'Internet Service Providers' (ISPs), each of which would operate its own backbone, enabling the old NSF backbone to be decommissioned. Customers would connect to one of the companies' backbones, and the ISPs would operate a set of gateways at which a number of ISPs could interconnect their systems, allowing traffic to pass smoothly from one network to another, giving end users the illusion of interacting with a seamless, unitary system." (Naughton, 2016). The commercial Internet is born.
- A prototype of what will become the JavaScript language is integrated into Netscape Communicator in May 1995. Netscape is credited with creating the JavaScript programming language, the most widely used language for client-side scripting of web pages, developing Security Socket Layer (SSL) – that was used for securing online communications before its successor Transport Layer Security (TLS) took over. Marc Andreessen, founder of Netscape Communications and part of the ex-Mosaic team, had the vision that the web needed a way to become more dynamic. Animations, interactions, and other forms of small automation should be part of the web of the future. Consequently, the web needed a small scripting language that could be used by designers rather than software engineers. Java was on the rise as well, and Java applets were to be a reality soon. Indeed, the web was static. HTML was still young and simple enough for non-developers to pick up. Whatever was to be part of the browser to make the web more dynamic should be accessible to non-programmers. The idea of Mocha was born.

Mocha was to become a scripting language for the web. Simple, dynamic, and accessible to non-developers. The developments were picked up by Brendan Eich who then became the father of **JavaScript**. In short time, it was renamed to LiveScript and eventually Java Script.

- The *Apache* web server project begins. Up to this year, the most widespread web server was the public HTTP daemon developed by Rob McCool at the NCSA (National Center for Supercomputing Application), University of Illinois.[4] Starting in 1994, the development of this server had stopped because its author had left NCSA. A group of webmasters therefore began to independently develop patches to this software. A mailing list was created and, at the end of February 1995, the first working group of the Apache Group is formed: eight people take version 1.3 of the NCSA HTTP daemon as a starting point and add a series of patches and fixes. The first public release of Apache, 0.6.2, is released in April 1995. The name Apache arose from the fact that initially the server was simply a collection of *patches* to be applied to the NCSA server and, from the friendly name "a patchy server". Shortly thereafter in version 0.8.8 a new server architecture will be added, which will be given the code name of Shambala. The Apache web server will obtain a large success, with a Version 1.0 published in December 1995, and a Version 2.0 in 2000. The great success of this software is the clearest indicator of the *quality* and *reliability* of this product: according to a 2005 Netcraft survey,[5] on 75 million websites, about 52 million used Apache and in October 2006 the number had risen to 60 million (69.32% of the total). As of today, Apache web server is used by 51.01% of the total registered Italian domains.[6] Operationally, the architecture consists of a daemon - in a UNIX environment - or a service - in a Microsoft. Configuration file, allows access to one or more sites, managing various security features and being able to host different extensions for active (or dynamic) pages.

1996

- Larry Page and Sergey Brin – two computer science graduate students - develop the PageRank algorithm that will underlie the functioning of the Google search engine. Their venture had started in 1994, when the National Science Foundation sponsored their Stanford fellowship to study the web as a collection of pages. Together, Page and Brin constructed an ambitious prototype in their Stanford student offices. The equipment for the prototype, called *Back Rub*, was funded by the DLI project and other industrial contributions. The prototype used well-established technology to *crawl* from page to page by following links. However, in addition to compiling a standard text index, the prototype also mapped out a vast family tree that reflected the Web links among pages. The PageRank method they develop is aimed at providing a ranking of link importance within these web family trees. In short, the method ranks a particular Web

[4] For a comprehensive description see http://apache.org
[5] https://news.netcraft.com/archives/category/web-server-survey/
[6] https://news.netcraft.com/archives/2019/04/22/april-2019-web-server-survey.html

page highly if many other highly ranked Web page link to it. Brin and Page had to solve several complex algorithmic problems, among them system stability, independency of ranking methodologies. A web hyperlink matrix was driven by Graph theory, Random walks and Markov chains, discrete probability models stochastic matrices, finite and infinite Perron-Frobenius matrices, and computations for positive matrices, Ergodic limit-theorems, and Boolean methods (Greenstein 2014). In 1998 Larry Page will patent it with name of *Search Engine Algorithm*. Quoting directly, the patent states that the algorithm

> *"assigns importance ranks to nodes in a linked database, such as any database of documents containing citations, the www or any other hypermedia database. The rank assigned to a document is calculated from the ranks of documents citing it. In addition, the rank of a document is calculated from a constant representing the probability that a browser through the database will randomly jump to the document. The method is particularly useful in enhancing the performance of search engine results for hypermedia databases, such as the www, whose documents have a large variation in quality"*[7]

- The first version of JavaScript is included with Internet Explorer 3.0, released in August 1996.

1997

- Google is launched: the domain *google.com* was registered on September 15, 1997. Originally the search engine used Stanford's website with the domain *google.stanford.edu*.

1998

- The Google company, *Google Inc.*, is formally incorporated on September 4, 1998. By the end of 1998, Google has an index of about 60 million web pages.
- The Internet Corporations for Assigned Names and Numbers (ICANN) becomes the official coordinator for the Internet's DNS structure.
- Internet peer-to-peer file sharing is brought to the market with the launch of Napster in 1998. The software operates as a peer-to-peer file sharing network strictly used for music. The unique location of its server will eventually concur to its shutdown and subsequent demise. But its idea will have penetrated in the general public.

2000

- Google begins selling advertisements associated with search keywords. The ads are text-based to maintain an uncluttered page design and to maximize page loading speed. Keywords are sold based on a combination of price bid and click-through, with bidding starting at $.05 per click.

[7] See in Google Patents "*Methods for node ranking a linear database*" https://patents.google.com/patent/US6285999B1/en

This model of selling keyword advertising was pioneered by Goto.com, later renamed Overture Services, before being acquired by Yahoo! and rebranded as Yahoo! Search Marketing.

2001-2002, a brief timeline of the dot-com bubble crisis

- January 10, 2000: America Online agrees to purchase Time Warner for $165 billion in what would be the biggest merger in history. The company is renamed AOL Time Warner.
- February 2000: The US Federal Reserve announces a strong raise of interest rates.
- March 10, 2000: Nasdaq reaches 5048 points.
- March 15, 2000: Yahoo and eBay merge.
- April 2000: Nasdaq falls 25 % in a week.
- September 11, 2001: the fall of Nasdaq accelerates after the 9/11 attacks.
- 2001-2002: the accounting scandals of Enron, Worldcom and Adelphia unravel.
- October 9 2002: Nasdaq has dropped to 1,114, down by 78% from its peak.

Web 2.0: the invention and diffusion of the Portal and Social Internet Technologies (2000-2008)

The Web 2.0 story starts several years before the end of the dot economy. As we have recalled, between 1994 and 1995, some of the first Web search tools appear on the scene: Brin and Page begin their fellowship at Stanford, two Stanford students start Yahoo!, and other early search engines emerged, such as Lycos and WebCrawler, and begin automatically indexing Web pages, focusing on keyword-based techniques to rank search results.

The history of Facebook, one of the protagonists of this second phase of the Internet age, is in some ways linked to the one of Google, as their basic technological platforms leverage similar languages and algorithms. In 2003, Mark Zuckerberg creates and publishes Facemash, a website that lets Harvard students judge the attractiveness of each other to create rankings. Facebook is launched by February. It has a profile where you could upload a photo, share your interests, and connect with other people. It also offers a network visualization of your connections. Initially it is only opened to people with a Harvard email address; within the first month half of the college students has signed up. Later, it extends to other universities' academic community, and then to the public without restrictions. Facebook's power derives from what Jeff Rothschild, its vice president of technology, calls the *social graph* – the sum of the wildly various connections between the site's users and their friends; between people and events; between events and photos; between photos and people; and between a huge number of discrete objects linked by metadata describing them and their connections. Many of the social network's pages and features are created using PHP, a computer scripting language specialized for simple, automated functions. But Facebook also develops complex core applications using a variety of full-featured computer languages, including C++, Java, Python, and Ruby. To manage the complexity of this approach, the company creates

Apache Thrift in 2007, an application framework that lets programs compiled from different languages work together. Facebook receives 15 million requests per second for both data and connections. Bulked-up cache servers, running Linux and the open-source Mem cache software, fill the gap.

Facebook technologies, like other social networks of the same period, belong to the so-called *Rich Internet Application* or RIA and in general to the Web 2.0 period. As a term, "Web 2.0" had a spike in popularity after a conference in 2004 promoted by O'Reilly Media and Media Live Web 2.0. But what makes it different from from the "Web 1.0"? In the latter, web pages were *static* and the content was *not* user generated. Web 2.0 allowed users to *interact* with each other as well as the content of the web pages. To use an RIA on a website the user must first install the plug-in that the RIA requires. The three most common plug-ins are Adobe Flash, JavaFX, and Microsoft Silverlight. These plugin-based frameworks are on the verge of being replaced by HTML5/Javascript based alternatives. This will make it much more universal so that the user does not have to have more than one plug-in installed on their computer.[8]

Web 3.0: the invention and diffusion of Mobile and Semantic Web Technologies (2008-ongoing)

While the periodization and distinctive features of Web 1.0 and 2.0 are now commonly recognized both in the media and in academia, the later phase of Web 3.0 (and, even more, Web 4.0) are still subject of debate. In fact, it is easier to identify the major differences between Web 1.0 – in which users passively consult web pages and for the most part do not participate in generating content - and Web 2.0 – in which users can create content and interact with sites and with each other through social media, forums, etc. The distinction between Web 2.0 and Web 3.0 is not as clearly defined. The term, coined by the reporter John Markoff of The New York Times in 2006 (Markoff, 2006) refers to a new evolution of the web, its third generation, and includes specific innovations and practices.

More specifically, the 3.0 phase involves the *Semantic Web*, a concept whose vision was anticipated by Berners-Lee in 1999:

'*I have a dream for the Web [in which computers] become capable of analyzing all the data on the Web – the content, links, and transactions between people and computers. A "Semantic Web", which makes this possible, has yet to emerge, but when it does, the day-to-day mechanisms of trade, bureaucracy and our daily lives will be handled by machines talking to machines. The "intelligent agents" people have touted for ages will finally materialize.*' (Berners-Lee and Fischetti, 2001)

In other words, the Semantic Web represents a web of *data* that can be read, interpreted and processed by machines, so that its internal connections are not merely composed by textual hyperlinks established by human intention, but are instead established by machines who read and understand the meaning of the information contained in the nodes of the web, and determine their links accordingly. Indeed, the Semantic Web aims at improving the ability of web technologies to generate, share and connect content

[8] For a comprehensive analysis, see among others: www.technopedia.com/definition/4923/web-3.0

through search and analysis based on the meaning of words, sentences, and texts, rather than on sheer keywords or numbers. Combining this capability with Natural Language Processing techniques, in the Semantic Web computers can begin to understand information in the way humans do, in order to provide faster and more relevant results. They become more intelligent to satisfy the needs of users.

The major aim of the Semantic Web is therefore that of making the Internet machine-readable. In technical terms, this is to be accomplished via specific standards developed within the World Wide Web Consortium (W3C). In this respect, we can identify three main phases in the development of the Semantic Web.[9] During the first, foundational phase, from 2001 to 2005, the W3C trailblazed the establishment of new standards for the future functioning of the Semantic web, and in particular the Resource Description Framework (RDF) standard. RDF was intended to become the basic grammar in which Semantic webpages expressed information, based on "triplets" of subject, predicate, and object.

The basic architecture of the Semantic Web as standardized by W3C is illustrated by the Semantic Web Stack in Figure 1. The layered nature of the stack means that every element described or included in a given layer is compliant with the standards defined at the lower layers.

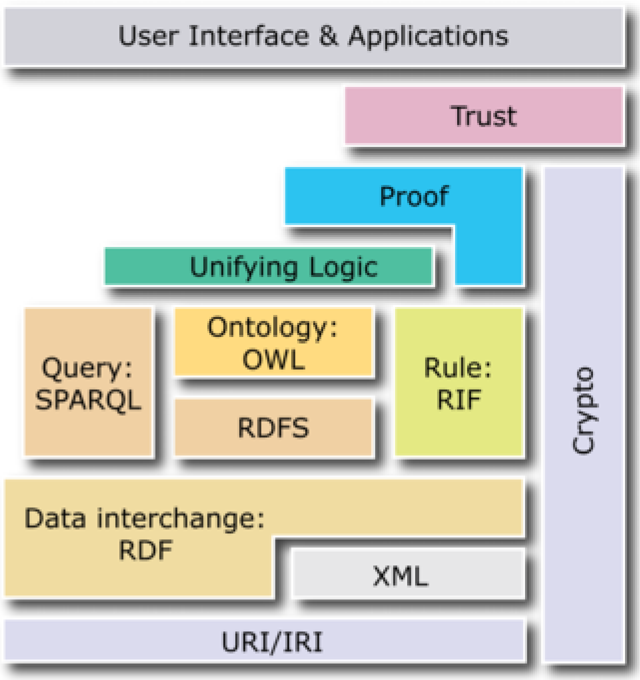


Figure 1 - Semantic Web Stack

Following and quoting the *Resource Description Framework (RDF) Database Systems* guide edited by Curé and Blin (2015), the five fundamental bottom layers of the Stack can be described as follows (from bottom to top layer):

[9] See the resume in https://twobithistory.org/2018/05/27/semantic-web.html, and an informal discussion of the Semantic Web trajectory in https://lists.w3.org/Archives/Public/public-lod/2017Oct/0003.html

1. *URI/IRI*. The lowest layer of the stack; "it provides a global identification solution for the resources found on the Web. In Figure 1 they are referred to as uniform/internationalized resource identifiers (URIs/IRIs). URIs and IRIs are now used interchangeably. […]
2. The second layer supports the definition of a *syntax* that is based on XML, a metalanguage based on the notion of *tags*. Note that XML comes with some associated technologies that enable the definition of schemata for document instances, such as document type definition (DTD) or XML Schema, and a naming convention (i.e., namespaces) is supported to disambiguate the use of overlapping tags coming from different languages.
3. The third layer is qualified as *data interchange* because its objective is to enable the exchange of facts among agents. […]
4. The fourth layer provides a reply to the limitation that RDF represents facts only. With RDF Schema (RDFS), a first solution to define metadata on some elements of an RDF document instance is proposed. The features of this language do not support the specification of very expressive vocabularies, but this aspect is taken care of in the next layer.
5. The fifth layer is composed of the *Web Ontology Language* (OWL). *Ontology* refers to the definition of a domain in terms of its concepts and their relationships. For instance, we can define an ontology for a bedroom where we would find concepts such as bed, mattress, and pillow. Some relationships among these concepts are *on* (to state that a pillow is on a mattress) or *composedOf* (to specify that a bed is composed of a mattress). Of course, ontologies can be defined for domains far more complex than a bedroom, such as medicine or biology. And some of the languages used to define these ontologies have to be more or less expressive. *Expressivity* characterizes the precision with which the concepts and relationships can be defined. OWL enables us to define more expressive ontologies than RDFS does, but it comes at an increased computational complexity of reasoning.

Finally, spreading across layers four and five are *SPARQL* and the *Resource Interchange Format* (RIF). SPARQL is most widely used as a *query language* over RDF data. Therefore, it can be considered as the SQL for RDF stores. RIF supports an inference form that is based on the processing of rules (i.e., prolog and datalog like), and is usually not considered in RDF database systems." (Curé and Blin, 2015, Ch. 3, italics added).

The second phase, from 2005 to c. 2008, was devoted to exploit the theoretical standards and the toy example to create and diffuse large RDF datasets. As the website Two Bit History (2018) recalls,

"*Perhaps the most successful of these datasets was DBpedia, a giant repository of RDF triplets extracted from Wikipedia articles. DBpedia, which made heavy use of the Semantic Web standards that had been developed in the first half of the 2000s, was a standout example of what could be accomplished using the W3C's new formats. Today DBpedia describes 4.58 million entities and is used by organizations like the NY Times, BBC, and IBM, which employed DBpedia as a knowledge source for IBM Watson, the Jeopardy-winning artificial intelligence system.*"

During the third phase, from 2008 onwards, the focus of developers shifted towards adapting the W3C's standards to fit the actual practices and preferences of web developers. Notwithstanding the coordination and development efforts at W3C, the Semantic Web has not still expressed its full potential.

Another, unrelated distinctive feature of Web 3.0 is the diffusion of three-dimensional graphics interfaces on web pages. Museum guides, computer games, ecommerce, geospatial contexts, etc. are all examples that use 3D graphics.

With Web 3.0, information is more connected thanks to semantic metadata. Thus, the user experience evolves to another level of connectivity that leverages all the available information. Content is accessible by multiple applications, every device is connected to the web, the services can be used everywhere.

Finally, during this phase we can begin to appreciate the ever-increasing penetration of the Internet along the entirety of business processes, going above and beyond the facilitation and enhancement of sales and marketing processes.

The contemporary developments (2015-nowadays)

The major contemporary development of the Internet focuses around the *Internet of Things* (IoT), which in its simplest definition, is the connection between humans, computers and things, in a way that moves beyond user-user interaction, towards a direct device-device, computer-object interaction. A recent state-of-the-art of the technology published in IEEE (Suresh et al., 2014) traces a brief history of the concept:

> 'Ever since the birth of the internet in 1989, connecting "Things" in the internet began widely. Trojan Room coffee pot is possibly the first application of this kind. In **1990** John Romkey created the first Internet 'device', a toaster that could be turned on and off over the Internet. WearCam was invented in **1994** by Steve Mann. It had a near-real-time performance using a 64-processor system. Paul Saffo's gave the first brief description about sensors and their future course of action in **1997**. In **1999** The Internet of Things term was coined by Kevin Ashton, executive director of the Auto-ID Center, MIT. They also invented a global RFID-based item identification system in the same year. As a major leap in commercializing IoT, in **2000** electronics giant LG announced its plans of revealing a smart refrigerator that would determine itself whether or not the food items stored in it are replenished. In **2003** RFID was deployed at a massive level in US army in their Savi program. The same year saw retail giant Walmart to deploy RFID in all its shops across the globe to a greater extent. In **2005** mainstream publications like The Guardian, Scientific American and Boston Globe cited many articles about IoT and its future course. In **2008** a group of companies launched the IPSO Alliance to promote the use of Internet Protocol (IP) in networks of "smart objects" and to enable the Internet of Things. In **2008** the FCC approved the usage of the "white space spectrum".'

In **2009**, Google started testing self-driving cars. The launch of IPv6 in **2011** triggered massive growth and interests in this field. Later IT giants like Cisco, IBM, Ericson took a lot of educational and commercial initiatives with IoT. In **2013**, Google Glass was released, only to be later withdrawn due to privacy issues. In **2014**, Amazon released the Echo, the first major commercial smart home hub market. In **2015**, the Global Standards Initiative on the Internet of Things was launched by the International Telecommunication Union (ITU) Telecommunication Standardization Bureau. In **2016**, many companies, including GM, Lyft, Uber, and Tesla started extensive tests on self-driving cars.

The Internet of Things is being developed, and is expected to be further extended, in the areas of urban design and infrastructure management (enabling some "Smart City" features, such as "tracking vehicle parking arrangements, Monitoring seismic vibrations in buildings, tracking pollution levels and radiation levels of a city, managing traffic, disaster recovery, waste management, supply chain management (…)" (Suresh et al., 2014)), security and emergencies, logistics and transport, and both in both domestic and industrial environments (Suresh et al., 2014).

Along the idea of independent and distributed network we can also place *blockchain* technologies.

The first work on a cryptographically secured chain of blocks was described by Haber and Stornetta (1990). In 1992, Bayer, Haber and Stornetta incorporated Merkle trees to the design, which improved its efficiency by allowing several documents to be collected into one block. The first blockchain was conceptualized by a person (or group of people) known as Satoshi Nakamoto in 2008 in the white paper "*Bitcoin: A Peer-to-Peer Electronic Cash System*".[10] It was implemented the following year by Nakamoto as a core component of the cryptocurrency bitcoin, where it serves as the public ledger for all transactions on the network. Thanks to the use of a blockchain, bitcoin became the first digital currency to solve the double spending problem without requiring a trusted authority and has been the inspiration for many additional applications. A blockchain is a decentralized, distributed and public digital ledger that is used to record transactions across many computers so that the record cannot be altered retroactively without the alteration of all subsequent blocks and the collusion of the network.

Following and quoting from Grant Thornton's timeline, we can identify the following recent developments in blockchain technologies.

- "3 January 2009. The first bitcoin transactions – the 'Genesis Block' – are mined.
- 12 January 2009. The first bitcoin transaction takes place (between Hal Finney and Satoshi Nakamoto).
- 31 October 2009. The first bitcoin exchange, the Bitcoin Market, is established.
- 22 May 2010. Bitcoins are used to make a purchase for the first time: two pizzas were bought for 10,000 bitcoin ($25 at the time, approx $46m at Nov '17).
- 9 February 2011. Bitcoin exchange value reaches parity with the US dollar.
- March 2013. Market capitalisation of bitcoin reaches $1bn.
- June 2013. The first major virtual currency theft: 25,000 bitcoin stolen from Bitcoin Forum founder's wallet.

[10] Retrievable at the following link: https://nakamotoinstitute.org/bitcoin/

- December 2013. Vitalik Buterin introduces Ethereum and smart contracts in a white paper. China's central bank bars financial institutions from handling bitcoin.
- February 2014. HMRC in the UK classifies bitcoin as private money: VAT will not be charged on the mining or exchange of bitcoin. Bitcoin exchange Mt. Gox is hacked.
- July 2014. The Ethereum Project is launched via crowdfunding as the first smart contract.
- April 2015. NASDAQ begins a blockchain trial.
- September 2015. Blockchain tech company R3 is founded by a consortium of financial institutions including Barclays, Credit Suisse, Goldman Sachs, JP Morgan and RBS.
- December 2015. The Linux Foundation establishes the Hyperledger Project.
- May 2016. The DAO (Decentralised Autonomous Organisation) sets a crowdfunding record by raising more than $150m investment (11.5m ethers).
- June 2016. The DAO loses a third of its ethers – approx $50m – in a vulnerability attack.
- January 2017. Seven major european banks announce Digital Trade Chain, a partnership to offer a trade finance platform via blockchain.
- April 2017. Virtual currencies are officially recognised in Japan.
- July 2017. Bitcoin exchange Bitthumb is hacked.
- August 2017. The number of bitcoins in circulation reaches 16.5m.
- January 2018. Switzerland to begin accepting tax payments in bitcoin." [11]

Evolution of Internet Transport technologies after year 2000

The Internet had its origins in the development of packet switching in the 1960s and has continued to respond to new technological developments over the last 40 years. The introduction of commercial optical fiber communication in the 1980s in the form of synchronous optical net- working (SONET/SDH) held the promise of vastly increased communication capacity for such networks. The introduction of frame relay, ATM switching, LANs, and, more recently, MPLS added to the mix of underlying transport and switching media over which the Internet can operate. (Cerf 2004, p. 1362).

The diffusion of the Internet, the penetration rate of mobile phones and smartphones, and all the services that utilize networks—such as video distribution services like YouTube, terrestrial digital television (TV), three-dimensional TV, online shopping, and e-government—have exceeded expectations for communication network services and continue to grow. These types of broadband services are supported by terrestrial and wireless communication networks: fiber to the home (FTTH) has brought the optical era to people's homes. High-speed, high-capacity transport technology has contributed greatly in the configuration of these communication networks by cost-effectively accommodating a vigorous 1.5- fold annual increase in traffic. Figure 2 and Table 1 illustrate these developments.

[11] Retrievable at the following link: https://www.grantthornton.global/globalassets/1.-member-firms/global/insights/blockchain-hub/blockchain-timeline_final.pdf

More specifically, Figure 2 – taken from a Bouwfounds's Fiber Optics insight report[12] - shows the trajectories of technical improvements over time of four different transportation media for the Internet, namely Fibre optic, coaxial cables, copper cables and mobile waves.

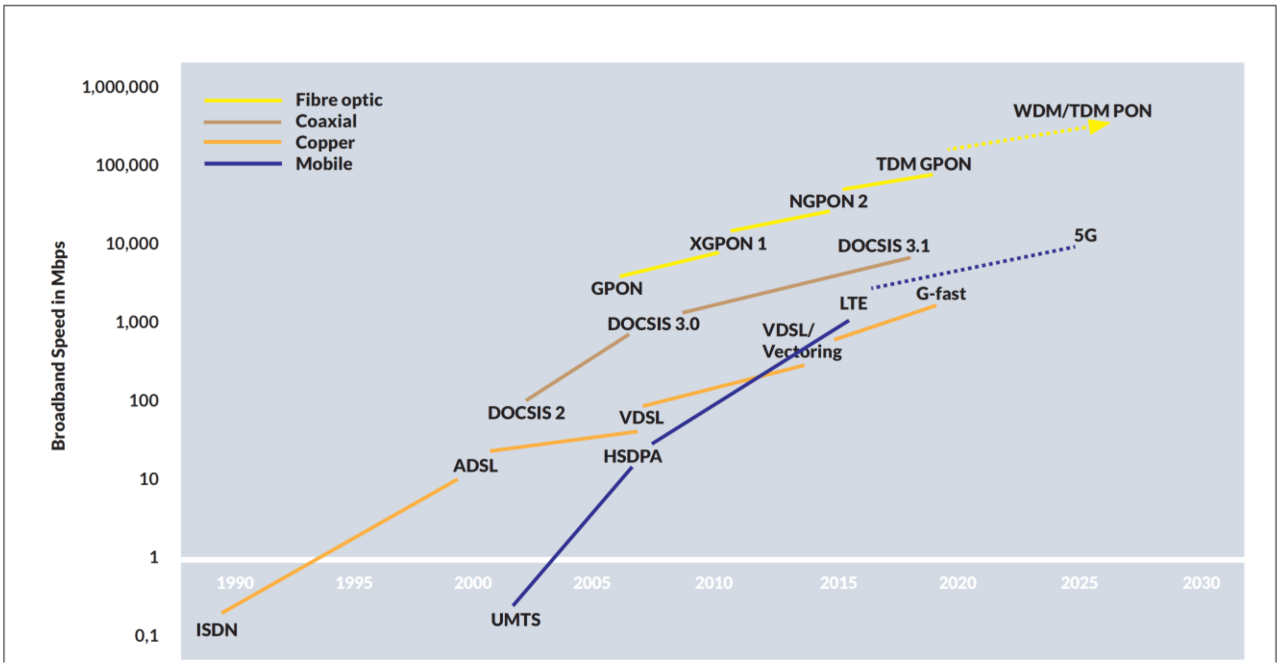


Figure 2 – Trajectories of technical improvements in the data transportation technologies.

Sources:

•State and Future of Broadband Technologies, European Commission, DG Connect (2015)

• Muhammad Yussuf, Selection between DSL and PON, GTP Broadband Batch, Hong Kong (2014)

• DandO_White_Paper, FTTH Council Europe (2014)

Table 1 describes instead the evolution of mobile telecommunication technologies, where it is possible to see that the Internet becomes the communication standard from 4G on.

[12] Retrievable at the following link: http://www.bouwfondsim.com/wp-content/uploads/2017/06/Fibre-optics-21st-century-communication-backbone.pdf

Technology Features	3G	4G	5G
Data Bandwidth	2Mbps	2Mbps to 1Gbps	1Gbps & Higher
Standards	WCDMA CDMA- 2000	Single unified standard	Single Unified Standard
Technology	Broad bandwidth CDMA, IP Technology	Unified IP and seamless combination of broadband. LAN/WAN/PAN and WLAN	Unified and seamless combination of broadband. LAN/WAN/PAN/ WLAN/ and WWWW
Service	Integrated high quality audio, video and data	Dynamic information access, wearable devices	Dynamic information access, wearable devices with AI capabilities
Multiple Access	CDMA	CDMA	CDMA & BDMA
Core Network	Packet Network	Internet	Internet
Handoff	Horizontal	Horizontal & Vertical	Horizontal & Vertical

Table 1 - The evolution of mobile telecommunication technologies

By 4G we define a generation of technologies, or the 4th, which respects certain standards of performance. LTE and LTE+ represent connection formulas progressing toward the performance of 4G. The acronym LTE stands for Long Term Evolution, while LTE + means Long Term Evolution Advance, and is essentially an evolution of the first, characterized by an increase in maximum speeds that can be achieved but is not widely used by users who mainly use the LTE network.

The 4G has reached a base of 326.4 Mbit in download and 86.4 Mbit in upload for LTE only, up to the large numbers achieved by the Advance version, which can get at 500 Mbit / s. The 4G network offers high-level performance, its browsing speed allows to make video calls, watch streaming content and take advantage of other multimedia services.

5G represents the fifth generation technology standard for cellular networks, introduced starting from 2019, and with the potential of upgrading 4G's maximum speed to up to a hundred times.

Correlated innovations

Along with the core hardware and software innovations, several other correlated innovations in electronic equipment and computer science were relevant for the development of the Internet. In particular, we must remember:

- the ASCII standard, that underlies the exchangeability of alpha-numeric information between computer machines from different manufacturers;
- the IBM and DEC computers, whose diffusion enabled the growing demand for computer networking;
- the emergence and diffusion of semiconductors, the fundamental technological building block of computers;

- the UNIX operating system;
- the C programming language.

ASCII

Following the account of Wang and Ledley (2012), in 1963 "a joint industry-government committee develops ASCII (American Standard Code for Information Interchange), the first universal standard for computers. It permits machines from different manufacturers to exchange data. 128 unique 7-bit strings stand for either a letter of the English alphabet, one of the Arabic numerals, one of an assortment of punctuation marks and symbols, or a special function, such as the carriage return."

IBM and DEC

In 1964 "IBM's new System 360 computers c[a]me onto the market and set the de facto worldwide standard of the 8-bit byte, making the 12-bit and 36-bit word machines almost instantly obsolete. The $5 billion investment by IBM into this family of six mutually compatible computers pays off, and within two year orders for the System 360 reach[ed] 1,000 per month" (Greenstein, 2014).

In 1965, "DEC unveils the PDP-8, the first commercially successful minicomputer. Small enough to sit on a desktop, it sells for $18,000 — one-fifth the cost of a low-end IBM/360 mainframe. The combination of speed, size, and cost enables the establishment of the minicomputer in thousands of manufacturing plants, offices, and scientific laboratories." (Wang and Ledley, 2012)

Semiconductors

The birth of semiconductors can be placed between 1941 - when Bell Labs invented the first point-contact transistor, 1961 - when Texas and Fairchild introduced the first Integrated Circuit, and 1971 - when first microprocessors were introduced (Dosi 1992). It has been demonstrated the milestone role of this industry in influencing the whole ICT paradigm.[13]

Unix Operating System

In the 1960s, Dennis Ritchie at Bell Labs (AT&T), along with some of his colleagues, had been working on developing an operating system which could be used by many users simultaneously. This operating system was known as Multics, and it was meant to allow many users to share common computing resources. Multics offered many benefits, but also had many problems so Bell decided to drop the project.[14]

[13] See e.g. Malerba et al., 1999, Perez, 1985
[14] See among others Salus, 1994.

Ritchie later joined Ken Thompson and Brian Kernighan in another project to develop a new *file system*. Thompson developed a new file system, UNIX, for the DEC PDP-7 supercomputer in assembly language and got many features from Multics. To interpret and operate UNIX, the languages Fortran and B were used. It is here that the idea of developing the C language began to form in the minds of its creators (Pal 2017).

C Language. The B language was a useful one in the context of the challenges the creators of UNIX faced with the operating system. UNIX was written in *assembly* language. To perform even small operations in UNIX, one needed to write many pages of code. B solved this problem. Unlike assembly language, B needed significantly fewer lines of code to carry out a task in UNIX. Still, there was a lot that B could not do. Much more was expected from B in the context of rapidly changing requirements. For example, B did not recognize data types. Even with B, data types were expressed with machine language. B also did not support data structures.

It was clear something had to change. So, Ritchie and his colleagues got down to overcoming the limitations. The C language was developed in 1971-73. Note that for all its limitations, C owes its birth to B because C retained a lot of what B offered, while adding features such as data types and data structures. The name C was chosen because it succeeded B. In its early days, C was designed keeping UNIX in mind. C was used to perform tasks and operate UNIX. So, keeping performance and productivity in mind, many of the UNIX components were rewritten in C from assembly language. For example, the UNIX kernel itself was rewritten in 1973 on a DEC PDP-11 (Pal, 2017).

4. Patenting the Internet[15]

The purpose of this section is to provide an introductory assessment of the patenting activity surrounding the emergence, development and consolidation of the Internet technology. The descriptive evidence we will present will serve as a basis for a further in-depth exploration of the Internet patent landscape.

Methodology

We survey the USPTO patent database looking for the following set of fundamental keyboards related to the Internet:

packet switching	URL
TCP	Hypertext Transfer Protocol
IP	HTTP
TCP/IP	browser
UDP	web browser
POP3	cookies
socket interface	security socket layer
Domain Name Server	SSL
DNS	transport layer security
@	TSL
email	page ranking
world wide web	mediagraph
w.w.w.	search engine
HyperText Markup Language	hypermedia database
HTML	social graph
Uniform Resource Identifier	rich internet
URI	HTML5
	semantic web

Table 2 - Internet-related patent keyboards

The extraction of the relevant patents refers to the Internet as a telecommunications technology – focusing therefore on networking equipment – as well as to its applications, on a timeframe covering from 1970 to 2014. The resulting dataset identifies 34.000 companies, and approximately 277.000 patents.

As an introductory disclaimer, we highlight a couple of aspects that define and limit the following analysis: first, the fact that some companies start a consistent patenting activity only sometime after their market success, possibly explaining the scarce presence, if not the total absence, of some recent important Internet companies (such as Facebook) in our dataset; second, the heterogeneity of practices regarding patenting activity and, relatedly, its strategic nature for firms, such that in some cases, for example, large companies

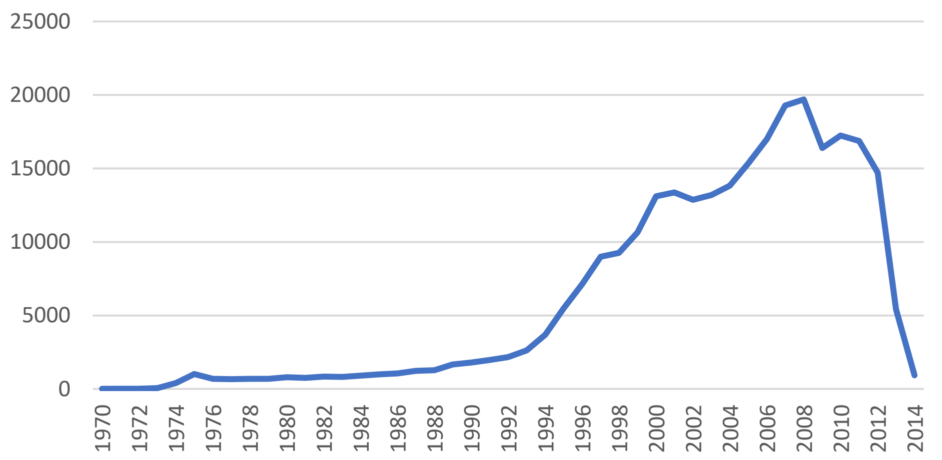
[15] We thank professor Arianna Martinelli for the extraction and elaboration of the patent data in this section from the USPTO database.

may figure having few patents assigned as a result of delegating R&D activity to a set of subsidiaries with a different name.

Time trends in patenting volume

The 1990s are the decade in which Internet patenting takes off, with a steep increase in assigned patents up to the 2000. Such a dynamic may reflect the gradual privatization of the network, with the subsequent lock-in attempts put in place by the dominant companies leading the emerging market at that time. This period is followed by a rather flat patenting rate up to 2004, probably as a consequence of the Internet bubble burst. Patenting activity jumps again from 2004 onwards, reaching a peak in 2007. After that year, patenting starts declining again.

Figure 3 - Number of USPTO Internet patents assigned by year



Analysis by Country

COUNTRY	Frequency	Percentage	Cumulative
USA	188.316	67,87	67,87
Japan	35.326	12,73	80,6
S. Korea	8.674	3,13	83,73
Germany	7.167	2,58	86,31
Canada	7.068	2,55	88,86
Finland	4.511	1,63	90,48
Sweden	4.469	1,61	92,09
France	3.980	1,43	93,53
Taiwan	3.149	1,13	94,66
Great Britain	2.750	0,99	95,65

Table 3 - Breakdown of Internet patent dataset by country

More than 95% of the patents' assignees in the dataset are from a set of just ten countries throughout the 1970-2014 period we consider. More than two thirds of them are from the United States, followed at large by Japan (with 12% of the set), and, even further, by South Korea (3,13 %). The other countries have an ever smaller share of the total.

Analysis by assignee

Making a rough assessment of company presence it appears that:

Telco and Computer Companies are the top patenting ones, looking at patent content transmitting technologies are prevailing. It is confirmed the path of the internet mainly as a networking technology, at least in the period here represented.

Exceptions to this trend are Microsoft (patents almost only on portal technologies), SAP and Oracle (who patents with several brands).

We have also to note that Semiconductors players are not leading the patenting of the Internet. We find a small bunch of semiconductor players into the patent set but not in a leading position.

Table 4 - Top assignees in the dataset (by number of patents assigned)

Assignee	Number of patents	Percentage
IBM CORP	22997	8%
MICROSOFT CORP	12565	5%
GOOGLE INC	4203	2%
SAMSUNG ELECT CO LTD	3944	1%
NEC CORP	3773	1%
SONY CORP	3696	1%
MOTOROLA INC	3629	1%
FUJITSU LTD	3575	1%
QUALCOMM INC	3263	1%
INTEL CORP	3005	1%
CISCO TECH INC	2906	1%
HEWLETT PACKARD DEV CO LP	2783	1%
NOKIA CORP	2779	1%
AT&T INTELLECTUAL PROPERTY I LP	2657	1%
TELEFON AB LM ERICSSON PUBL	2594	1%
SAP AG	2594	1%
HITACHI LTD	2568	1%
CANON CO LTD	2269	1%
APPLE INC	2183	1%
ORACLE INT CORP	2162	1%
BROADCOM CORP	2099	1%
LG ELECT INC	2091	1%
LUCENT TECH INC	2068	1%
SUN MICROSYSTEMS INC	2004	1%
CO LTD TOSHIBA	1871	1%
RESEARCH IN MOTION LTD	1865	1%
MATSUSHITA ELECT IND CO LTD	1649	1%
AT&T CORP	1579	1%
AMAZON TECH INC	1401	1%

Microsoft and IBM collects together 13 % of the whole patent set. In different periods, both have tried to become dominant in the Internet and fail.

Looking at the presence of assignees by decade we can observe IBM forcing patenting around the privatization phase, Microsoft pushing forward around the battle with Netscape, and later, Google affirming itself in the segment of search engines

NEC, Samsung, Fujitsu and other lower ranking among the top assignees seem to show the typical pattern of imitation of the technological leaders.

Table 5 – Top assignees by decade (by number of patents assigned)

COMPANY	COUNTRY	DECADE	PATENT PORTFOLIO	TOTAL NUMBER OF PATENTS IN THE DECADE	C5: SUM OF THE PATENT SHARE OF THE TOP FIVE PLAYER	HHI: LOW VALUES INDICATE LARGE DISPERSION OF THE PATENT SHARES
BELL TELEPHONE LABORATORIES INC	US	70	260	4218	0,1443812	0,0090887
MOTOROLA INC	US	70	108			
TEXAS INSTRUMENTS INC	US	70	86			
IBM CORP	US	70	84			
HITACHI LTD	JP	70	71			
THE UNITED STATES OF AMERICA AS REPRESENTED B	US	70	70			
US PHILIPS CORP	US	70	69			
HEWLETT PACKARD CO	US	70	68			
RCA CORP	US	70	67			
NIPPON ELECT CO LTD	JP	70	66			
IBM CORP	US	80	478	10312	0,1649535	0,0091984
MOTOROLA INC	US	80	408			
NEC CORP	JP	80	297			
HITACHI LTD	JP	80	279			
US PHILIPS CORP	US	80	239			
SHARP CO LTD	JP	80	229			
CO LTD TOSHIBA	JP	80	207			
AT&T BELL LABORATORIES	US	80	188			
PITNEY BOWES INC	US	80	152			
TEXAS INSTRUMENTS INC	US	80	145			
IBM CORP	US	90	4474	53662	0,196545	0,0136894
MOTOROLA INC	US	90	1890			
NEC CORP	JP	90	1520			
LUCENT TECH INC	US	90	1377			
MICROSOFT CORP	US	90	1286			
FUJITSU LTD	JP	90	1096			
AT&T CORP	US	90	973			
SUN MICROSYSTEMS INC	US	90	878			
SONY CORP	JP	90	809			
ERICSSON INC	US	90	751			
IBM CORP	US	0	14271	154090	0,2014667	0,0159456
MICROSOFT CORP	US	0	9409			
SAMSUNG ELECT CO LTD	KR	0	2616			
HEWLETT PACKARD DEV CO LP	US	0	2380			
NOKIA CORP	FI	0	2368			
CISCO TECH INC	US	0	2259			
SONY CORP	JP	0	2142			
SAP AG	DE	0	2105			
QUALCOMM INC	US	0	2089			
INTEL CORP	US	0	1892			
IBM CORP	US	10	3690	55187	0,1831591	0,0117086
GOOGLE INC	US	10	2746			
MICROSOFT CORP	US	10	1870			
APPLE INC	US	10	917			
TELEFON AB LM ERICSSON PUBL	SE	10	885			
SAMSUNG ELECT CO LTD	KR	10	862			
QUALCOMM INC	US	10	849			
AMAZON TECH INC	US	10	805			
AT&T INTELLECTUAL PROPERTY I LP	US	10	780			
BLACKBERRY LTD	CA	10	722			

Top patents

The following tables lists the top 30 patents by number of forward citations in the dataset.

It is interesting to note that the majority of the most highly cited date back to the second half of the 1990s, during the explosion of the commercial Internet. Their assignees are most frequently the telecommunications giant MCI together with Verizon and Worldcomm, the two incumbents who became leader of the Internet Service Provider landscape.

Here a brief review of the content of some of them:

- US7225249 of MCI describes a method of generating an updated graphical user interface and a generator of related metadata.
- US7058600, again of MCI, describes an Intranet/Internet/Web-based data management tool that provides a common GUI enabling the requesting, customizing, scheduling and viewing of various types of unpriced call detail data reports pertaining to a customer's telecommunications network traffic.
- US8073777 interestingly regards a billing integrated business systems for web-based telecommunications management, a clear OSS of the Internet,
- US7447736 is a joint MCI- Worldcomm patent, related to a customer interface system for managing communications services toll free services.
- US6763376 is for an integrated customer interface system for communications network management. In a time of dramatic growth of Internet users it represented an enhancement on network management systems.

patent_numl	publn_auth	publn_nr	nber	uspc	uspc_sub	appl_dt	APPLN_YEAR	han_id	harm_id	appln_id	clean_name	person_ctry_	fwd_cits5
US7225249	US	7225249	22	709	227	24-set-98	1998	1949812	1949812	48267189	MCI LLC	US	2937
US7058600	US	7058600	25	705	34	24-set-98	1998	2078746	2078746	48264869	MCI INC	US	2731
US8073777	US	8073777	25	705	50	27-apr-05	2005	3223455	3223455	47741640	VERIZON BUSINESS GLOBAL LLC	US	2573
US7447736	US	7447736	22	709	203	30-apr-04	2004	1901735	1917849	53721643	MCI COMMS CORP	US	2550
US7447736	US	7447736	22	709	203	30-apr-04	2004	3392676	3392676	53721643	VERIZION BUSINESS GLOBAL LLC	US	2550
US6763376	US	6763376	22	709	223	25-set-98	1998	1901735	1917849	48275921	MCI COMMS CORP	US	2304
US6745229	US	6745229	22	709	206	24-set-98	1998	3316050	3316050	48264877	WORLDCOM INC	US	2279
US8315554	US	8315554	21	455	3	19-gen-10	2010	890338	890338	324059601	DIGIMARC CORP	US	2248
US6714979	US	6714979	22	709	225	24-set-98	1998	3316050	3316050	48264854	WORLDCOM INC	US	2218
US8620685	US	8620685	25	705	2	30-ago-12	2012	2459230	2462270	405243905	ROBERT BOSCH HEALTHCARE SYSTEMS INC	US	2176
US8712790	US	8712790	25	705	2	19-set-00	2000	2456791	2456792	417263325	ROBERT BOSCH GMBH	DE	2176
US6631402	US	6631402	22	709	217	24-set-98	1998	3316050	3316050	48264908	WORLDCOM INC	US	2104
US8155582	US	8155582	21	455	3	19-mar-09	2009	890338	890338	57856122	DIGIMARC CORP	US	2088
US6615258	US	6615258	22	709	223	24-set-98	1998	3316050	3316050	48265655	WORLDCOM INC	US	2071
US8527640	US	8527640	22	709	228	02-set-09	2009	3409782	3409782	273943044	TELESHUTTLE TECH2 LLC	US	2042
US8161172	US	8161172	22	709	228	02-set-09	2009	3409782	3409782	273943438	TELESHUTTLE TECH2 LLC	US	2042
US6587836	US	6587836	25	705	26	24-set-98	1998	3316050	3316050	48264902	WORLDCOM INC	US	2034
US7624028	US	7624028	25	705	3	20-ott-99	1999	1500892	1514790	273458227	HEALTH HERO NETWORK INC	US	2031
US8160968	US	8160968	25	705	77	20-giu-08	2008	890338	890338	55524271	DIGIMARC CORP	US	2029
US6574661	US	6574661	22	709	223	24-set-98	1998	1901735	1917849	48267251	MCI COMMS CORP	US	2003

Table 6 - Top patents by number of forward citations

5. Using Technological Paradigm and Trajectories to interpret the Internet Innovation

Now that we have understood the most important aspects of the Internet history, let us highlight which parts of it fall in line with the framework of technological paradigm and technological trajectories, that we have exposed in Section 1 of this work. Indeed, while the whole technology system surrounding the Internet is better interpreted within the more 'macro' lenses of techno-economic paradigms, within each fundamental component of such a system we can certainly recognize the distinctive features of the 'micro'-technological paradigms and trajectories.

While we leave to future research efforts an in-depth analytical treatment of specific segments and industries of the Internet techno-economic paradigm, here we will focus on a selection of fundamental 'paradigmatic' traits of the Internet development, namely:

1. the radical discontinuity introduced by two of its fundamental features:
    a. packet switching as a novel information transmission method overcoming the limitations of circuit switching;
    b. its 'open architecture' design, that has allowed for fruitful waves of 'innovation to the edges';
2. the emergence of a 'dominant design': the TCP/IP protocol suite;
3. the presence of a set of public policies and institutions that anticipated its emergence, and later allowed its maturation and consolidation;
4. the evidence of trajectories of technical improvement, identified by decreases in cost and increases in speed of the infrastructure.

First, as we have recalled, a technological paradigm comprises "*specific knowledge bases building on selected chemical or physical principles, problem-solving procedures, search heuristics and often also some 'dominant design' of the artefacts produced on grounds of the paradigm itself*" (Dosi and Nelson, 2016, p. 1).

While the analysis of the specific search heuristics involved in the development of the Internet would require further inquiry, the other aspects of the definition suit well the first phases of its emergence. More specifically, the *specific knowledge bases* of the Internet, at its core, are those revolving around the *packet switching* transmission method, which draws from telecommunications engineering for the *hardware* part, and from computer science for the *software* part. The *problem-solving procedures*, as we have seen in the focus on the operations and management side of the Internet history, were those typical of the "wild ducks" working at DARPA, and involved a dense correspondence between the participants of the project, through which opinions about new prototypes were shared and decisions about them - made by rough consensus – were made.

Furthermore, technological paradigms can be understood as embodying a "cognitive outlook", a conceptual framework implicitly or explicitly shared by the actors involved in the emergence of the technology. Although such a definition is relatively difficult to empirically ascertain, the historical narrative tells us that it can apply quite well to the Internet. Indeed, the motivations that had spurred the theorization of packet switching at Rand and NPL, and the first computer networking attempts at ARPA, show that all the pioneering researchers involved had a clear understanding of the technological problems that needed to be addressed in order to make communications more secure, flexible and efficient. This very same perception led to the proposal of packet switching, that ended up representing a radical departing from the previously dominant circuit switching communication method (Kavassalis et al.,1996). The subsequent developments and refinements were often introduced in response to technological challenges arising with the scaling up of the technology. Such a collective understanding of what the Internet was and in which direction it would have gone kept maturing also later, by means of conferences and reports: for example, Leiner et al. (2004, p. 28) recall that

> "<i>n 1994, a National Research Council report, again chaired by Kleinrock (and with Kahn and Clark as members again), Entitled "Realizing The Information Future: The Internet and Beyond" was released. This report, commissioned by NSF, was the document in which a blueprint for the evolution of the information superhighway was articulated and which has had a lasting affect on the way to think about its evolution. It anticipated the critical issues of intellectual property rights, ethics, pricing, education, architecture and regulation for the Internet."

Second, the other discontinuity engendered by the Internet resides in the specific software technology underlying its proper 'internetworking' nature: the TCP/IP protocol suite. Naughton (2016) recalls two of its main features that substantially contributed to the innovative fertility of the Internet: first, the intrinsic affordability of organic growth that it entailed: "as long as a given network 'spoke' TCP/IP (as it were) it was free to join the Internet. And because the system was not owned or controlled by anybody […] there were no gatekeepers to control admission to it."; second, and most importantly, the almost immediate adaptability to novel applications that it allowed: indeed,

> "<t>he designers also faced the puzzle of how to create a network that would be as future-proof as possible, that is, one that could cope with applications that had not been anticipated by the designers. Their solution was to design a system that was not optimised for any particular application (in contrast to, say, the analogue telephone network, which had been optimised for voice calls but proved inadequate for computer-to-computer communication). The Internet, concluded its designers, should do only one thing: it should take in data packets at one end and do its best to deliver them to their destination. It would be entirely agnostic about the contents or purpose of the packets. In this way, all of the ingenuity would be left to users of the network. If someone had an idea that could be realised using data packets, then the Internet would do it for them with no questions asked" (Naughton, 2016)

Such a combination of the modularity, layering and end-to-end connection principles of TCP/IP allowed the "innovation without permission" (Van Schewick, 2012) that characterizes the commercial Internet.

Third, the technological and institutional history that we have delineated in Section 2 highlights the public origin of the Internet, and the role of public institutions and policies – typical of the "well-known unusual mix of institutions and policies that characterized the post-1945 US national innovation system"

(Mowery and Rosenberg 1993) - that acted as fundamental uncertainty-reducing mechanisms and focusing devices for its development.

The 1999 National Research Council book *Funding a Revolution: Government Support for Computing Research* traces an effective overview of the sources of funding and public support for the Internet:

> "Federal funding for research in computer science and electrical engineering has come through several federal agencies whose roles and levels of support have shifted over time. Because of the emphasis it placed on computing as a means of enhancing U.S. military capabilities during the Cold War, the U.S. Department of Defense (DOD) has long been the largest funder of computing and communications research. Early funding came from the Army and Office of Naval Research, but within 2 years of establishing its Information Processing Techniques Office in 1962, the Defense Advanced Research Projects Agency (DARPA) became the dominant source of funding, providing more support for computer science research than all other federal agencies combined. Between 1976 and 1995, **DOD provided some 60 percent of total federal research funding in computer science and over 75 percent of total research funding in electrical engineering** (ibid). With the affirmation of the NSFNET in 1973, the importance of federal funding grew significantly, New York State Education and Research Network, or NYSERNet) and universities to interconnect. The connections program provided 2 years of financial support, after which participants were expected to assume financial responsibility. Under the federal government's National Research and Education Network program, different federal agencies, including NSF, NASA, DOE, DARPA, and the National Library of Medicine, launched or expanded separate, interconnected networking efforts that served specific communities. **NSF's funding for NSFNET grew from $6.5 million in 1987 to $25 million in 1992, during which time the capacity of the backbone was upgraded several times**. With the commercialization of the Internet in 1993, NSF's responsibility for managing the network declined, but it continued to fund development and deployment of high-speed network infrastructure, including the very high speed backbone networking system and the Next-Generation Internet. Expenditures on such network infrastructure reached $42 million in 1996." (National Research Council, 1999)

To further highlight the importance of funding, it is important to recall that during the pioneering phase, there had been several efforts in other countries, notably in UK (the NPL, where Donald Davies coined the "packet switching" term) and in France (with the 1992 Cyclades computer network). However, these attempts did not take off as successfully as ARPANET did, yet it is commonly accepted that DARPA success was not due to a major technological advance but rather to a significant difference in the critical mass of funding. Moreover, it is true that some key invention came from outside the United States (such as HTTP and HTML) but eventually they were imported, streamlined, and marketed in the US, an effective "appropriation" pattern typical of the American National Innovation System (Mowery and Simcoe, 2002). A clear difference from the semiconductor technology path resides in the fact that while in the latter, military spending was favoring large established corporations such as Bell Labs, in this second environment US institution played a more technology-neutral role that in many ways was against US major IT corporations.

As a matter of fact, DARPA procurement strategy and R&D funding orientation often gave autonomy to several centers of excellence such as UCB, MIT, Stanford and others and to small firms such as BBN.

After DARPA's first trailblazing, the testimony of key influencer of the development of the Internet went to NSF who endorsed TCP/IP as standard and similarly pushed for its inclusion in BSD 4.2 Unix, another open source available platform. Up to the early 1990 the coordination effort of the Internet was also supported by Federal funding within the activity of the IAB (Internet Advisory Board). Examining other US federal policies, it is commonly accepted that, while the National Information Infrastructure Plan provide a little of federal funding, the breakup of AT&T mandated ten years before with the 1982 Consent Decree, had a major impact in the future diffusion of VOIP as standard in telecommunication (Cerf 2004). Indeed, "*<a>lthough not anticipated, the Internet's commercial future became linked to both AT&T divestiture and IBM's inability to dominate any market other than its traditional market, large-scale computing*" (Greenstein 2014, p. 37).

This notwithstanding, it was the same NSF that oversaw and determined the final privatization of the Internet backbone, officialized in 1995. Such a decision was due to a series of motivations. First, the awareness that the Internet had become a strong and reliable network where to deploy piles of applications with a great economic potential. Second, the perception that NSF funding were already not sufficient to provide the development of the network, who was projected to furtherly grow in a substantial manner. In other terms, it appears that the privatization of the internet was not due to a takeover attempt by large computer or telecommunication companies who felt the business opportunity, but by the Internet community itself! The inability of large computer and telecommunication vendors to catch and ride the internet opportunity, coupled with the vendor-independent (thanks to TCP/IP) role played by DARPA and NSF have strongly influenced the nature of the Internet trajectory.

Role of US market as conducive environment. As we have already underlined above, military programs, what we can more extensively call the 'Military cluster' (military institutions, R&D centers and universities connected to them) influenced both demand and supply side of the internet, at least until the privatization. The approach of DARPA – pragmatic and vendor-independent – has been fundamental in shaping the direction of technical change, its fundaments, and its boundaries. After a first phase, the one that we can place between 1960 and 1985, the US market has been a very conducive environment and a powerful incentive to further technological innovation.

How did consumers and demand-side factors later influence Internet evolution from a scientific practice to a huge market? During the 1990s, the relationship between innovative leadership of US internet companies and a favorable market environment produced a sort of virtuous circle that helped the development of a very solid industry, at least in terms of number of connections, data centers, IT applications enabled and sheer quantity of people, technical practitioners as well as general public, involved. Mowery and Simcoe (2002) quote data from US Department of Commerce stating that expenses in software and information technology accounted for a total of 24 % of US private investments in 1970, and ITs share of annual private sector investment flows grew during the next thirty years, reaching US$ 542.2 billion (1996 dollars) by 1999. In parallel with the US internal demand, a second extremely powerful market factor that affected the development of the internet from the privatization onwards was *venture capital*. The huge difference in size of funding, power to drive the development of companies, capability to select winning companies of the VC funding industry in the US with respect to other countries has been playing a pivotal role from the Netscape IPO on. As the industry became more established, VC players took the leadership as key factors in transforming inventions (such as the one of cookies, or that of mediagraphs) first in areas where to push start-ups to invest their efforts, and then in selecting the best companies after the seeding phase. At the same time, they often set the stage for some of the most dangerous technology hypes such as the one of dotcom economy, then the one of social web, and in recent times the one of bitcoins.

In sum, private-sector institutions played a key role in the *expansion* and *maturation* of the Internet. As an example, privately financed R&D brought to the scene Unix and Ethernet, two extremely relevant innovation who heavily drove the development of TPC/IP (Mowery and Simcoe, 2002). Moreover, there was a strong investment flow driven by the US Information Technology industry that acted as positive background for the development of subsequent networking industry leaders such as Novell and Cisco, as well as ISPs such as AOL and Compuserve.

Collective invention

Differently from many others radical innovation we can say that the Internet was a sort of collective invention (Allen, 1983) of different research communities, in some ways connected with US military or government programs. One of the key common features of these communities was the sharing of results for the sake of collective benefit. The theoretical concept of packet switching became operational as a groundbreaking way to transfer data from and to supercomputers. Initially there were quite a few Universities and the military to leverage the Internet to exchange data and mails; then, the same initial institutions worked to manage its privatization. This collective approach has remained a common way of operating up to our days in several coordinating entities, research and software development communities. We can find similar approaches for Apache, Linux, the C language and Blockchain. Looking at these phenomena with the eyes of Schumpeterian theory, we can argue that together with the Internet, they belong to the so-called *creative disruption* process that leads to new market leaderships.

Non-proprietary, General purpose, end-to-end and platform technology.

Like many other technologies in the computer industry, the Internet has been for a long time considered as a **platform**, a standard bundle of components with the characteristics of being modular and scalable. In the computer culture the concept of platform is strongly correlated to the idea of open source and collective invention (on the concept of Internet as platform see Hafner and Lyon, 1996). A second groundbreaking concept was the one of projecting the Internet as **end-to-end networking** solution meaning that intelligence and applications were not placed at the routing level but at the end of the network, notably at servers and personal computer client level (see the technical paper of Saltzer, Reed, and Clark, 1984 and the already mentioned work of van Schewick, 2010). End-to-end was conceptually opposite to the common mainframe and telecommunication architecture, and its choice has been influential in all the subsequent developments of the Internet, including the recent edge computing and Internet of Things novelties. A third key innovative feature of the Internet is around the design concept of **General Purpose Technology (GPT).** Several authors have been studying this kind of innovations since the steam industry (see for instance Rosenberg and Trajtenberg, 2004). A GPT in computer science is not the one built for vertical application, but suitable for many variations of them. A GPT can become an **Industry standard** itself. When the Internet was born there was little choice between the networks to use. One could choose among proprietary SNA (IBM) or DECNET (Digital). As Cerf (2004) recalls, "*To avoid being constrained to a single vendor's equipment and networking technology, DARPA set out in 1973 to develop a nonproprietary networking standard that would support computer-based command and control. It called the project Internetting*".

Finally, technological trajectories entail the presence of *learning effects*, characterized by increasing speed, increasing reliability and decreasing costs. These learning effects have been appreciated in the infrastructural part of the Internet. For example, Figure 3 describes the sustained increase in average speed of the U.S. Internet, where between 2007 and 2018 the average Internet speed has grown from 3609.31 kbps to 18747.58 kbps. Figure 4 describes a more general evolution of the maximum Internet bandwidth attainable from 1983 to 2019.

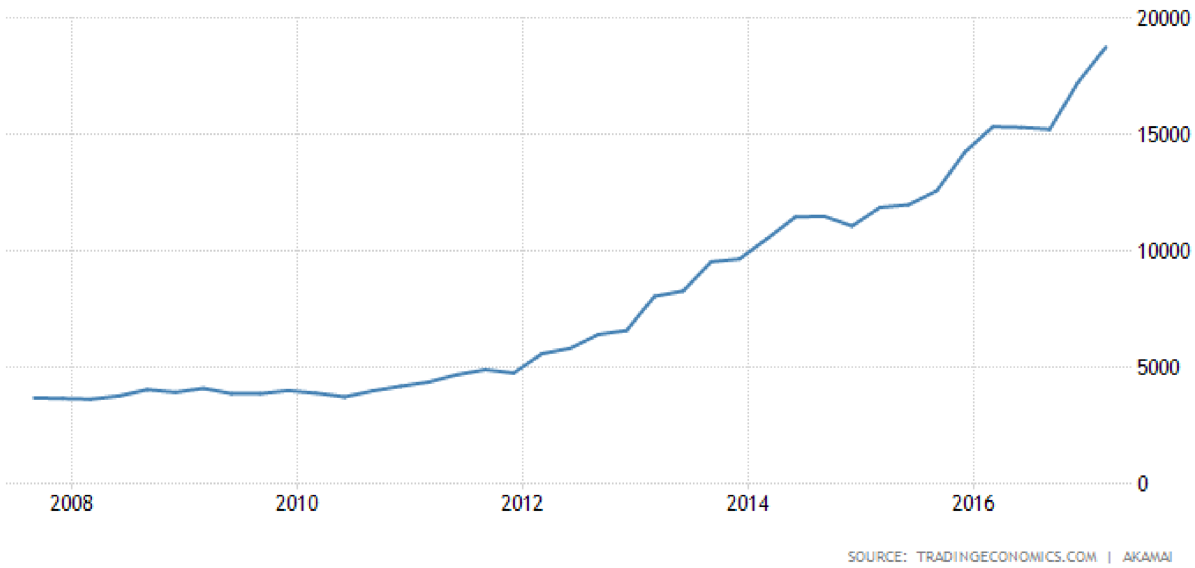


Figure 3 – USA 2007-2018. Average Internet Speed

Source: TradingEconomics.com, accessible at https://tradingeconomics.com/united-states/internet-speed

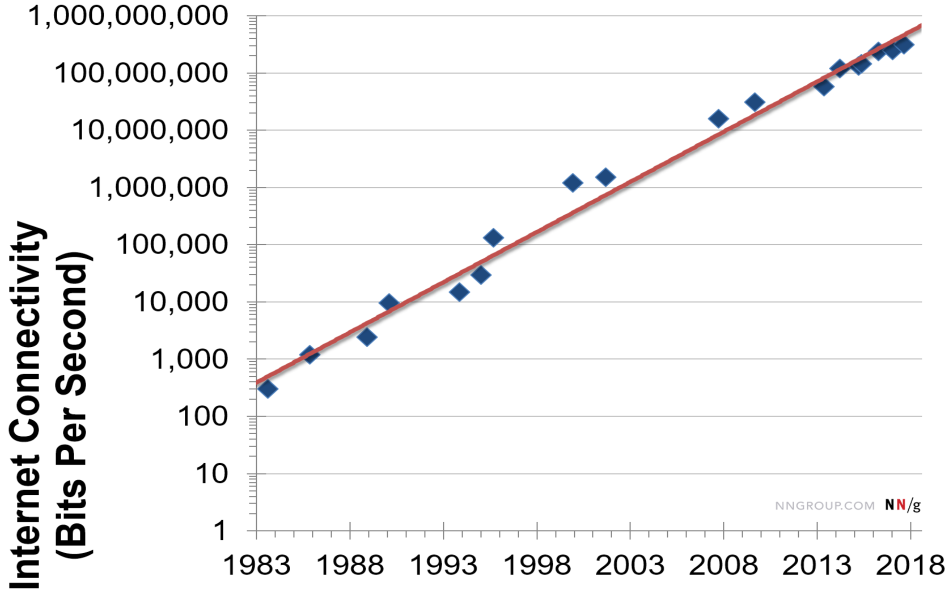


Figure 4 – Nielsen's Law of Internet Bandwidth

Source: Nielsen (2019)

Evolution of Internet connectivity speed, from an early acoustic modem speed at 300 bps in 1984 to 300 Mbps in 2018. As the y-axis of Figure 4 is logarithmic, the straight line fit almost perfectly the 50 % year on year exponential growth curve stated by the Nielsen Law, the Internet "counterpart" of the Moore's Law found in semiconductors (Moore, 1965). Technical analyses state that the Nielsen Law grows at a slightly lower rate than the Moore Law (for this analysis see Nielsen, 2019).

Table 7 and Figure 5 – Trends in Internet prices.

Source: DrPeering.net

Internet Transit Pricing (1998-2015)

Source: http://DrPeering.net

Year	Internet Transit Price		% decline
1998	$1,200.00	per Mbps	
1999	$800.00	per Mbps	33%
2000	$675.00	per Mbps	16%
2001	$400.00	per Mbps	41%
2002	$200.00	per Mbps	50%
2003	$120.00	per Mbps	40%
2004	$90.00	per Mbps	25%
2005	$75.00	per Mbps	17%
2006	$50.00	per Mbps	33%
2007	$25.00	per Mbps	50%
2008	$12.00	per Mbps	52%
2009	$9.00	per Mbps	25%
2010	$5.00	per Mbps	44%
2011	$3.25	per Mbps	35%
2012	$2.34	per Mbps	28%
2013	$1.57	per Mbps	33%
2014	$0.94	per Mbps	40%
2015	$0.63	per Mbps	33%

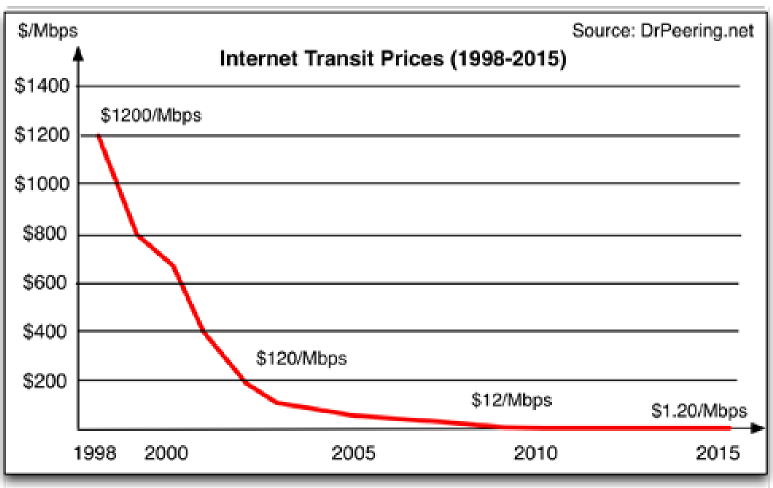


Table 7 and Figure 5 describe instead the trends of cost of Internet transit pricing by Megabit per second. The decrease of pricing has been constantly dramatic from 1999 to 2015, roughly at an average rate of

35 % year on year. This dynamic, as described in the previous chapter, is primarily driven by the introduction of new routing devices, by the diffusion of the fiber, and by economies of scale. We can find a technical explanation and a relevant correlation between the evolution of the semiconductor technology and that of the Internet. As routers and computers are made by semiconductors, the evolution of the latter influences the speed of the Internet. A lag in efficiency can be explained by many factors: the impossibility to immediately translate into routing technologies of innovations in semiconductors, complex execution in networking upgrades made by telecommunication players and enlargement of internet users mainly made at low speed level (Blyler, 2015).

6. Conclusions

The analysis we have provided allows us to trace some preliminary conclusions, together with a clear agenda of research questions to be tackled in the future.

First, the multi-industry, multi-technology nature of the Internet as a whole *technology system* makes it better understood under the lenses of *techno-economic paradigms*. At the same time, within its fundamental technological blocks, it is possible to uncover the micro-technological traits of *technological paradigms* and *trajectories*, and more specifically those originating from the discontinuity entailed by the novelties of *packet switching theory* and the open architectural design underpinned by the *TCP/IP protocol suite*, the fundamental bases of the Internet. In doing so, we have stressed the importance of institutional and policy factors that have acted as catalyst and focusing devices in the emergence of the technology.

Notwithstanding the preliminary evidence collected so far, built on insights from the engineering, economics, technological history and innovation studies academic literatures, as well as from business intelligence sources, several research questions still need to be addressed with further detail and rigour to properly put to test the economic implications of the two previously mentioned evolutionary theories of technical change. In this respect, the foregoing exposition also serves as a fruitful starting point for other future research projects, such as:

- A detailed study of the patent landscape and of the scientific literature related to the Internet, aimed at a more fine-grained characterization of its development;
- An empirical analysis of the structure and dynamics of the Internet industries;
- An inquiry on the patterns of adoption of the Internet by firms, and of its impact on productivity and labor;
- The analysis of business models and value chain of the Internet Companies;
- The exploration of the relationship between Internet and the cluster of technologies surrounding the so-called “Fourth Industrial Revolution”.

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