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The Information Technology Revolution

Which Revolution?

"Gradualism," wrote paleontologist Stephen J. Gould, "the idea that all change must be smooth, slow, and steady, was never read from the rocks. It represented a common cultural bias, in part a response of nineteenth century liberalism to a world in revolution. But it continues to color our supposedly objective reading of life's history . . . The history of life, as I read it, is a series of stable states, punctuated at rare intervals by major events that occur with great rapidity and help to establish the next stable era."[1] My starting-point, and I am not alone in this assumption,[2] is that, at the end of the twentieth century, we lived through one of these rare intervals in history. An interval characterized by the transformation of our "material culture"[3] by the works of a new technological paradigm organized around information technologies.

By technology I understand, in a straight line from Harvey Brooks and Daniel Bell, "the use of scientific knowledge to specify ways of

1 Gould (1980: 226).
2 Melvin Kranzberg, one of the leading historians of technology, wrote "The information age has indeed revolutionized the technical elements of industrial society" (1985: 42). As for its societal effects: "While it might be evolutionary, in the sense that all changes and benefits will not appear overnight, it will be revolutionary in its effects upon our society" (1985: 52). Along the same line of argument, see also, for instance, Nora and Minc (1978); Dizard (1982); Perez (1983); Forester (1985); Darbon and Robin (1987); Stourdze (1987); Dosi et al. (1988a); Bishop and Waldholz (1990); Salomon (1992); Petrella (1993); Ministry of Posts and Telecommunications (Japan) (1995); Negroponte (1995).
3 On the definition of technology as "material culture," which I consider to be the appropriate sociological perspective, see the discussion in Fischer (1992: 1–32), especially: "Technology here is similar to the idea of material culture."

doing things in a *reproducible* manner."[4] Among information technologies, I include, like everybody else, the *converging set* of technologies in micro-electronics, computing (machines and software), telecommunications/broadcasting, and opto-electronics.[5] In addition, unlike some analysts, I also include in the realm of information technologies genetic engineering and its expanding set of developments and applications.[6] This is not only because genetic engineering is focused on the decoding, manipulation, and eventual reprogramming of the information codes of living matter, but also because biology, electronics, and informatics seem to be converging and interacting in their applications, in their materials, and, more fundamentally, in their conceptual approach, a topic that deserves further mention below in this chapter.[7] Around this nucleus of information technologies, in the broad sense as defined, a constellation of major technological breakthroughs took place in the last two decades of the twentieth century in advanced materials, in energy sources, in medical applications, in manufacturing techniques (current or potential, such as nano-technology), and in transportation technology, among others.[8] Furthermore, the current process of technological transformation expands exponentially because of its ability to create an interface between technological fields through common digital language in which information is generated, stored, retrieved, processed, and transmitted. We live in a world that, in the expression of Nicholas Negroponte, has become digital.[9]

The prophetic hype and ideological manipulation characterizing most discourses on the information technology revolution should not mislead us into underestimating its truly fundamental significance. It is, as this book will try to show, at least as major an historical event as was the eighteenth-century industrial revolution, inducing a pattern of discontinuity in the material basis of economy, society, and culture. The historical record of technological revolutions, as compiled by Melvin Kranzberg and Carroll Pursell,[10] shows that they are all characterized by their *pervasiveness*, that is by their penetration of all

4 Brooks (1971: 13) from unpublished text, quoted with emphasis added by Bell (1976: 29).
5 Saxby (1990); Mulgan (1991).
6 Hall (1987); Marx (1989).
7 For a stimulating, informed, although deliberately controversial, account of the convergence between the biological revolution and the broader information technology revolution, see Kelly (1995).
8 Forester (1988); Edquist and Jacobsson (1989); Herman (1990); Drexler and Peterson (1991); Lincoln and Essin (1993); Dondero (1995); Lovins and Lovins (1995); Lyon and Gorner (1995).
9 Negroponte (1995).
10 Kranzberg and Pursell (1967).

domains of human activity, not as an exogenous source of impact, but as the fabric in which such activity is woven. In other words, *they are process-oriented*, besides inducing new products. On the other hand, unlike any other revolution, *the core* of the transformation we are experiencing in the current revolution refers to *technologies of information processing and communication*.[11] Information technology is to this revolution what new sources of energy were to the successive industrial revolutions, from the steam engine to electricity, to fossil fuels, and even to nuclear power, since the generation and distribution of energy was the key element underlying the industrial society. However, this statement on the pre-eminent role of information technology is often confused with the characterization of the current revolution as essentially dependent upon new knowledge and information. This is true of the current process of technological change, but so it is of preceding technological revolutions, as is shown by leading historians of technology, such as Melvin Kranzberg and Joel Mokyr.[12] The first industrial revolution, although not science-based, relied on the extensive use of information, applying and developing pre-existing knowledge. And the second industrial revolution, after 1850, was characterized by the decisive role of science in fostering innovation. Indeed, R&D laboratories appeared for the first time in the German chemical industry in the last decades of the nineteenth century.[13]

11 A full understanding of the current technological revolution would require the discussion of the specificity of new information technologies *vis-à-vis* their historical ancestors of equally revolutionary character, such as the discovery of printing in China probably in the late seventh century, and in Europe in the fifteenth century, a classical theme of communications literature. Without being able to address the issue within the limits of this book focused on the sociological dimension of technological change, let me suggest a few topics for the reader's attention. Electronic-based information technologies (including electronic printing) feature incomparable memory storage capacity and speed of combination and transmission of bits. Electronic text allows for substantially greater flexibility of feedbacks, interaction, and reconfiguration of text, as any word-processing writer will acknowledge, thus altering the process of communication itself. On-line communication, combined with flexibility of text, allows for ubiquitous, asynchronous space/time programming. As for the social effects of information technologies, I propose the hypothesis that the depth of their impact is a function of the pervasiveness of information throughout the social structure. Thus, while printing did substantially affect European societies in the modern age, as well as medieval China to a lesser extent, its effects were somewhat limited because of widespread illiteracy in the population and because of the low intensity of information in the productive structure. Thus, the industrial society, by educating citizens and by gradually organizing the economy around knowledge and information, prepared the ground for the empowering of the human mind when new information technologies became available. See, for an historical comment on this earlier information technology revolution, Boureau et al. (1989). For some elements of the debate on technological specificity of electronic communication, including McLuhan's perspective, see chapter 5.

12 M. Kranzberg, "Prerequisites for industrialization," in Kranzberg and Pursell (1967: I, ch. 13); Mokyr (1990).

13 Ashton (1948); Clow and Clow (1952); Landes (1969); Mokyr (1990: 112).

What characterizes the current technological revolution is not the centrality of knowledge and information, but the application of such knowledge and information to knowledge generation and information processing/communication devices, in a cumulative feedback loop between innovation and the uses of innovation.[14] An illustration may clarify this analysis. The uses of new telecommunications technologies in the past two decades have gone through three distinct stages: the automation of tasks, an experimentation of uses, and a reconfiguration of applications.[15] In the first two stages, technological innovation progressed through learning *by using*, in Rosenberg's terminology.[16] In the third stage, the users learned technology *by doing*, and ended up reconfiguring the networks, and finding new applications. The feedback loop between introducing new technology, using it, and developing it into new realms becomes much faster under the new technological paradigm. As a result, diffusion of technology endlessly amplifies the power of technology, as it becomes appropriated and redefined by its users. New information technologies are not simply tools to be applied, but processes to be developed. Users and doers may become the same. Thus users can take control of technology, as in the case of the Internet (see below in this chapter, and in chapter 5). There is therefore a close relationship between the social processes of creating and manipulating symbols (the culture of society) and the capacity to produce and distribute goods and services (the productive forces). For the first time in history, the human mind is a direct productive force, not just a decisive element of the production system.

Thus, computers, communication systems, and genetic decoding and programming are all amplifiers and extensions of the human mind. What we think, and how we think, become expressed in goods, services, material and intellectual output, be it food, shelter, transportation and communications systems, computers, missiles, health, education, or images. The growing integration between minds and machines, including the DNA machine, is canceling what Bruce Mazlish calls the "fourth discontinuity"[17] (the one between humans and machines), fundamentally altering the way we are born, we live, we learn, we work, we produce, we consume, we dream, we fight, or we die. Of course, cultural/institutional contexts and purposeful social action decisively interact with the new technological system, but this system has its own, embedded logic, characterized by the capacity to translate

14 Dizard (1982); Forester (1985); Hall and Preston (1988); Saxby (1990).

15 Bar (1990).

16 Rosenberg (1982); Bar (1992).

17 Mazlish (1993).

all inputs into a common information system, and to process such information at increasing speed, with increasing power, at decreasing cost, in a potentially ubiquitous retrieval and distribution network.

There is an additional feature characterizing the information technology revolution in comparison with its historical predecessors. Mokyr[18] has shown that technological revolutions took place only in a few societies, and diffused in a relatively limited geographic area, often living in isolated space and time *vis-à-vis* other regions of the planet. Thus, while Europeans borrowed some of the discoveries that took place in China, for many centuries China and Japan adopted European technology only on a very limited basis, mainly restricted to military applications. The contact between civilizations at different technological levels often took the form of the destruction of the least developed, or of those who had predominantly applied their knowledge to non-military technology, as in the case of American civilizations annihilated by Spanish conquerors, sometimes through accidental biological warfare.[19] The industrial revolution did extend to most of the globe from its original West European shores during the next two centuries. But its expansion was highly selective, and its pace rather slow by current standards of technological diffusion. Indeed, even in Britain by the mid-nineteenth century, sectors that accounted for the majority of the labor force, and at least half the gross national product, were not affected by new industrial technologies.[20] Furthermore, its planetary reach in the following decades more often than not took the form of colonial domination, be it in India under the British empire; in Latin America under commercial/industrial dependency on Britain and the United States; in the dismembering of Africa under the Berlin Treaty; or in the opening to foreign trade of Japan and China by the guns of Western ships. In contrast, new information technologies have spread throughout the globe with lightning speed in less than two decades, between the mid-1970s and the mid-1990s, displaying a logic that I propose as characteristic of this technological revolution: the immediate application to its own development of technologies it generates, connecting the world through information technology.[21] To be sure, there are large areas of the world, and considerable segments of the population, switched off from the new technological system: this is precisely one of the central arguments of this book. Furthermore, the speed of technological diffusion is selective, both

18 Mokyr (1990: 293, 209ff).
19 See, for instance, Thomas (1993).
20 Mokyr (1990: 83).
21 Pool (1990); Mulgan (1991).

socially and functionally. Differential timing in access to the power of technology for people, countries, and regions is a critical source of inequality in our society. The switched-off areas are culturally and spatially discontinuous: they are in the American inner cities or in the French *banlieues*, as much as in the shanty towns of Africa or in the deprived rural areas of China or India. Yet dominant functions, social groups, and territories across the globe are connected at the dawn of the twenty-first century in a new technological system that, as such, started to take shape only in the 1970s.

How did this fundamental transformation happen in what amounts to an historical instant? Why is it diffusing throughout the globe at such an accelerated, if uneven, pace? Why is it a "revolution?" Since our experience of the new is shaped by our recent past, I think the answers to these basic questions could be helped by a brief reminder of the historical record of the industrial revolution, still present in our institutions, and therefore in our mind-set.

Lessons from the Industrial Revolution

Historians have shown that there were at least two industrial revolutions: the first started in the last third of the eighteenth century, characterized by new technologies such as the steam engine, the spinning jenny, the Cort's process in metallurgy, and, more broadly, by the replacement of hand-tools by machines; the second one, about 100 years later, featured the development of electricity, the internal combustion engine, science-based chemicals, efficient steel casting, and the beginning of communication technologies, with the diffusion of the telegraph and the invention of the telephone. Between the two there are fundamental continuities, as well as some critical differences, the main one being the decisive importance of scientific knowledge in sustaining and guiding technological development after 1850.[22] It is precisely because of their differences that features common to both may offer precious insights in understanding the logic of technological revolutions.

22 Singer et al. (1958); Mokyr (1985). However, as Mokyr himself points out, an interface between science and technology was also present in the first industrial revolution in Britain. Thus, Watt's decisive improvement of the steam engine designed by Newcomen took place in interaction with his friend and protector Joseph Black, professor of chemistry at the University of Glasgow, where Watts was appointed in 1757 as "Mathematical Instrument Maker to the University," and where he conducted his own experiments on a model of the Newcomen engine; see Dickinson (1958). Indeed, Ubbelohde (1958: 673) reports that "Watt's development of a condenser for the steam, separated from the cylinder in which the piston moved, was closely linked up with and inspired by the scientific researches of Joseph Black (1728–99) the professor of chemistry at Glasgow University."

First of all, in both cases, we witness what Mokyr describes as a period of "accelerating and unprecedented technological change"[23] by historical standards. A set of macro-inventions prepared the ground for the blossoming of micro-inventions in the realms of agriculture, industry, and communications. Fundamental historical discontinuity, in an irreversible form, was introduced into the material basis of the human species, in a path-dependent process whose inner, sequential logic has been researched by Paul David and theorized by Brian Arthur.[24] They were indeed "revolutions," in the sense that a sudden, unexpected surge of technological applications transformed the processes of production and distribution, created a flurry of new products, and shifted decisively the location of wealth and power in a planet that became suddenly within the reach of those countries and elites able to master the new technological system. The dark side of this technological adventure is that it was inextricably tied to imperialist ambitions and inter-imperialist conflicts.

Yet this is precisely a confirmation of the revolutionary character of new industrial technologies. The historical ascent of the so-called West, in fact limited to Britain and a handful of nations in Western Europe as well as to their North American, and Australian offspring, is fundamentally linked to the technological superiority achieved during the two industrial revolutions.[25] Nothing in the cultural, scientific, political, or military history of the world prior to the industrial revolution would explain such indisputable "Western" (Anglo-Saxon/German, with a French touch) supremacy between the 1750s and the 1940s. China was a far superior culture for most of pre-Renaissance history; the Muslim civilization (taking the liberty of using such a term) dominated much of the Mediterranean and exerted a significant influence in Africa and Asia throughout the modern age; Asia and Africa remained by and large organized around autonomous cultural and political centers; Russia ruled in splendid isolation a vast expanse across East Europe and Asia; and the Spanish empire, the laggard European culture of the industrial revolution, was the major world power for more than two centuries after 1492. Technology, expressing specific social conditions, introduced a new historical path in the second half of the eighteenth century.

This path originated in Britain, although its intellectual roots can be traced back all over Europe and to the Renaissance's spirit of discovery.[26] Indeed, some historians insist that the necessary scientific knowledge underlying the first industrial revolution was available 100 years earlier, ready to be used under mature social conditions; or, as others argue, waiting for the technical ingenuity of self-trained inventors, such as Newcomen, Watt, Crompton or Arkwright, able to translate available knowledge, combined with craft experience, into decisive new industrial technologies.[27] However, the second industrial revolution, more dependent on new scientific knowledge, shifted its center of gravity towards Germany and the United States, where the main developments in chemicals, electricity, and telephony took place.[28] Historians have painstakingly dissected the social conditions of the shifting geography of technical innovation, often focusing on the characteristics of education and science systems, or on the institutionalization of property rights. However, the contextual explanation for the uneven trajectory of technological innovation seems to be excessively broad and open to alternative interpretations. Hall and Preston, in their analysis of the changing geography of technological innovation between 1846 and 2003, show the importance of *local* seedbeds of innovation, of which Berlin, New York, and Boston are crowned as the "high technology industrial centers of the world" between 1880 and 1914, while "London in that period was a pale shadow of Berlin."[29] The reason lies in the territorial basis for the interaction of systems of technological discovery and applications, namely in the synergistic properties of what is known in the literature as "milieux of innovation."[30]

Indeed, technological breakthroughs came in clusters, interacting with each other in a process of increasing returns. Whichever conditions determined such clustering, the key lesson to be retained is that *technological innovation is not an isolated instance.*[31] It reflects a given state of knowledge, a particular institutional and industrial environment, a certain availability of skills to define a technical problem and to solve it, an economic mentality to make such application cost-efficient, and a network of producers and users who can communicate their experiences cumulatively, learning by using and by doing: elites

23 Mokyr (1990: 82).
24 David (1975); David and Bunn (1988); Arthur (1989).
25 Rosenberg and Birdzell (1986).
26 Singer et al. (1957).

27 Rostow (1975); see Jewkes et al. (1969) for the argument, and Singer et al. (1958) for the historical evidence.
28 Mokyr (1990).
29 Hall and Preston (1988: 123).
30 The origin of the concept of "milieu of innovation" can be traced back to Aydalot (1985). It was also implicitly present in the work of Anderson (1985) and in the elaboration by Arthur (1985). Around the same time, Peter Hall and I in Berkeley, Roberto Camagni in Milan, and Denis Maillat in Lausanne, together for a brief period with the late Philippe Aydalot, started to develop empirical analyses of milieux of innovation, a theme that, rightly so, has become a cottage research industry in the 1990s.
31 The specific discussion of the historical conditions for the clustering of technological innovations cannot be undertaken within the limits of this chapter. Useful reflections on the matter can be found in Gille (1978) and Mokyr (1990). See also Mokyr (1990: 298).

learn by doing, thereby modifying the applications of technology, while most people learn by using, thus remaining within the constraints of the packaging of technology. The interactivity of systems of technological innovation and their dependence on certain "milieux" of exchange of ideas, problems, and solutions are critical features that can be generalized from the experience of past revolutions to the current one.[32]

The positive effects of new industrial technologies on economic growth, living standards, and the human mastery of a hostile Nature (reflected in the dramatic lengthening of life expectancy, which did not improve steadily before the eighteenth century) over the long run are indisputable in the historical record. However, they did not come early, in spite of the diffusion of the steam engine and new machinery. Mokyr reminds us that "per capita consumption and living standards increased little initially [at the end of the eighteenth century] but production technologies changed dramatically in many industries and sectors, preparing the way for sustained Schumpeterian growth in the second half of the nineteenth century when technological progress spread to previously unaffected industries."[33] This is a critical assessment that forces us to evaluate the actual effects of major technological changes in light of a time lag highly dependent on the specific conditions of each society. The historical record seems to indicate however that, in general terms, the closer the relationship between the sites of innovation, production, and use of new technologies, the faster the transformation of societies, and the greater the positive feedback from social conditions on the general conditions for further innovation. Thus, in Spain, the industrial revolution diffused rapidly in Catalonia, as early as the late eighteenth century, but followed a much slower pace in the rest of Spain, particularly in Madrid and in the south; only the Basque Country and Asturias had joined the process of industrialization by the end of the nineteenth century.[34] The boundaries of industrial innovation were to a large extent coterminous with areas that were prohibited to trade with the Spanish American colonies for about two centuries: while Andalusian and Castilian elites, as well as the crown, could live from their American rents, Catalans had to provide for themselves through their trade and ingenuity, while being submitted to the pressure of a centralist state. Partly as a result of this historical trajectory, Catalonia and the Basque Country were the only fully industrialized regions until the 1950s and the main seedbeds of

32 Rosenberg (1976, 1982); Dosi (1988).
33 Mokyr (1990: 83).
34 Fontana (1988); Nadal and Carreras (1990).

entrepreneurialism and innovation, in sharp contrast with trends in the rest of Spain. Thus, specific social conditions foster technological innovation that itself feeds into the path of economic development and further innovation. Yet the reproduction of such conditions is cultural and institutional, as much as economic and technological. The transformation of social and institutional environments may alter the pace and geography of technological development (for example, Japan after the Meiji Restoration, or Russia for a brief period under Stolypin), although past history does bear considerable inertia.

A last and essential lesson from the industrial revolutions that I consider relevant to this analysis is controversial: although they both brought a whole array of new technologies that actually formed and transformed an industrial system in successive stages, at their core there was fundamental innovation in the generation and distribution of energy. R. J. Forbes, a classic historian of technology, affirms that "the invention of the steam engine is the central fact in the industrial revolution," followed by the introduction of new prime movers and by the mobile prime mover, under which "the power of the steam-engine could be created where needed and to the extent desired."[35] And although Mokyr insists on the multifaceted character of the industrial revolution, he also thinks that "the protestations of some economic historians notwithstanding, the steam engine is still widely regarded as the quintessential invention of the industrial revolution."[36] Electricity was the central force of the second revolution, in spite of other extraordinary developments in chemicals, steel, the internal combustion engine, telegraphy and telephony. This is because only through electrical generation and distribution were all the other fields able to develop their applications and be connected to each other. A case in point is the electric telegraph which, first used experimentally in the 1790s and widely in existence since 1837, could only grow into a communication network, connecting the world on a large scale, when it could rely on the diffusion of electricity. The widespread use of electricity from the 1870s onwards changed transportation, telegraphy, lighting, and, not least, factory work by diffusing power in the form of the electrical engine. Indeed, while factories have been associated with the first industrial revolution, for almost a century they were not concomitant with the use of the steam engine that was widely used in craft shops, while many large factories continued to use improved water-power sources (and thus were known for a long time as mills). It was the electrical engine that both made possible and induced large-scale

35 Forbes (1958: 150).
36 Mokyr (1990: 84).

organization of work in the industrial factory.[37] As R. J. Forbes wrote (in 1958):

> During the last 250 years five great new prime movers have produced what is often called the Machine Age. The eighteenth century brought the steam-engine; the nineteenth century the water-turbine, the internal combustion engine and the steam-turbine; and the twentieth the gas-turbine. Historians have often coined catch-phrases to denote movements or currents in history. Such is "The Industrial Revolution," the title for a development often described as starting in the early eighteenth century and extending through much of the nineteenth. It was a slow movement, but wrought changes so profound in their combination of material progress and social dislocation that collectively they may well be described as revolutionary if we consider these extreme dates.[38]

Thus, by acting on the process at the core of all processes – that is, the necessary power to produce, distribute, and communicate – the two industrial revolutions diffused throughout the entire economic system and permeated the whole social fabric. Cheap, accessible, mobile energy sources extended and augmented the power of the human body, creating the material basis for the historical continuation of a similar movement toward the expansion of the human mind.

The Historical Sequence of the Information Technology Revolution

The brief, yet intense history of the information technology revolution has been told so many times in recent years as to render it unnecessary to provide the reader with another full account.[39] Besides, given the

37 Jarvis (1958); Canby (1962); Hall and Preston (1988). One of the first detailed specifications for an electric telegraph is contained in a letter signed C.M. and published in *Scots Magazine* in 1753. One of the first practical experiments with an electrical system was proposed by the Catalan Francisco de Salva in 1795. There are unconfirmed reports that a single-wire telegraph, using Salva's scheme, was actually constructed between Madrid and Aranjuez (26 miles) in 1798. However, it was only in the 1830s (William Cooke in England, Samuel Morse in America) that the electric telegraph was established, and in 1851 the first submarine cable laid out between Dover and Calais (Garratt 1958); see also Sharlin (1967); Mokyr (1990).
38 Forbes (1958: 148).
39 A good history of the origins of the information technology revolution, naturally superseded by developments since the 1980s, is Braun and Macdonald (1982). The most systematic effort at summarizing the developments of the early information technology revolution was conducted by Tom Forester in a series of books (1980, 1985, 1987, 1989, 1993). For good accounts of the origins of genetic engineering, see Elkington (1985) and Russell (1988). For an authoritative history of computing, see Ceruzzi (1998). For the history of the Internet, see Abbate (1999) and Naughton (1999) .

acceleration of its pace, any such account would be instantly obsolete, so that between my writing this and your reading it (let's say 18 months), microchips will have doubled in performance at a given price, according to the generally acknowledged "Moore's law."[40] Nevertheless, I find it analytically useful to recall the main axes of technological transformation in information generation/processing/transmission, and to place them in the sequence that drifted toward the formation of a new socio-technical paradigm.[41] This brief summary will allow me, later on, to skip references to technological features when discussing their specific interaction with economy, culture, and society throughout the intellectual itinerary of this book, except when new elements of information are required.

Micro-engineering macro-changes: electronics and information

Although the scientific and industrial predecessors of electronics-based information technologies can be found decades before the 1940s[42] (not the least being the invention of the telephone by Bell in 1876, of the radio by Marconi in 1898, and of the vacuum tube by De Forest in 1906), it was during the Second World War, and in its aftermath, that major technological breakthroughs in electronics took place: the first programmable computer, and the transistor, source of micro-electronics, the true core of the information technology revolution in the twentieth century.[43] Yet I contend that only in the 1970s did new information technologies diffuse widely, accelerating their synergistic development and converging into a new paradigm. Let us retrace the stages of innovation in the three main technological fields that, although closely interrelated, constituted the history of electronics-based technologies: micro-electronics, computers, and telecommunications.

40 An accepted "law" in the electronics industry, originated by Gordon Moore, chairman of Intel, the legendary Silicon Valley start-up company, today the world's largest and one of the most profitable firms in micro-electronics.
41 The information reported in this chapter is widely available in newspapers and magazines. I extracted much of it from my reading of *Business Week, The Economist, Wired, Scientific American,* the *New York Times, El Pais* and the *San Francisco Chronicle*, which constitute my daily/weekly information staple. It also comes from occasional chats on technology matters with colleagues and friends around Berkeley and Stanford, knowledgeable about electronics and biology and acquainted with industry sources. I do not consider it necessary to provide detailed references to data of such general character, except when a given figure or quote could be hard to find.
42 See Hall and Preston (1988); Mazlish (1993).
43 I think that, as with the industrial revolutions, there will be several information technology revolutions, of which the one constituted in the 1970s is only the first. Probably the second, in the early twenty-first century, will give a more important role to the biological revolution, in close interaction with new computer technologies.

The transistor, invented in 1947 at Bell Laboratories in Murray Hill, New Jersey, by three physicists, Bardeen, Brattain, and Shockley (recipients of the Nobel Prize for this discovery), made possible the processing of electric impulses at a fast pace in a binary mode of interruption and amplification, thus enabling the coding of logic and of communication with and between machines: we call these processing devices semiconductors, and people commonly call them chips (actually now made of millions of transistors). The first step in the transistor's diffusion was taken with the invention by Shockley of the junction transistor in 1951. Yet its fabrication and widespread use required new manufacturing technologies and the use of an appropriate material. The shift to silicon, literally building the new revolution on sand, was first accomplished by Texas Instruments (in Dallas) in 1954 (a move facilitated by the hiring in 1953 of Gordon Teal, another leading scientist from Bell Labs). The invention of the planar process in 1959 by Fairchild Semiconductors (in Silicon Valley) opened up the possibility of the integration of miniaturized components with precision manufacturing.

Yet the decisive step in micro-electronics had taken place in 1957: the integrated circuit (IC) was co-invented by Jack Kilby, a Texas Instrument engineer (who patented it), and Bob Noyce, one of the founders of Fairchild. But it was Noyce who first manufactured ICs by using the planar process. It triggered a technological explosion: in only three years, between 1959 and 1962, prices of semiconductors fell by 85 percent, and in the next ten years production increased by 20 times, 50 percent of which went to military uses.[44] As a point of historical comparison, it took 70 years (1780–1850) for the price of cotton cloth to drop by 85 percent in Britain during the industrial revolution.[45] Then, the movement accelerated during the 1960s: as manufacturing technology improved and better chip design was helped by computers using faster and more powerful micro-electronic devices, the average price of an integrated circuit fell from $50 in 1962 to $1 in 1971.

The giant leap forward in the diffusion of micro-electronics in all machines came in 1971 with the invention by an Intel engineer, Ted Hoff (also in Silicon Valley), of the microprocessor, that is the computer on a chip. Thus, information-processing power could be installed everywhere. The race was on for ever-greater integration capacity of circuits on a single chip, the technology of design and manufacturing constantly exceeding the limits of integration previously thought to be physically impossible without abandoning the use of silicon material.

44 Braun and Macdonald (1982).
45 Mokyr (1990: 111).

In the mid-1990s, technical evaluations still gave 10–20 years of good life for silicon-based circuits, although research in alternative materials was stepped up. The level of integration has progressed by leaps and bounds in the past two decades. While technical details have no place in this book, it is analytically relevant to indicate the speed and extent of technological change.

As is known, the power of chips can be evaluated by a combination of three characteristics: their integration capacity, indicated by the smallest line width in the chip measured in microns (1 micron = 1 millionth of 1 meter); their memory capacity, measured in bits: thousands (k), and millions (megabits); and the speed of the microprocessor measured in megahertz. Thus, the first 1971 processor was laid in lines of about 6.5 microns; in 1980, it reached 4 microns; in 1987, 1 micron; in 1995, Intel's Pentium chip featured a size in the 0.35 micron range; and projections were for reaching 0.25 micron in 1999. Thus, where in 1971 2,300 transistors were packed on a chip the size of a thumbtack, in 1993 there were 35 million transistors. Memory capacity, as indicated by DRAM (dynamic random access memory) capacity, was in 1971, 1,024 bits; in 1980, 64,000; in 1987, 1,024,000; in 1993, 16,384,000; and projected in 1999, 256,000,000. As for the speed, mid-1990s 64–bit microprocessors were 550 times faster than the first Intel chip in 1972; and MPUs are doubling every 18 months. Projections to 2002 forecast an acceleration of micro-electronics technology in integration (0.18 micron chips), in DRAM capacity (1,024 megabits), and microprocessor speed (500+ megahertz as compared to 150 in 1993). Combined with dramatic developments in parallel processing using multiple microprocessors (including, in the future, linking multiple microprocessors on a single chip), it appears that the power of micro-electronics is still being unleashed, thus relentlessly increasing computing capacity. Furthermore, greater miniaturization, further specialization, and the decreasing price of increasingly powerful chips made it possible to place them in every machine in our everyday life, from dishwashers and microwave ovens to automobiles, whose electronics, in the 1990s standard models, were already more valuable than their steel.

Computers were also conceived from the mother of all technologies that was the Second World War, but they were only born in 1946 in Philadelphia, if we except the war-related tools of the 1943 British Colossus applied to deciphering enemy codes, and the German Z-3 reportedly produced in 1941 to help aircraft calculations.[46] Yet most allied effort in electronics was concentrated in research programs at

46 Hall and Preston (1988).

MIT, and the actual experimentation of the calculators' power, under US army sponsorship, took place at the University of Pennsylvania, where Mauchly and Eckert produced in 1946 the first general purpose computer, the ENIAC (electronic numerical integrator and calculator). Historians will recall that the first electronic computer weighed 30 tons, was built on metal modules nine feet tall, had 70,000 resistors and 18,000 vacuum tubes, and occupied the area of a gymnasium. When it was turned on, its electricity consumption was so high that Philadelphia's lighting twinkled.[47]

Yet the first commercial version of this primitive machine, UNIVAC–1, produced in 1951 by the same team, then under the Remington Rand brand name, was extremely successful in processing the 1950 US census. IBM, also supported by military contracts and relying partly on MIT research, overcame its early reservations about the computer age, and entered the race in 1953 with its 701 vacuum tube machine. In 1958, when Sperry Rand introduced a second-generation computer mainframe machine, IBM immediately followed up with its 7090 model. But it was only in 1964 that IBM, with its 360/370 mainframe computer, came to dominate the computer industry, populated by new (Control Data, Digital), and old (Sperry, Honeywell, Burroughs, NCR) business machines companies. Most of these firms were ailing or had vanished by the 1990s: this is how fast Schumpeterian "creative destruction" has proceeded in the electronics industry. In that ancient age, that is 30 years from the time of writing, the industry organized itself in a well-defined hierarchy of mainframes, minicomputers (in fact, rather bulky machines), and terminals, with some specialty informatics left to the esoteric world of supercomputers (a cross-fertilization of weather forecasting and war games), in which the extraordinary ingenuity of Seymour Cray, in spite of his lack of technological vision, reigned for some time.

Micro-electronics changed all this, inducing a "revolution within the revolution." The advent of the microprocessor in 1971, with the capacity to put a computer on a chip, turned the electronics world, and indeed the world itself, upside down. In 1975, Ed Roberts, an engineer who had created a small calculator company, MITS, in Albuquerque, New Mexico, built a computing box with the improbable name of Altair, after a character in the *Star Trek* TV series, that was the object of admiration of the inventor's young daughter. The machine was a primitive object, but it was built as a small-scale computer around a microprocessor. It was the basis for the design of Apple I, then of Apple II, the first commercially successful micro-

47 See the description by Forester (1987).

computer, realized in the garage of their parents' home by two young school drop-outs, Steve Wozniak and Steve Jobs, in Menlo Park, Silicon Valley, in a truly extraordinary saga that has by now become the founding legend of the Information Age. Launched in 1976, with three partners and $91,000 capital, Apple Computers had by 1982 reached $583 million in sales, ushering in the age of diffusion of computer power. IBM reacted quickly: in 1981 it introduced its own version of the microcomputer, with a brilliant name: the Personal Computer (PC), which became in fact the generic name for microcomputers. But because it was not based on IBM's proprietary technology, but on technology developed for IBM by other sources, it became vulnerable to cloning, which was soon practiced on a massive scale, particularly in Asia. Yet while this fact eventually doomed IBM's business dominance in PCs, it also spread the use of IBM clones throughout the world, diffusing a common standard, in spite of the superiority of Apple machines. Apple's Macintosh, launched in 1984, was the first step towards user-friendly computing, with the introduction of icon-based, user-interface technology, originally developed by Xerox's Palo Alto Research Center.

A fundamental condition for the diffusion of microcomputers was fulfilled with the development of new software adapted to their operation.[48] PC software also emerged in the mid-1970s out of the enthusiasm generated by Altair: two young Harvard drop-outs, Bill Gates and Paul Allen, adapted BASIC for operating the Altair machine in 1976. Having realized its potential, they went on to found Microsoft (first in Albuquerque, two years later moving to Seattle, home of Bill Gates's parents), today's software giant, which parlayed dominance in operating-system software into dominance in software for the exponentially growing microcomputer market as a whole.

In the last 20 years of the twentieth century, increasing chip power resulted in a dramatic enhancement of microcomputing power. By the early 1990s, single-chip microcomputers had the processing power of IBM only five years earlier. Furthermore, since the mid-1980s, microcomputers cannot be conceived of in isolation: they perform in networks, with increasing mobility, on the basis of portable computers. This extraordinary versatility, and the capacity to add memory and processing capacity by sharing computing power in an electronic network, decisively shifted the computer age in the 1990s from centralized data storage and processing to networked, interactive computer power-sharing. Not only did the whole technological system change, but its social and organizational interactions as well. Thus, the aver-

48 Egan (1995).

age cost of processing information fell from around $75 per million operations in 1960 to less than one-hundredth of a cent in 1990.

This networking capability only became possible, naturally, because of major developments both in telecommunication and computer-networking technologies during the 1970s. But, at the same time, such changes were only made possible by new micro-electronic devices and stepped-up computing capacity, in a striking illustration of the synergistic relationships of the information technology revolution.

Telecommunications have been revolutionized also by the combination of "node" technologies (electronic switches and routers) and new linkages (transmission technologies). The first industrially produced electronic switch, the ESS-1, was introduced by Bell Labs in 1969. By the mid-1970s, progress in integrated circuit technologies had made possible the digital switch, increasing speed, power, and flexibility, while saving space, energy, and labor, *vis-à-vis* analog devices. Although ATT, parent of the discoverer Bell Labs, was initially reluctant about its introduction, because of the need to amortize the investment already made in analog equipment, when in 1977 Canada's Northern Telecom captured a share of the US market through its lead in digital switching, the Bell companies joined the race and triggered a similar movement around the world.

Major advances in opto-electronics (fiber optics and laser transmission) and digital packet transmission technology dramatically broadened the capacity of transmission lines. The integrated broadband networks (IBNs) envisioned in the 1990s could surpass substantially the revolutionary 1970s proposals for an integrated services digital network (ISDN): while the carrying capacity of ISDN on copper wire was estimated at 144,000 bits, the 1990s IBNs on optic fibers, if and when they can be realized, though at a high price, could carry a quadrillion bits. To measure the pace of change, let us recall that in 1956 the first transatlantic cable phone carried 50 compressed voice circuits; in 1995, optical fibers could carry 85,000 such circuits. This opto-electronics-based transmission capacity, together with advanced switching and routing architectures, such as the asynchronous transmission mode (ATM) and transmission control protocol/interconnection protocol (TCP/IP), are the foundation of the Internet.

Different forms of utilization of the radio spectrum (traditional broadcasting, direct satellite broadcasting, microwaves, digital cellular telephony), as well as coaxial cable and fiber optics, offer a diversity and versatility of transmission technologies, which are being adapted to a whole range of uses, and make possible ubiquitous communication between mobile users. Thus, cellular telephony diffused with force all over the world in the 1990s, literally dotting Asia with unsophisticated pagers and Latin America with status-symbol cellular phones. In 2000, technologies were available for a universal-coverage, personal communication device, only waiting for a number of technical, legal, and business issues to be sorted out before reaching the market. Each leap and bound in a specific technological field amplifies the effects of related information technologies. The convergence of all these electronic technologies into the field of interactive communication led to the creation of the Internet, perhaps the most revolutionary technological medium of the Information Age.

The creation of the Internet

The creation and development of the Internet in the last three decades on the twentieth century resulted from a unique blending of military strategy, big science cooperation, technological entrepreneurship, and countercultural innovation.[49] The origins of the Internet lie in the work of one of the most innovative research institutions in the world: the US Defense Department's Advanced Research Projects Agency (ARPA). When in the late 1950s the launching of the first Sputnik alarmed the American high-tech military establishment, ARPA undertook a number of bold initiatives, some of which changed the history of technology and ushered in the Information Age on a grand scale. One of these strategies, developing an idea conceived by Paul Baran at Rand Corporation in 1960–4, was to design a communications system invulnerable to nuclear attack. Based on packet-switching communication technology, the system made the network independent of command and control centers, so that message units would find their own routes along the network, being reassembled in coherent meaning at any point in the network.

When, later on, digital technology allowed the packaging of all kind of messages, including sound, images, and data, a network was formed that was able to communicate its nodes without using control centers. The universality of digital language and the pure networking logic of the communication system created the technological conditions for horizontal, global communication.

The first computer network, named ARPANET after its powerful sponsor, went on-line on September 1, 1969, with the first four nodes of the network being established at the University of California, Los Angeles, Stanford Research Institute, University of California, Santa

49 For excellent histories of the Internet, see Abbate (1999) and Naughton (1999). See also Hart et al. (1992). On the contribution of "hacker" culture to the development of the Internet, see Hafner and Markoff (1991); Naughton (1999); Himannen (2001).

Barbara, and University of Utah. It was opened to research centers cooperating with the US Defense Department, but scientists started to use it for their own communication purposes, including a science fiction enthusiasts' messaging network. At one point it became difficult to separate military-oriented research from scientific communication and personal chatting. Thus, scientists of all disciplines were given access to the network, and in 1983 there was a split between ARPANET, dedicated to scientific purposes, and MILNET, directly oriented to military applications. The National Science Foundation also became involved in the 1980s in creating another scientific network, CSNET, and – in cooperation with IBM – still another network for non-science scholars, BITNET. Yet all networks used ARPANET as their backbone communication system. The network of networks that formed during the 1980s was called ARPA-INTERNET, then INTERNET, still supported by the Defense Department and operated by the National Science Foundation. Having become technologically obsolete after more than 20 years of service, ARPANET was closed down on February 28, 1990. Then, NSFNET, operated by the National Science Foundation, took over as the backbone of the Internet. Yet, commercial pressures, the growth of private corporate networks, and of non-profit, cooperative networks, led to the closing of this last, government-operated Internet backbone, in April 1995, ushering in the full privatization of the Internet, as a number of commercial spin-offs of NSF's regional networks joined forces to form cooperative arrangements between private networks. Once privatized, the Internet did not have any actual overseeing authority. A number of *ad hoc* institutions and mechanisms, created throughout the development of the Internet, took some informal responsibility for coordinating technical configurations and brokering agreements in assigning Internet addresses. In January 1992, under the initiative of the National Science Foundation, the Internet Society, a non-profit organization, was given responsibility over pre-existing coordinating organizations, the Internet Activities Board, and the Internet Engineering Task Force. Internationally, the main coordination function remains the multilateral agreements in assigning domain addresses throughout the world, a very contentious matter.[50] Despite the establishment in 1998 of a new, American-based regulatory body (IANA/ICANN), in 1999 there was no indisputable, clear authority over the Internet, either in the US or in the world – a sign of the free-wheeling characteristics of the new medium, both in technological and cultural terms.

For the network to be able to sustain exponential growth in the volume of communication, transmission technology had to be enhanced. In the 1970s, ARPANET was using 56,000 bits-per-second links. In 1987, the network lines transmitted 1.5 million bits per second. By 1992, the NSFNET, backbone network behind the Internet, operated at transmission speeds of 45 million bits per second, enough capacity to send 5,000 pages per second. In 1995, gigabit transmission technology was in the prototype stage, with capacity equivalent to transmitting the US Library of Congress in one minute.

50 Conseil d'Etat (1998).

However, transmission capacity was not enough to establish a worldwide communication web. Computers had to be able to talk to each other. The first step in this direction was the creation of a communication protocol that could be used by all kinds of networks, a seemingly impossible task in the early 1970s. In the summer of 1973, Vinton Cerf and Robert Kahn, computer scientists doing research at ARPA, designed the basic architecture of the Internet, building on work toward a communication protocol conducted by Kahn at his research firm, BBN. They called a meeting at Stanford, attended by researchers from ARPA and various universities and research centers, including PARC/Xerox, where Robert Metcalfe was working on packet-communication technology that would lead to the creation of local area networks (LANs). Technological cooperation also included various groups in Europe, particularly the French researchers associated with the Cyclades program. Working on the basis of this Stanford seminar, Cerf, Metcalfe, and Gerard Lelann (from Cyclades) specified a transmission control protocol that would accommodate the requests of different researchers, and of different existing networks. In 1978, Cerf, Postel (from UCLA), and Cohen (from USC) split the protocol in two parts: host-to-host (TCP) and internetworks protocol (IP). The resulting TCP/IP protocol became the standard for computer communication in the US by 1980. Its flexibility allowed the adoption of a multilayered structure of links between computer networks, which showed its capacity to adapt to various communication systems and to a variety of codes. When, in the 1980s, telecommunication carriers, particularly in Europe, imposed as international standard a different communication protocol (the x.25) the world came very close to being split into non-communicable computer networks. Yet, the capacity of TCP/IP to accommodate diversity ultimately prevailed. With some adaptation (assigning x.25 and TCP/IP to different layers of the communication network, then setting up links between the layers, and making the two protocols complementary) TCP/IP was able to win acceptance as the common standard for computer communication protocols. From then on, computers were able to encode, and decode, for each other data packages traveling at high speed in the Internet network. Another instance of technological convergence was still necessary for computers to communicate: the adaptation of TCP/IP to UNIX, an operating system enabling access from computer to computer. The UNIX system was invented by Bell Laboratories in 1969, but became widely used only after 1983, when Berkeley researchers (again funded by ARPA) adapted to UNIX the TCP/IP protocol. Since the new version of UNIX was financed with public funds, the software was made available just for the cost of distribution. Networking was born on a large scale as local area networks and regional networks connected to each other, and started to spread anywhere where there were telephone lines and computers were equipped with modems, an inexpensive piece of equipment.

Behind the development of the Internet there was the scientific, institutional, and personal networks cutting across the Defense Department, National Science Foundation, major research universities (particularly MIT, UCLA, Stanford, University of Southern California, Harvard, University of California at Santa Barbara, and University of California at Berkeley), and specialized technological think-tanks, such as MIT's Lincoln Laboratory, SRI (formerly Stanford Research Institute), Palo Alto Research Corporation (funded by Xerox), ATT's Bell Laboratories, Rand Corporation, and BBN (Bolt, Beranek & Newman). Key technological players in the 1960s–1970s were, among others, J. C. R. Licklider, Paul Baran, Douglas Engelbart (the inventor of the mouse), Robert Taylor, Ivan Sutherland, Lawrence Roberts, Alex McKenzie, Robert Kahn, Alan Kay, Robert Thomas, Robert Metcalfe, and a brilliant computer science theoretician Leonard Kleinrock, and his cohort of outstanding graduate students at UCLA, who would become some of the key minds behind the design and development of the Internet: Vinton Cerf, Stephen Crocker, Jon Postel, among others. Many of these computer scientists moved back and forth between these various institutions, creating a networked milieu of innovation whose dynamics and goals became largely autonomous from the specific purposes of military strategy or supercomputing link-ups. They were technological crusaders, convinced that they were changing the world, as eventually they did.

Many of the applications of the Internet came from the unexpected inventions of its early users, inducing a practice and a technological trajectory that would become essential features of the Internet. Thus, in the early stages of ARPANET, the rationale for computer link-ups was the possibility of time-sharing through remote computing, so that scattered computer resources could be fully utilized on-line. Yet, most users did not really need that much computer power, or were not ready to redesign their systems in accordance with the communication requirements. But what really caught fire was e-mail communication between the network participants, an application created by Ray Tomlinson at BBN, and this remains the most popular use of computer communication in the world today.

But this is only one side of the story. In parallel with the efforts of the Pentagon and big science to establish a universal computer network with public access, within "acceptable use" norms, a sprawling computer counterculture emerged in the United States, often intellectually associated with the aftershocks of the 1960s' movements in their most libertarian/utopian version. An important element of the system, the modem, was one of the technological breakthroughs emerging from the pioneers of this counterculture, originally labeled "the hackers" before the term took on its malignant connotation. The modem for PCs was invented by two Chicago students, Ward Christensen and Randy Suess, in 1978, when they were trying to find a system to transfer microcomputer programs to each other through the telephone to avoid traveling in the Chicago winter between their distant locations. In 1979 they diffused the XModem protocol which allowed computers to transfer files directly without going through a host system. And they diffused the technology at no cost because their purpose was to spread communication capabilities as much as possible. Computer networks that were excluded from ARPANET (reserved to elite science universities in its early stages) found a way to start communicating with each other on their own. In 1979, three students at Duke University and the University of North Carolina, not included in ARPANET, created a modified version of the UNIX protocol which made it possible to link up computers over the regular telephone line. They used it to start a forum of on-line computer discussion, Usenet, which quickly became one of the first large-scale electronic conversation systems. The inventors of Usenet News also diffused freely their software in a leaflet circulated at the UNIX users conference. In 1983, Tom Jennings designed a system to post bulletin boards on PCs, by adding a modem and special software that allowed other computers to link up with a PC equipped with this interface technology. This was the origin of one of the most original, grassroots networks, Fidonet, which by 1990 was connecting 2,500 computers in the US. Because it was cheap, open, and cooperative, Fidonet was particularly successful in poor countries around the world, such as Russia, especially among countercultural groups,[51] until its technological limitations, and the development of the Internet, brought most of its users into the shared world wide web. Conferencing systems, such as Well in the San

51 Rohozinski (1998).

Francisco Bay area, brought together computer users in networks of affinity.

Ironically, this countercultural approach to technology had a similar effect to the military-inspired strategy of horizontal networking: it made available technological means to whoever had the technical knowledge and a computing tool, the PC, which soon began a spectacular progression of increasing power and decreasing price at the same time. The advent of personal computing and the communicability of networks spurred the development of bulletin board systems (BBS), first in the United States, then worldwide. Bulletin board systems did not need sophisticated computer networks, just PCs, modems, and the telephone line. Thus, they became the electronic notice-boards of all kinds of interests and affinities, creating what Howard Rheingold named "virtual communities."[52] In the late 1980s, several million computer users were using computer-mediated communication in cooperative or commercial networks that were not part of the Internet. Often, these networks used protocols that were not compatible, so they shifted to Internet protocols, a move that, in the 1990s, assured their integration into the Internet and thus the expansion of the Internet itself.

Yet by 1990 the Internet was still difficult to use for the uninitiated. There was very limited graphic transmission capability, and it was extremely hard to locate and retrieve information. A new technological leap allowed the diffusion of the Internet into the mainstream of society: the design of a new application, *the world wide web*, organizing the Internet sites' content by information rather than by location, then providing users with an easy search system to locate the desired information. The invention of the world wide web took place in Europe, in 1990, at the Centre Européen pour Recherche Nucleaire (CERN) in Geneva, one of the leading physics research centers in the world. It was invented by a group of researchers at CERN led by Tim Berners-Lee and Robert Cailliau. They built their research not on the ARPANET tradition, but on the contribution of the hackers' culture of the 1970s. In particular, they partly relied on the work of Ted Nelson who, in 1974, in his pamphlet "Computer Lib," called upon people to seize and use computer power for their own benefit. Nelson imagined a new system of organizing information which he called "hypertext," based on horizontal information links. To this pioneering insight, Berners-Lee and co-workers added new technologies adapted from the multimedia world to provide an audiovisual language to their application. The CERN team created a format for

52 Rheingold (1993).

hypertext documents that they named hypertext markup language (HTML), designed in the Internet tradition of flexibility, so that computers could adapt their specific languages within this shared format, adding this formatting on top of the TCP/IP protocol. They also set up a hypertext transfer protocol (HTTP) to guide communication between web browsers and web servers, and they created a standard address format, the uniform resource locator (URL) which combines information on the application protocol and on the computer address holding the requested information. Here again, URL could relate to a variety of transfer protocols, not just HTTP, thus facilitating general interface. CERN distributed world wide web (www) software free over the Internet, and the first web sites were established by major scientific research centers around the world. One of these centers was the National Center for Supercomputer Applications (NCSA) at the University of Illinois, one of the oldest NSF supercomputer centers. Because of the decline of uses for these machines, NCSA's researchers, as in most other supercomputer centers, were looking for new tasks. So were some staff members, including Marc Andreessen, a college student doing part-time work at the center for $6.85 an hour. "In late 1992, Marc, technically capable, and 'bored off his ass,' decided it was fun to take a crack at giving the Web the graphical, media rich face that it lacked."[53] The result was a web browser called Mosaic, designed to run on personal computers. Marc Andreessen and his collaborator Eric Bina posted Mosaic free on the NCSA web in November 1993, and in the spring of 1994 several million copies were in use. Andreessen and his team were then approached by a legendary Silicon Valley entrepreneur, Jim Clark, who was getting bored with the company that he had created with great success, Silicon Graphics. Together they founded another company, Netscape, which produced and commercialized the first reliable Internet browser, Netscape Navigator, released in October 1994.[54] New browsers, or search engines, developed quickly, and the whole world embraced the Internet, literally creating a world wide web.

Network technologies and pervasive computing

In the late 1990s, the communication power of the Internet, together with new developments in telecommunications and computing, induced another major technological shift, from decentralized, stand-alone microcomputers and mainframes to pervasive computing by intercon-

53 Reid (1997: 6).
54 Lewis (2000).

nected information-processing devices, coming in multiple formats. In this new technological system computer power is distributed in a communicated network built around web servers using common Internet protocols, and enabled with access capability to mega-computer servers, usually differentiated between database servers and application servers. Although the new system was still in the process of formation at the time of writing, users were accessing the network from a variety of single-purpose, specialized devices distributed in all spheres of life and activity, at home, at work, at shopping, at entertainment places, in transportation vehicles, and ultimately everywhere. These devices, many of them portable, can communicate among themselves, without needing their own operating system. Thus, computing power, applications, and data are stored in the servers of the network, and computing intelligence is placed in the network itself: web sites communicate with each other, and have at their disposal the necessary software to connect any appliance to a universal computer network. New software programs, such as Java (1995) and Jini (1999) designed by Bill Joy at Sun Microsystems, enabled the network to become the actual information-processing system. The networking logic epitomized by the Internet became applicable to every domain of activity, to every context, and to every location that could be electronically connected. The ascent of mobile telephony, spearheaded by Finland's Nokia, Sweden's Ericsson, and America's Motorola, created the possibility of accessing the Internet from mobile devices. Third-generation mobile phones, unveiled by Nokia and Ericsson in 1997, could transfer data at 384 kilobits per second outdoors and 2 megabits indoors, compared to copper line's ability to carry 64 kilobits per second of data. Furthermore, the extraordinary increase of transmission capacity with broadband communication technology provided the opportunity to use the Internet, or Internet-related communication technologies, to transmit voice, as well as data, through packet switching, thus revolutionizing telecommunications – and the telecommunications industry. According to Vinton Cerf, "Today you go through a circuit switch to get a packet switch. Tomorrow you'll go through a packet switch to get a circuit switch."[55] In another technological vision, Cerf asserted that "during the latter half of the next decade – that is around 2005–2010 – there will be a new (technological) driver: billions of devices attached to the Internet."[56] So, ultimately, the communications network will be packet switched, with data transmission accounting for the overwhelming share of traffic, and voice transmission being but

55 Cerf (1999).
56 Quoted in *The Economist* (1997: 33).

one, specialized service. This volume of communication traffic will require a gigantic expansion of capacity, both trans-oceanic and local. The building of a new, global telecommunications infrastructure based on fibre-optic and digital transmission was well underway at the turn of the century, with transatlantic fiber-optic cable transmission capacity approaching 110 gigabits per second in 2000, in comparison with about 5 gigabits in 1993.

The frontier of information technology at the turn of the millennium appeared to be the application of a chemically based and/or biologically based nanotechnology-approach to chip making. Thus, in July 1999, the journal *Science* published the results of experimental work by computer scientist Phil Kuekes of Hewlett-Packard's laboratory in Palo Alto and chemist James Health of UCLA. They found a way to make electronic switches using chemical processes instead of light, thus shrinking the switches to the size of a molecule. While these ultra-tiny electronic components are still some way away from operational stage (at least for a decade), this and other experimental programs seem to indicate that molecular electronics is a possible avenue to overcoming the physical limits of increasing density in silicon chips, while ushering in an era of computers 100 billion times as fast as a Pentium microprocessor: this would make it possible to pack the computing power of a hundred 1999 computer workstations into a space the size of a grain of salt. Based on these technologies, computer scientists envisage the possibility of computing environments where billions of microscopic information-processing devices will be spread everywhere "like pigment in the wall paint." If so, then computer networks will be, materially speaking, the fabric of our lives.[57]

The 1970s' technological divide

This technological system, in which we are fully immersed at the dawn of the twenty-first century, came together in the 1970s. Because of the significance of specific historical contexts for technological trajectories, and for the particular form of interaction between technology and society, it is important to recall a few dates associated with essential discoveries in information technologies. All of them have something essential in common: while mainly based on previously existing knowledge, and developed in prolongation of key technologies, they represented a qualitative leap forward in the massive diffusion of technology in commercial and civilian applications because of their accessibility and their decreasing cost with increasing quality. Thus, the

57 Hall (1999a); Markoff (1999a, b).

microprocessor, the key device in spreading micro-electronics, was invented in 1971 and began to diffuse by the mid-1970s. The microcomputer was invented in 1975 and the first successful commercial product, Apple II, was introduced in April 1977, around the same time that Microsoft started to produce operating systems for microcomputers. The Xerox Alto, the matrix of many software technologies for 1990s' personal computers, was developed at PARC labs in Palo Alto in 1973. The first industrial electronic switch appeared in 1969, and digital switching was developed in the mid-1970s and commercially diffused in 1977. Optic fiber was first industrially produced by Corning Glass in the early 1970s. Also by the mid-1970s, Sony started to produce VCR machines commercially, on the basis of 1960s' discoveries in America and England that never reached mass production. And last, but not least, it was in 1969 that the US Defense Department's Advanced Research Projects Agency (ARPA) set up a new, revolutionary electronic communication network, which would grow during the 1970s to become the current Internet. It was greatly helped by the invention by Cerf and Kahn in 1973 of TCP/IP, the interconnection network protocol that ushered in "gateway" technology, allowing different types of networks to be connected. I think we can say, without exaggeration, that the information technology revolution, as a revolution, was born in the 1970s, particularly if we include in it the parallel emergence and diffusion of genetic engineering around the same dates and places, a development that deserves, to say the least, a few lines of attention.

Technologies of life

Although biotechnology can be traced all the way back to a 6000 BC Babylonian tablet on brewing, and the revolution in microbiology to the scientific discovery of the basic structure of life, DNA's double helix, by Francis Crick and James Watson at Cambridge University in 1953, it was only in the early 1970s that gene splicing and recombinant DNA, the technological foundation of genetic engineering, made possible the application of cumulative knowledge. Stanford's Stanley Cohen and University of California at San Francisco's Herbert Boyer are generally credited with the discovery of gene-cloning procedures in 1973, although their work was based on research by Stanford's Nobel Prize winner Paul Berg. In 1975 researchers at Harvard isolated the first mammalian gene, out of rabbit hemoglobin; and in 1977 the first human gene was cloned.

What followed was a rush to start up commercial firms, most of them spin-offs from major universities and hospital research centers,

clusters of such firms emerging in northern California, New England, Maryland, Virginia, North Carolina, and San Diego. Journalists, investors, and social activists alike were struck by the awesome possibilities opened up by the potential ability to engineer life, including human life. Genentech in south San Francisco, Cetus in Berkeley, and Biogen in Cambridge, Massachusetts were among the first companies, organized around Nobel Prize winners, to use new genetic technologies for medical applications. Agro-business followed soon; and micro-organisms, some of them genetically altered, were given an increasing number of assignments, not least to clean up pollution, often generated by the same companies and agencies that were selling the superbugs. Yet scientific difficulties, technical problems, and major legal obstacles derived from justified ethical and safety concerns slowed down the much-vaunted biotechnological revolution during the 1980s. A considerable amount of venture capital investment was lost and some of the most innovative companies, including Genentech, were absorbed by pharmaceutical giants (Hoffman-La Roche, Merck) who, better than anybody else, understood that they could not replicate the costly arrogance that established computer firms had displayed toward innovative start-ups: to buy small, innovative firms, along with their scientists' services, became a major insurance policy for pharmaceutical and chemical multinationals to both internalize the commercial benefits of the biological revolution and to control its pace. A slowing down of this pace followed, at least in the diffusion of its applications.

However, in the late 1980s and in the 1990s a major science push, and a new generation of daring scientist entrepreneurs, revitalized biotechnology, with a decisive focus on genetic engineering, the truly revolutionary technology in the field. Genetic cloning entered a new stage when, in 1988, Harvard formally patented a genetically engineered mouse, thus taking the copyright of life away from God and Nature. In the next seven years, an additional seven mice were also patented as newly created forms of life, identified as the property of their engineers. In August 1989 researchers from the University of Michigan and Toronto discovered the gene responsible for cystic fibrosis, opening the way for genetic therapy. In February 1997, Wilmut and his collaborators at the Roslin Institute in Edinburgh announced the cloning of a sheep, which they named Dolly, realized from the DNA of an adult sheep. In July 1998 the journal *Nature* published the findings of a potentially even more significant experiment: the research by two biologists at the University of Hawaii, Yanagimachi and Wakayama, who proceeded with a massive cloning of 22 mice, including seven clones of clones, thus proving the possibility of the sequential production of clones, under more difficult conditions than sheep cloning, since mice embryos have a much faster development than sheep. Also in 1998, scientists at Portland State University succeeded in cloning adult monkeys, although without being able to reproduce the conditions of their experiment.

In spite of all the media hype – and the horror stories – human cloning is not on the cards for anyone, and, in strict terms, it is indeed physically impossible, since living beings form their personality and their organism in interaction with their environment. Animal cloning is economically inefficient because, if practiced on a massive scale, it would raise the possibility of the complete destruction of the entire livestock in the event of an infection – since all animals of a given kind would be vulnerable to the same deadly agent. But other possibilities emerge, particularly in medical research: the cloning of human organs, and the large-scale cloning of genetically engineered animals for the purpose of experimentation, and for the replacement of human organs. Furthermore, rather than replacing organs with organ transplants, new biological research, with powerful medical and commercial applications, aims at inducing self-regenerating capabilities in humans. A survey of potential applications in process in the late 1990s revealed the following projects, all of them expected to be operational between 2000 and 2010, all of them related to inducing self-regeneration or growth of organs, tissue, or bones in the human body by biological manipulation: bladder, in project by the company Reprogenesis; urinary conduct by Integra Life Sciences; maxilar bones by Osiris Therapeutics; insulin-producing cells, replacing the pancreas function, by BioHybrid Technologies; cartilage by ReGen Biologics; teeth by a variety of companies; spinal cord nerves by Acorda; cartilage breasts by Reprogenesis; a complete human heart, on the basis of genetically manipulated proteins already tested as being capable of producing blood vessels, by Genentech; and liver regeneration, on the basis of tissue on which liver cells are planted, by Human Organ Sciences.

The most decisive frontier of biological research and application is genetic therapy and genetic prevention on a large scale. Behind this potential development is the effort initiated in 1990 by the US government to sponsor and fund a $3 billion, 15-year collaborative program, coordinated by James Watson, bringing together some of the most advanced microbiology research teams to map the human genome; that is, to identify and locate the 60,000–80,000 genes that compose the alphabet of the human species.[58] The map was expected to be completed in 2001, ahead of schedule. In April 2000, the University of California teams assembled in a research center at Walnut Creek completed the sequence of three of the 23 human chromosomes. Through this and other efforts, a continuous stream of human genes related to various diseases are being identified. This effort prompted widespread reservations and criticism on ethical, religious, and legal grounds. Yet, while scientists, regulators, and ethicists debated the humanistic implications of genetic engineering, researchers-turned-business-entrepreneurs took the short path, setting up mechanisms for legal and financial control of knowledge of the human genome. The most daring attempt in this sense was the project initiated in 1990 in Rockville, Maryland, by two scientists, J. Craig Venter, then with the National Institute of Health, and William Haseltine, then at Harvard. Using supercomputer power, they sequenced in only five years parts of about 85 percent of all human genes, creating a gigantic genetic database.[59] Later on, they split and created two companies. One of these companies, Venter's Celera Genomics, raced the Human Genome Project to complete the sequencing in 2000. The problem is that they do not know, and will not know for some time, which gene's piece is what or where it is located: their database comprises hundreds of thousands of gene fragments with unknown functions. What was then the interest? On the one hand, focused research on specific genes may (and does in fact) use to its advantage the data contained in such sequences. But, more import-antly and the main reason for the whole project, Craig and Haseltine have been busy patenting all their data, so that, literally, they may one day own the legal rights to a large portion of the knowledge to manipulate the human genome. The threat posed by such a development was serious enough that, while on the one hand they have attracted tens of millions of dollars from investors, on the other hand, a major pharmaceutical company, Merck, gave in 1994 substantial funding to Washington University to proceed with the same blind sequencing and to make the data public, so that there would be no private control of bits and pieces of knowledge which could block development of products based on a future, systematic understanding of the human genome. And the publicly funded Human Genome Project published its results to prevent private ownership of genetic knowledge. The lesson for the sociologist of such business battles is not just another instance of human greed. It signals an accelerating tempo in the spread and deepening of the genetic revolution.

The development of genetic engineering creates the possibility of acting on genes, making humankind able not only to control some

58 On the early development of biotechnology and genetic engineering, see, for instance, Hall (1987); Teitelman (1989); Bishop and Waldholz (1990); US Congress, Office of Technology Assessment (1991).

59 See *Business Week* (1995e).

diseases, but to identify biological predispositions and to intervene in such predispositions, potentially altering genetic fate. In the 1990s, scientists were able to identify precise defects in specific human genes as sources of various diseases. This prompted the expansion of the apparently most promising field of medical research, gen-etic therapy.[60] But experimental researchers hit a wall: how to deliver a modified gene with an instruction to correct the defective gene in the body to the proper place, even when they knew where the target was. Investigators generally used viruses, or artificial chromosomes, but the rate of success was extremely low. Thus, medical researchers started to experiment with other tools, such as tiny fat globules designed to carry tumor-suppressor genes directly into cancer tumors, a technology used by firms such as Valentis and Transgene. Some biologists think that this engineering mentality (one target, one messenger, one impact) overlooks the complexity of biological interaction, with living organisms adapting to various environments and changing their predicted behavior.[61]

When and if gene therapy starts yielding results, the ultimate goal of genetic-based medical therapy is prevention; that is, identifying genetic defects in human sperm and eggs, and acting on the human carriers before they develop the programmed illness, thus eliminating the genetic deficiency from them, and from their offspring, while there is still time. This perspective, of course, is full of promise as well as of dangers. Lyon and Gorner conclude their balanced survey of developments in human genetic engineering with a prediction and an admonition:

> We could in a few generations do away with certain mental illnesses, perhaps, or diabetes, or high blood pressure, or almost any affliction we selected. The important thing to keep in mind is that the quality of decision making dictates whether the choices to be made are going to be wise and just . . . The rather inglorious way that the scientific and administrative elite are handling the earliest fruits of gene therapy is ominous . . . We humans have evolved intellectually to the point that, relatively soon, we will be able to understand the composition, function, and dynamics of the genome in much of its intimidating complexity. Emotionally however, we are still apes, with all the behavioral baggage that the issue brings. Perhaps the ultimate form of gene therapy would be for our species to rise above its baser heritage and learn to apply its new knowledge wisely and benignly.[62]

60 *Business Week* (1999a: 94–104).
61 Capra (1999a); Sapolsky (2000).
62 Lyon and Gorner (1995: 567).

All indications point toward the full blossoming of genetic engineering, and its applications, in the early years of the new millennium, thus triggering a fundamental debate about the now blurred frontier between nature and society.

Social context and the dynamics of technological change

Why were discoveries in new information technologies clustered in the 1970s, and mostly in the United States? And what are the consequences of such timed/placed clustering for their future development and for their interaction with societies? It would be tempting to relate directly the formation of this technological paradigm to the characteristics of its social context, particularly if we remember that in the mid-1970s the United States and the capitalist world were shaken by a major economic crisis, epitomized (but not caused) by the oil shock of 1973–4: a crisis that prompted the dramatic restructuring of the capitalist system on a global scale, actually inducing a new model of accumulation in historical discontinuity with post-Second World War capitalism, as I proposed in the Prologue of this book. Was the new technological paradigm a response by the capitalist system to overcome its internal contradictions? Or, alternatively, was it a way to ensure military superiority over the Soviet foe, responding to its technological challenge in the space race and nuclear weaponry? Neither explanation seems to be convincing. While there is an historical coincidence between the clustering of new technologies and the economic crisis of the 1970s, their timing was too close, the "technological fix" would have been too quick, and too mechanical, when we know from the lessons of the industrial revolution and other historical processes of technological change that economic, industrial, and technological paths, while related, are slow-moving and imperfectly fitting in their interaction. As for the military argument, the Sputnik shock of 1957–60 was answered in kind by the massive technological build-up of the 1960s, not the 1970s; and the new major American military technology push was launched in 1983 around the "Star Wars" program, actually using and furthering technologies developed in the preceding, prodigious decade. And while the Internet originated from research sponsored by the Defense Department, it was not in fact used in military applications until much later, at about the same time as it started to diffuse in countercultural networks.

In fact, it seems that the emergence of a new technological system in the 1970s must be traced to the autonomous dynamics of technological discovery and diffusion, including synergistic effects between various key technologies. Thus, the microprocessor made possible the microcomputer; advances in telecommunications, as mentioned above, enabled microcomputers to function in networks, thus increasing their power and flexibility. Applications of these technologies to electronics manufacturing enhanced the potential for new design and fabrication technologies in semiconductor production. New software was stimulated by the fast-growing microcomputer market which, in turn, exploded on the basis of new applications and user-friendly technologies churned out from software writers' minds. Computer networking could expand by using software that made possible a user-oriented world wide web. And so on.

The strong, military-induced technological push of the 1960s prepared American technology for the leap forward. But Ted Hoff's invention of the microprocessor, while trying to fulfill an order for a Japanese hand calculator company in 1971, came out of knowledge and ingenuity accumulated at Intel, in close interaction with the milieu of innovation created since the 1950s in Silicon Valley. In other words, the first information technology revolution clustered in America, and to some extent in California, in the 1970s, building on developments of the two preceding decades, and under the influence of various institutional, economic, and cultural factors. But it did not come out of any pre-established necessity: it was technologically induced rather than socially determined. However, once it came into existence as a system, on the basis of the clustering I have described, its development and applications, and ultimately its content, were decisively shaped by the historical context in which it expanded. Indeed, by the 1980s, capitalism (specifically, major corporations and governments of the club of G-7 countries) did undertake a substantial process of economic and organizational restructuring, in which new information technology played a fundamental role and was decisively shaped by the role it played. For instance, the business-led movement toward deregulation and liberalization in the 1980s was decisive in the reorganization and growth of telecommunications, most notably after the 1984 divestiture of ATT. In turn, the availability of new telecommunication networks and information systems prepared the ground for the global integration of financial markets and the segmented articulation of production and trade throughout the world, as I shall examine in chapter 2.

Thus, to some extent, the availability of new technologies constituted as a system in the 1970s was a fundamental basis for the process of socio-economic restructuring in the 1980s. And the uses of such technologies in the 1980s largely conditioned their uses and trajectories in the 1990s. The rise of the network society, which I shall attempt to analyze in the following chapters of this volume, cannot be

understood without the interaction between these two relatively autonomous trends: the development of new information technologies and the old society's attempt to retool itself by using the power of technology to serve the technology of power. However, the historical outcome of such a half-conscious strategy is largely undetermined since the interaction of technology and society depends on stochastic relationships between an excessive number of quasi-independent variables. Without necessarily surrendering to historical relativism, it can be said that the information technology revolution was culturally, historically, and spatially contingent on a very specific set of circumstances whose characteristics earmarked its future evolution.

Models, Actors, and Sites of the Information Technology Revolution

If the first industrial revolution was British, the first information technology revolution was American, with a Californian inclination. In both cases scientists and industrialists from other countries did play an important role, both in the discovery and in the diffusion of new technologies. France and Germany were key sources of talent and applications in the industrial revolution. Scientific discoveries originated in England, France, Germany, and Italy were at the roots of new technologies in electronics and biology. The ingenuity of Japanese companies has been critical in the improvement of manufacturing processes in electronics and in the penetration of information technologies into everyday life around the world through a flurry of innovative products, from VCRs and faxes to video games and pagers.[63] Indeed, in the 1980s, Japanese companies came to dominate semiconductor production in the world market, although by the mid-1990s American companies by and large had retaken the competitive lead. The whole industry evolved toward interpenetration, strategic alliances, and networking between firms of different countries, as I shall analyze in chapter 3. This made differentiation by national origin somewhat less relevant. Yet not only were US innovators, firms, and institutions at the origins of the revolution in the 1970s, but they have continued to play a leading role in its expansion, which is likely to be sustained into the twenty-first century, although we shall undoubtedly witness an increasing presence of Japanese, Chinese, Korean, and Indian firms, as well as important European contributions in biotechnology, advanced chemistry, software, and telecommunications.

63 Forester (1993).

To understand the social roots of the information technology revolution in America, beyond the myths surrounding it, I shall recall briefly the process of formation of its most notorious seedbed of innovation: Silicon Valley. As I have already mentioned, it was in Silicon Valley that the integrated circuit, the microprocessor, the microcomputer, among other key technologies, were developed, and that the heart of electronics innovation has beaten for four decades, sustained by about a quarter of a million information technology workers.[64] In addition, the San Francisco Bay area at large (including other centers of innovation such as Berkeley, Emeryville, Marin County, and San Francisco itself) was also at the origins of genetic engineering and is, at the turn of the century, one of the world's leading centers of advanced software, genetic engineering, Internet design and development, and multimedia computing design.

Silicon Valley (Santa Clara County, 30 miles south of San Francisco, between Stanford and San Jose) was formed as a milieu of innovation by the convergence on one site of new technological knowledge; a large pool of skilled engineers and scientists from major universities in the area; generous funding from an assured market with the Defense Department; the development of an efficient network of venture capital firms; and, in the very early stage, the institutional leadership of Stanford University. Indeed, the unlikely location of the electronics industry in a charming, semi-rural area of northern California can be traced back to the establishment in 1951 of Stanford Industrial Park by Stanford University's visionary Dean of Engineering and Provost, Frederick Terman. He had personally supported two of his graduate students, William Hewlett and David Packard, in creating an electronics company in 1938. The Second World War was a bonanza for Hewlett Packard and other start-up electronics companies. Thus, naturally, they were the first tenants of a new, privileged location where only firms that Stanford judged innovative could benefit from a notional rent. As the Park was soon filled, new electronics firms started to locate down freeway 101 toward San Jose.

The decisive event was the moving to Palo Alto in 1955 of William Shockley, the inventor of the transistor. And this was a fortuitous development, although it reflects on the historical inability of established electronics firms to seize revolutionary micro-electronics technology. Shockley had solicited the support of large companies on the East Coast, such as RCA and Raytheon, to develop his discovery into industrial production. When he was turned down he took a job in Silicon Valley,

64 On the history of formation of Silicon Valley, two useful, easy-reading books are Rogers and Larsen (1984) and Malone (1985).

with a subsidiary of Beckman Instruments, mainly because his mother lived in Palo Alto. With the support of Beckman Instruments he decided to create there his own company, Shockley Transistors, in 1956. He recruited eight brilliant young engineers, mainly from Bell Labs, attracted by the possibility of working with Shockley; one of them, although not precisely from Bell Labs, was Bob Noyce. They were soon disappointed. While learning the fundamentals of cutting-edge micro-electronics from Shockley, they were turned off by his authoritarianism and stubbornness which led the firm into dead-ends. In particular, they wanted, against his decision, to work on silicon as the most promising route to the larger integration of transistors. Thus, after only one year they left Shockley (whose firm collapsed) and created (with the help of Fairchild Cameras) Fairchild Semiconductors, where the invention of the planar process and of the integrated circuit took place in the next two years. While Shockley, after repeated business failures, finally took refuge in a Stanford professorship in 1963, the "Fairchild Eight," as soon as they discovered the technological and business potential of their knowledge, left Fairchild one by one to start their own firms. And their new recruits did the same after some time, so that one-half of the 85 largest American semiconductors firms, including today's leading producers such as Intel, Advanced Micro Devices, National Semiconductors, Signetics, and so on, can be traced back to this spin-off from Fairchild.

It was this technology transfer from Shockley to Fairchild, then to a network of spin-off companies, that constituted the initial source of innovation on which Silicon Valley and the micro-electronics revolution were built. Indeed, by the mid-1950s Stanford and Berkeley were not yet leading centers in electronics; MIT was, and this was reflected in the original location of the electronics industry in New England. However, as soon as knowledge was available in Silicon Valley, the dynamism of its industrial structure and the continuous creation of start-up firms anchored Silicon Valley as the world's micro-electronics center by the early 1970s. Anna Saxenian compared the development of electronics complexes in the two areas (Boston's Route 128 and Silicon Valley) and concluded that the decisive role was played by the social and industrial organization of companies in fostering or stymieing innovation.[65] Thus, while large, established companies in the East were too rigid (and too arrogant) to constantly retool themselves toward new technological frontiers, Silicon Valley kept churning out new firms, and practicing cross-fertilization and knowledge diffusion by job-hopping and spin-offs. Late-evening conversations at the

65 Saxenian (1994).

Walker's Wagon Wheel Bar and Grill in Mountain View did more for the diffusion of technological innovation than most seminars in Stanford.

As I have elaborated elsewhere,[66] another key factor in the formation of Silicon Valley was the existence of a network of venture capital firms early on.[67] The significant factor here is that many of the early investors originated from the electronics industry, and thus they were knowledgeable about the technological and business projects on which they were betting. For instance, Gene Kleinert, of one of the most important venture capital firms in the 1960s, Kleinert, Perkins, and partners, was one of the Fairchild Eight engineers. In 1988, it could be estimated that "venture capital accounted for about one-half of the new product and service investment associated with the information and communication industry."[68]

A similar process took place in the development of the microcomputer, which introduced an historical divide in the uses of information technology.[69] By the mid-1970s Silicon Valley had attracted tens of thousands of bright young minds from around the world, coming to the excitement of the new technological Mecca in a quest for the talisman of invention and money. They gathered in loose groups, to exchange ideas and information on the latest developments. One such gathering was the Home Brew Computer Club, whose young visionaries (including Bill Gates, Steve Jobs, and Steve Wozniak) would go on to create in the following years up to 22 companies, including Microsoft, Apple, Comenco, and North Star. It was the club's reading, in *Popular Electronics*, of an article reporting Ed Roberts's Altair machine which inspired Wozniak to design a microcomputer, Apple I, in his Menlo Park garage in the summer of 1976. Steve Jobs saw the potential, and together they founded Apple, with a $91,000 loan from an Intel executive, Mike Markkula, who came in as a partner. At about the same time Bill Gates founded Microsoft to provide the operating system for microcomputers, although he located his company in 1978 in Seattle to take advantage of the social contacts of his family.

A parallel story could be told about the growth of genetic engineering, with leading scientists at Stanford, UC San Francisco and Berkeley bridging into companies, first located in the Bay area. They would also go through the process of frequent spin-off, while keeping close ties with their alma maters.[70] Comparable processes took place in Boston/Cambridge around Harvard–MIT, in the research triangle around Duke University and the University of North Carolina, and, more importantly, in Maryland around major hospitals, national health research institutes, and The Johns Hopkins University.

66 Castells (1989b: ch. 2).
67 Zook (2000c).
68 Kay (1990: 173).
69 Levy (1984); Egan (1995). For an interesting case study of the complex interaction between technological creativity and business strategies, see Hiltzik (1999) on the experience of one of most important centers of innovation in Silicon Valley, Xerox-PARC.
70 Blakely et al. (1988); Hall et al. (1988).

The conclusion to be drawn from these colorful stories is twofold: first, the development of the information technology revolution contributed to the formation of the milieux of innovation where discoveries and applications would interact, and be tested, in a recurrent process of trial and error, of learning by doing; these milieux required (and still do in the early twenty-first century, in spite of on-line networking) the spatial concentration of research centers, higher-education institutions, advanced-technology companies, a network of ancillary suppliers of goods and services, and business networks of venture capital to finance start-ups. Secondly, once a milieu is consolidated, as Silicon Valley was in the 1970s, it tends to generate its own dynamics, and to attract knowledge, investment, and talent from around the world. Indeed, in the 1990s Silicon Valley benefited from a proliferation of Japanese, Taiwanese, Korean, Indian, and European companies, and from the influx of thousands of engineers and computer experts, mainly from India and China, for whom an active presence in the Valley is the most productive linkage to the sources of new technology and valuable business information.[71] Furthermore, because of its positioning in the networks of technological innovation, and because of its built-in business understanding of the rules of the new information economy, the San Francisco Bay area has been able to jump on any new development. In the 1990s, when the Internet was privatized, and became a commercial technology, Silicon Valley was also able to capture the new industry. Leading Internet equipment companies (such as Cisco Systems), computer networking companies (such as Sun Microsystems), software companies (such as Oracle), and Internet portals (such as Yahoo!) started in Silicon Valley.[72] Moreover, most of the Internet start-ups that introduced e-commerce, and revolutionized business (such as Ebay), also clustered in Silicon Valley. The coming of multimedia in the mid-1990s created a network of technological and business linkages between computer-design capabilities from Silicon Valley companies and image-producing studios in Hollywood, immediately labeled the "Siliwood" industry. And in a run-down corner of San Francisco (South of Market), artists, graphic designers, and software writers came together in the so-called "Multimedia Gulch" that threatens to flood our living rooms with images coming from their fevered minds – in the

71 Saxenian (1999).
72 Reid (1997); Bronson (1999); Kaplan (1999); Lewis (2000); Zook (2000c).

process creating the most dynamic multimedia design center in the world.[73]

Can this social, cultural, and spatial pattern of innovation be extrapolated throughout the world? To answer this question, in 1988 my colleague Peter Hall and I began a several years' tour of the world that brought us to visit and analyze some of the main scientific/technological centers of this planet, from California to Japan, New England to Old England, Paris-Sud to Hsinchu–Taiwan, Sophia-Antipolis to Akademgorodok, Szelenograd to Daeduck, Munich to Seoul. Our conclusions[74] confirm the critical role played by milieux of innovation in the development of the information technology revolution: clusters of scientific/technical knowledge, institutions, firms, and skilled labor are the furnaces of innovation in the Information Age. Yet they do not need to reproduce the cultural, spatial, institutional and industrial pattern of Silicon Valley or, for that matter, of other American centers of technological innovation, such as southern California, Boston, Seattle, or Austin.

Our most striking discovery is that the largest, old metropolitan areas of the industrialized world are the main centers of innovation and production in information technology outside the United States. In Europe, Paris-Sud constitutes the largest concentration of high-technology production and research; and London's M4 corridor is still Britain's pre-eminent electronics site, in historical continuity with ordnance factories working for the crown since the nineteenth century. The displacement of Berlin by Munich was obviously related to the German defeat in the Second World War, with Siemens deliberately moving from Berlin to Bavaria in anticipation of American occupation of that area. Tokyo–Yokohama continues to be the technological core of the Japanese information technology industry, in spite of the decentralization of branch plants operated under the Technopolis Program. Moscow–Szelenograd and St Petersburg were and are the centers of Soviet and Russian technological knowledge and production, after the failure of Khrushchev's Siberian dream. Hsinchu is in fact a satellite of Taipei; Daeduck never played a significant role *vis-à-vis* Seoul-Inchon, in spite of being in the home province of dictator Park; and Beijing and Shanghai are, and will be, the core of Chinese technological development. And so are Mexico City in Mexico, São Paulo–Campinas in Brazil, and Buenos Aires in Argentina. In this sense, the technological fading of old American metropolises (New York/New Jersey, in spite of its prominent role up to the 1960s, Chicago, Detroit, Philadelphia) is the exception at the international level, linked to American exceptionalism of frontier spirit, and to its endless escapism from the contradictions of built cities and constituted societies. On the other hand, it would be intriguing to explore the relationship between this American exceptionalism and the indisputable American pre-eminence in a technological revolution characterized by the need to break mental molds to spur creativity.

73 Rosen et al. (1999).
74 Castells and Hall (1994).

Yet the metropolitan character of most sites of the information technology revolution around the world seems to indicate that the critical ingredient in its development is not the newness of the institutional and cultural setting, but its ability to generate synergy on the basis of knowledge and information, directly related to industrial production and commercial applications. The cultural and business strength of the metropolis (old or new – after all, the San Francisco Bay area is a metropolis of about 6.5 million people) makes it the privileged environment of this new technological revolution, actually demystifying the notion of placelessness of innovation in the Information Age.

Similarly, the entrepreneurial model of the information technology revolution seems to be overshadowed by ideology. Not only are the Japanese, European, and Chinese models of technological innovation quite different from the American experience, but even this leading experience is often misunderstood. The role of the state is generally acknowledged as decisive in Japan, where large corporations were guided and supported by the Ministry of International Trade and Industry (MITI) for a long time, well into the 1980s, through a series of bold technological programs, some of which failed (for example, the Fifth Generation Computer), but most of which helped to transform Japan into a technological superpower in just about 20 years, as Michael Borrus has documented.[75] No start-up innovative firms and little role for universities can be found in the Japanese experience. Strategic planning by MITI and the constant interface between the *keiretsu* and government are key elements in explaining the Japanese prowess that overwhelmed Europe and overtook the US in several segments of information technology industries. A similar story can be told about South Korea and Taiwan, although in the latter case multinationals played a greater role. India and China's strong technological bases are directly related to their military–industrial complex, under state funding and guidance.

But so was also the case for much of the British and French electronics industries, centered on telecommunications and defense, until the 1980s.[76] In the last quarter of the twentieth century, the European

75 Borrus (1988).
76 Hall et al. (1987).

Union proceeded with a series of technological programs to keep up with international competition, systematically supporting "national champions," even at a loss, and without much result. Indeed, the only way for European information technology companies to survive technologically has been to use their considerable resources (a substantial share of which comes from government funds) to make alliances with Japanese and American companies, which are increasingly their main source of know-how in advanced information technology.[77]

Even in the US it is a well-known fact that military contracts and Defense Department technological initiatives played decisive roles in the formative stage of the information technology revolution; that is, between the 1940s and the 1970s. Even the major source of electronics discovery, Bell Laboratories, played the role of a national laboratory: its parent company (ATT) enjoyed a government-enforced monopoly of telecommunications; a significant part of its research funds came from the US government; and ATT was in fact forced by the government from 1956, in return for its monopoly on public telecommunications, to diffuse technological discoveries into the public domain.[78] MIT, Harvard, Stanford, Berkeley, UCLA, Chicago, Johns Hopkins, and national weapons laboratories such as Livermore, Los Alamos, Sandia, and Lincoln, worked with and for Defense Department agencies on programs that led to fundamental breakthroughs, from the 1940s' computers to opto-electronics and artificial intelligence technologies of the 1980s' "Star Wars" programs. DARPA, the extraordinarily innovative Defense Department Research Agency, played in the US a role not too different from that of MITI in Japan's technological development, including the design and initial funding of the Internet.[79] Indeed, in the 1980s, when the ultra-*laissez-faire* Reagan administration felt the pinch of Japanese competition, the Defense Department funded SEMATECH, a consortium of American electronics companies to support costly R&D programs in electronics manufacturing, for reasons of national security. And the federal government also helped the effort by major firms to cooperate in micro-electronics by creating MCC, with both SEMATECH and MCC locating in Austin, Texas.[80] Also, during the decisive 1950s and 1960s, military contracts and the space program were essential markets for the electronics industry, both for the giant defense contractors of southern California and for the start-up innovators of Silicon Valley and New England.[81]

77 Castells et al. (1991); Freeman et al. (1991).
78 Bar (1990).
79 Tirman (1984); Broad (1985); Stowsky (1992).
80 Borrus (1988); Gibson and Rogers (1994).
81 Roberts (1991).

They could not have survived without the generous funding and protected markets of a US government anxious to recover technological superiority over the Soviet Union, a strategy that eventually paid off. Genetic engineering spun off from major research universities, hospitals, and health research institutes, largely funded and sponsored by government money.[82] Thus, the state, not the innovative entrepreneur in his garage, both in America and throughout the world, was the initiator of the information technology revolution.[83]

However, without these innovative entrepreneurs, such as those at the origin of Silicon Valley or of Taiwan's PC clones, the information technology revolution would have had very different characteristics, and it is unlikely that it would have evolved toward the kind of decentralized, flexible technological devices that are diffusing through all realms of human activity. Indeed, since the early 1970s, technological innovation has been essentially market driven:[84] and innovators, while still often employed by major companies, particularly in Japan and Europe, continue to establish their own businesses in America and, increasingly, around the world. This gives rise to an acceleration of technological innovation and a faster diffusion of such innovation, as ingenious minds, driven by passion and greed, constantly scan the industry for market niches in products and processes. *It is indeed by this interface between macro-research programs and large markets developed by the state, on the one hand, and decentralized innovation stimulated by a culture of technological creativity and role models of fast personal success, on the other hand, that new information technologies came to blossom.* In so doing, they clustered around networks of firms, organizations, and institutions to form a new socio-technical paradigm.

The Information Technology Paradigm

As Christopher Freeman writes:

> A techno-economic paradigm is a cluster of interrelated technical, organizational, and managerial innovations whose advantages are to be found not only in a new range of products and systems, but most of all in the dynamics of the relative cost structure of all possible inputs to production. *In each new paradigm a particular input or set of inputs may be described as the "key factor" in that paradigm characterized by*

82 Kenney (1986).
83 See the analyses gathered in Castells (1988b).
84 Banegas (1993).

> *falling relative costs and universal availability*. The contemporary change of paradigm may be seen as a shift from a technology based primarily on cheap inputs of energy to one *predominantly based on cheap inputs of information derived from advances in microelectronic and telecommunications technology*.[85]

The notion of the technological paradigm, elaborated by Carlota Perez, Christopher Freeman, and Giovanni Dosi, adapting the classic analysis of scientific revolutions by Kuhn, helps to organize the essence of current technological transformation as it interacts with economy and society.[86] Rather than refining the definition to include social processes beyond the economy, I think it would be useful, as a guide to our forthcoming journey along the paths of social transformation, to pinpoint those features that constitute the heart of the information technology paradigm. Taken together, they are the material foundation of the network society.

The first characteristic of the new paradigm is that information is its raw material: *these are technologies to act on information*, not just information to act on technology, as was the case in previous technological revolutions.

The second feature refers to the *pervasiveness of effects of new technologies*. Because information is an integral part of all human activity, all processes of our individual and collective existence are directly shaped (although certainly not determined) by the new technological medium.

The third characteristic refers to the *networking logic* of any system or set of relationships using these new information technologies. The morphology of the network seems to be well adapted to increasing complexity of interaction and to unpredictable patterns of development arising from the creative power of such interaction.[87] This topological configuration, the network, can now be materially implemented,

85 C. Freeman, "Preface to part II," in Dosi et al. (1988a: 10).
86 Kuhn (1962); Perez (1983); Dosi et al. (1988a).
87 Kelly (1995: 25–7) elaborates on the properties of networking logic in a few telling paragraphs: "The Atom is the past. The symbol of science for the next century is the dynamical Net . . . Whereas the Atom represents clean simplicity, the Net channels the messy power of complexity . . . The only organization capable of nonprejudiced growth, or unguided learning is a network. All other topologies limit what can happen. A network swarm is all edges and therefore open ended any way you come at it. Indeed, the network is the least structured organization that can be said to have any structure at all . . . In fact a plurality of truly divergent components can only remain coherent in a network. No other arrangement – chain, pyramid, tree, circle, hub – can contain true diversity working as a whole." Although physicists and mathematicians may take exception to some of these statements, Kelly's basic message is an interesting one: the convergence between the evolutionary topology of living matter, the open-ended nature of an increasingly complex society, and the interactive logic of new information technologies.

in all kinds of processes and organizations, by newly available information technologies. Without them, the networking logic would be too cumbersome to implement. Yet this networking logic is needed to structure the unstructured while preserving flexibility, since the unstructured is the driving force of innovation in human activity. Moreover, when networks diffuse, their growth becomes exponential, as the benefits of being in the network grow exponentially, because of the greater number of connections, and the cost grows in a linear pattern. Besides, the penalty for being outside the network increases with the network's growth because of the declining number of opportunities in reaching other elements outside the network. The creator of local area networks technology, Robert Metcalfe, proposed in 1973 a simple mathematical formula showing how the value of a network increases as the square of the number of nodes in the net. The formula is $V = n^{(n-1)}$ where n is the number of nodes in the network.

Fourthly, related to networking but a clearly distinct feature, the information technology paradigm is based on *flexibility*. Not only processes are reversible, but organizations and institutions can be modified, and even fundamentally altered, by rearranging their components. What is distinctive to the configuration of the new technological paradigm is its ability to reconfigure, a decisive feature in a society characterized by constant change and organizational fluidity. Turning the rules upside down without destroying the organization has become a possibility because the material basis of the organization can be reprogrammed and retooled.[88] However, we must stop short of a value judgment attached to this technological feature. This is because flexibility could be a liberating force, but also a repressive tendency if the rewriters of rules are always the powers that be. As Mulgan wrote: "Networks are created not just to communicate, but also to gain position, to outcommunicate."[89] It is thus essential to keep a distance between assessing the emergence of new social forms and processes, as induced and allowed by new technologies, and extrapolating the potential consequences of such developments for society and people: only specific analyses and empirical observation will be able to determine the outcome of interaction between new technologies and emerging social forms. Yet it is essential as well to identify the logic embedded in the new technological paradigm.

Then, a fifth characteristic of this technological revolution is the growing *convergence of specific technologies into a highly integrated system*, within which old, separate technological trajectories become

88 Tuomi (1999).
89 Mulgan (1991: 21).

literally indistinguishable. Thus, micro-electronics, telecommunications, opto-electronics, and computers are all now integrated into information systems. There still exists, and will exist for some time, some business distinction between chip makers and software writers, for instance. But even such differentiation is blurred by the growing integration of business firms in strategic alliances and cooperative projects, as well as by the inscription of software programs into chip hardware. Furthermore, in terms of technological system, one element cannot be imagined without the other: computers are largely determined by chip power, and both the design and the parallel processing of microprocessors depend on computer architecture. Telecommunications is now but one form of processing information; transmission and linkage technologies are at the same time increasingly diversified and integrated into the same network, operated by computers.[90] As I analyzed above, the development of the Internet is reversing the relationship between circuit switching and packet switching in communication technologies, so that data transmission becomes the predominant, universal form of communication. And data transmission is based on software instructions of coding and decoding.

Technological convergence increasingly extends to growing interdependence between the biological and micro-electronics revolutions, both materially and methodologically. Thus, decisive advances in biological research, such as the identification of human genes or segments of human DNA, can only proceed because of massive computing power.[91] Nanotechnology may allow sending tiny microprocessors into the systems of living organisms, including humans.[92] On the other hand, the use of biological materials in micro-electronics, although still very far from a generalized application, was already at the experimentation stage in the late 1990s. In 1995, Leonard Adleman, a computer scientist at the University of Southern California, used synthetic DNA molecules, and with the help of a chemical reaction made them work according to the DNA combining logic as the material basis for computing.[93] Although research has still a long way to go toward the material integration of biology and electronics, the logic of biology (the ability to self-generate unprogrammed, coherent sequences) is increasingly being introduced into electronic machines.[94] In 1999, Harold

90 Williams (1991).
91 Bishop and Waldholz (1990); *Business Week* (1995e, 1999b).
92 Hall (1999b).
93 Allen (1995).
94 See, for an analysis of trends, Kelly (1995); for an historical perspective on the convergence between mind and machines, see Mazlish (1993); for a theoretical reflection, see Levy (1994).

Abelson and his colleagues at MIT's computer science laboratory were trying to "hack" the *E. coli* bacterium so that it would be able to function as an electronic circuit, with the ability to reproduce itself. They were experimenting with "amorphous computing;" that is, mapping circuitry into biological material. Because biological cells could only compute as long as they were alive, this technology would combine with molecular electronics, by packing millions or billions of these biologically based switches in very tiny spaces, with the potential application of producing "smart materials" of all kinds.[95]

Some experiments of advanced research in human–computer interaction rely on the use of adaptive brain interfaces that recognize mental states from on-line spontaneous electroencephalogram (EEG) signals, based on artificial neural network theory. Thus, in 1999, at the European Union Joint Research Center in Ispra, Italy, computer scientist Jose Millan and his colleagues were able to show experimentally that people wearing a compact EEG helmet could communicate through conscious control of their thoughts.[96] Their approach was based on a mutual learning process whereby the user and the brain interface are coupled and adapt to each other. Therefore, a neural network learns user-specific EEG patterns while subjects learn to think in such a way that they are better understood by the personal interface.

The continuing convergence between different technological fields in the information paradigm results from their shared logic of information generation, a logic which is most apparent in the working of DNA and in natural evolution and which is increasingly replicated in the most advanced information systems, as chips, computers, and software reach new frontiers of speed, storage capacity, and flexible treatment of information from multiple sources. While the reproduction of the human brain, with its billions of circuits and unsurpassable recombining capacity, is strictly science fiction, the boundaries of information power of today's computers are being transgressed month by month.[97]

From the observation of such extraordinary changes in our machines and knowledge of life, and with the help provided by these machines and this knowledge, a deeper technological transformation is taking place: that of categories under which we think all processes. Historian of technology Bruce Mazlish proposes the idea of the necessary

> recognition that human biological evolution, now best understood in cultural terms, forces upon humankind – us – the consciousness that

95 Markoff (1999b).
96 Millan et al. (2000).
97 See the excellent prospective analysis by Gelernter (1991).

> tools and machines are inseparable from evolving human nature. It also requires us to realize that the development of machines, culminating in the computer, makes inescapable the awareness that the same theories that are useful in explaining the workings of mechanical contrivances are also useful in understanding the human animal – and vice versa, for the understanding of the human brain sheds light on the nature of artificial intelligence.[98]

From a different perspective, based on the fashionable discourses of the 1980s on "chaos theory," in the 1990s a network of scientists and researchers converged toward a shared epistemological approach, identified by the code word "complexity." Organized around seminars held at the Santa Fe Institute in New Mexico (originally a club of high-level physicists from Los Alamos Laboratory, soon joined by a select network of Nobel Prize winners and their friends), this intellectual circle aims at communicating scientific thought (including social sciences) under a new paradigm. They focus on understanding the emergence of self-organizing structures that create complexity out of simplicity and superior order out of chaos, through several orders of interactivity between the basic elements at the origin of the process.[99] Although this project is often dismissed by mainstream science as a non-verifiable proposition, it is one example of the effort being made in different quarters toward finding a common ground for the intellectual cross-fertilization of science and technology in the Information Age. Yet this approach seems to forbid any integrating, systemic framework. Complexity thinking should be considered as a method for understanding diversity, rather than as a unified meta-theory. Its epistemological value could come from acknowledging the self-organizing character of nature and of society. Not that there are no rules, but that rules are created, and changed, in a relentless process of deliberate actions and unique interactions. Thus, in 1999, a young researcher at the Santa Fe Institute, Duncan Watts, proposed a formal analysis of the networking logic underlying the formation of "small worlds;" that is, the widespread set of connections, in nature and in society, between elements which, even when they do not communicate directly, are in fact related by a short chain of intermediaries. For instance, he shows, mathematically, that if we represent systems of relations by a graph, the key to generating a small-world phenomenon

98 Mazlish (1993: 233).
99 The diffusion of chaos theory to a broad audience was largely due to the bestseller of Gleick (1987); see also Hall (1991). For a clearly written, intriguing history of the "complexity" school, see Waldrop (1992). I have also relied on personal conversations with Santa Fe Institute researchers during my visit to the Institute in November 1998. I am particularly grateful to Brian Arthur for sharing his thoughts.

(which epitomizes a networking logic) is the presence of a small fraction of very long-range, global edges, which contract otherwise distant parts of the graph, while most edges remain local, organized in clusters.[100] This accurately represents the logic of local/global networking of innovation, as documented in this chapter. The important contribution of the complexity theory school of thought is its emphasis on non-linear dynamics as the most fruitful approach to understanding the behavior of living systems, both in society and in nature. Most of the work of the Santa Fe Institute researchers is of a mathematical nature, not an empirically based analysis of natural or social phenomena. But there are researchers in a number of fields of science using non-linear dynamics as their guiding principle, with increasingly important scientific results. Fritjof Capra, a theoretical physicist and ecologist at Berkeley, has integrated many of these results in an outline of a coherent theory of living systems in a series of books, particularly in his remarkable *Web of Life*.[101] He built on the work of Nobel Prize winner Ilya Prigogine. Prigogine's theory of dissipative structures demonstrated the non-linear dynamics of self-organization of chemical cycles, and allowed new understanding of the spontaneous emergence of order as a key characteristic of life. Capra shows how cutting-edge research in areas as diverse as cell development, global ecological systems (as represented by the controversial Gaia theory, and by Lovelock's "Daisyworld" simulation model), neuroscience (as in the work of Gerald Edelman or Oliver Sacks), and studies on the origins of life based on emerging chemical network theory, are all manifestations of a non-linear dynamics perspective.[102] Key new concepts, such as attractors, phase portraits, emergent properties, fractals, offer new perspectives in making sense of observations of behavior in living systems, including social systems – thus paving the way for a theoretical linkage between various fields of science. Not by reducing them to a common set of rules, but by explaining processes and outcomes from the self-generating properties of specific living systems. Brian Arthur, a Stanford economist with the Santa Fe Institute, has applied complexity theory to formal economic theory, proposing concepts such as self-reinforcing mechanisms, path dependency, and emergent properties, and showing their relevance in understanding the features of the new economy.[103]

In sum, the information technology paradigm does not evolve toward its closure as a system, but toward its openness as a multi-edged

100 Watts (1999).
101 Capra (1996).
102 Capra (1999b).
103 Arthur (1998).

network. It is powerful and imposing in its materiality, but adaptive and open-ended in its historical development. Comprehensiveness, complexity, and networking are its decisive qualities. Thus, the social dimension of the information technology revolution seems bound to follow the law on the relationship between technology and society proposed some time ago by Melvin Kranzberg: "*Kranzberg's First Law reads as follows: Technology is neither good nor bad, nor is it neutral.*"[104] It is indeed a force, probably more than ever under the current technological paradigm that penetrates the core of life and mind.[105] But its actual deployment in the realm of conscious social action, and the complex matrix of interaction between the technological forces unleashed by our species, and the species itself, are matters of inquiry rather than of fate. I shall now proceed with such an inquiry.

104 Kranzberg (1985: 50).
105 For an informative, casual discussion of recent developments at the crossroads of science and the human mind, see Baumgartner and Payr (1995). For a more forceful, if controversial, interpretation by one of the founders of the genetic revolution, see Crick (1994).

2

The New Economy: Informationalism, Globalization, Networking

A new economy emerged in the last quarter of the twentieth century on a worldwide scale. I call it informational, global, and networked to identify its fundamental distinctive features and to emphasize their intertwining. It is *informational* because the productivity and competitiveness of units or agents in this economy (be it firms, regions, or nations) fundamentally depend upon their capacity to generate, process, and apply efficiently knowledge-based information. It is *global* because the core activities of production, consumption, and circulation, as well as their components (capital, labor, raw materials, management, information, technology, markets) are organized on a global scale, either directly or through a network of linkages between economic agents. It is *networked* because, under the new historical conditions, productivity is generated through and competition is played out in a global network of interaction between business networks. This new economy emerged in the last quarter of the twentieth century because the information technology revolution provided the indispensable, material basis for its creation. It is the historical linkage between the knowledge–information base of the economy, its global reach, its network-based organizational form, and the information technology revolution that has given birth to a new, distinctive economic system, whose structure and dynamics I shall explore in this chapter.

To be sure, information and knowledge have always been critical components of economic growth, and the evolution of technology has