

Knell, Mark; Vannuccini, Simone

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Mark Knell and Simone Vannuccini¹

Abstract

This chapter is about radical innovation and disruptive technological change. Discovering the nature and mechanisms of disruptive technological change can help to understand the long-run dynamics of innovation and map profound transformation in socio-economic systems. The chapter considers four concepts essential for the understanding radical and disruptive technological change: long waves, techno-economic paradigms, general purpose technologies (GPTs), and disruptive technologies. We conclude with some insights on the emerging technologies in the latest techno-economic paradigm. The tools and concepts given here remain the cornerstone of a useful theory of innovation and change even in our current complex socio-technical landscape.

Keywords: Radical innovation, Kondratiev; long wave cycle; Schumpeter; perennial gale of creative destruction; technological discontinuities, techno-economic paradigm; technological revolution; great surge of development; general purpose technology; disruptive technology; emerging technology

Introduction

This chapter is about radical innovation and disruptive technological change. Discovering the sources, nature and mechanisms of disruptive technological change can help to understand the long-run dynamics of innovation and map profound transformation in socio-economic systems. Schumpeter (1912) argued that innovation comes from within the economic system, will happen discontinuously, displace old equilibria, and create radically new conditions over extended periods of time. Innovative entrepreneurs and enterprises propel the evolution of the socioeconomic system by carrying out “‘new combinations’ of already existing ideas” (Kurz 2012: 872). These result in new products, new methods of production, new markets, new materials and resources, and new forms of business organization (including new business models and new types of networks). Schumpeter continued this line of inquiry in his book *Business Cycles* where he explains how technology and technological revolutions shape

¹ Knell: NIFU, mark.knell@nifu.no; Vannuccini: SPRU, University of Sussex, S.Vannuccini@sussex.ac.uk. The paper appeared as Chapter 4 in the “The Routledge Handbook of Smart Technologies: An Economic and Social Perspective”, edited by Heinz D. Kurz, Marlies Schütz, Rita Strohmaier, and Stella Zilian (2022).

exceptionally long run economic dynamics. These revolutionary disturbances can be enormous in the sense that they “will disrupt the existing system and enforce a distinct process of adaptation” (Schumpeter 1939: 101). Schumpeter (1942: 83) then described how the “process of industrial mutation [...] incessantly *revolutionizes* the economic structure from within, incessantly destroying the old one, incessantly creating a new one”.

Radical innovation, technological revolutions, and *creative destruction* are tools and concepts essential for understanding disruptive technological change and economic fluctuations from a Schumpeterian perspective. A central idea of Schumpeter (1935: 233) was that innovations are not ‘evenly distributed through time’ but “appear, if at all, discontinuously in groups or swarms”, often in close geographic proximity with other innovations. The resulting *swarms* of innovations created new and rapidly growing sectors, led to considerable structural transformation, a narrative Schumpeter (1942) referred to as the “perennial gale of creative destruction”. A vast literature appeared from these ideas, which now forms the post-Schumpeterian narrative that overlaps with the evolutionary approach to economics (Nelson et al. 2018), adaptive growth (Metcalf et al. 2006) and transformational growth (Nell 1998).

Technological discontinuities were a main concern of Schumpeter, but few economists use the same vocabulary today. This may be because economists typically look for the cumulative effects of the radical innovation, and not the radical innovation itself (Harris 1991). Yet, the very idea that technological discontinuities occur stem from a broader philosophical debate on the nature of change and evolution. Mokyr (1990) compares technological discontinuities (macroinventions) with biological speciation – the radical appearance of a new species that directly contradicts Darwin’s claim that *nature does not make leaps*. He characterises technological change by punctuated equilibria, with prolonged periods of incremental improvements succeeded by rapid bursts of radical novelties. From this perspective, technological change displays non-linear dynamics, and to have an idea whether these non-linearity show some identifiable pattern is important, as that would help the prediction of long-run outcomes.

Arthur (2009: 17) suggested that evolutionary models cannot account for radically novel technologies. Innovative technologies are supposedly “radical” when the functions they perform are novel and when, at the same time, they give rise to entirely new configurations of known functions (Langlois 2017). The invention of the microprocessor in 1971 is a good

example of a radical technological discontinuity that became the core technology of the digital revolution. It was truly transformational. Technological discontinuities appeared throughout history, and include the factory system, steam engine, electricity, steel, and the internet. Social scientists hardly notice them at first, but over time they transformed the way we live and work, enabled new business models, and the creation of new firms and industries. To derive an ideal type of technological discontinuities is not a trivial task, especially because of the recursive and systemic nature of technologies allows for the co-existence of discontinuities and incremental improvements at the same time and at different scales.¹

Schumpeter (1935, 1939) employed the idea of long waves to describe an industrial revolution or Kondratiev long cycle. The industrial revolution was a specific kind of technology revolution that began with the introduction of the water frame spinning machine introduced by Arkwright in the early 1770s. The idea of industrial revolution was initially part of the continental economic discourse in the mid-19th century when Friedrich Engels (1845: 307) used the term to describe how “the invention of the steam-engine and of machinery for working cotton” gave rise “to an industrial revolution, a revolution which altered the whole civil society”. Toynbee (1884) introduced the expression into the English discourse through a series of lectures on the industrial revolution, published posthumously.

The literature on the economics of technical change has only recently become aware of the heterogeneity characterising technologies. The idea of General Purpose Technology (GPT) takes this into account (Helpman 1998). A similar dynamic appears in the business and management literature, that represents major technological innovations as radical, breakthrough, discontinuous or disruptive innovations. All these constructs rely on similar foundations, but rarely refer to Schumpeter. Business Studies stress the importance of discontinuities, individual inventors, innovation networks, or sudden breakthroughs that allow firms, industries, and markets to appear, transform, or disappear (see Tushman and Anderson 1986, Christensen 1997, and Tushman and O’Reilly 1996). Christensen (1997) pioneered the term “disruptive innovation”, which takes a more product and market-oriented perspective on the issue of technological discontinuity. Disruptive innovations need not be radical but can produce a sizeable turbulence in the markets in which they appear. Technological discontinuities underlying the business cycle often have disruptive effects on the structure of an industry, and revolutionary effects on the fabric of society.

Finally, there is the issue of emerging technologies. Rotolo et al. (2015) define emerging technologies by five attributes: radical novelty, fast growth, coherence, prominent impact, and uncertainty and ambiguity. They use scientometric techniques to map emerging technologies in terms of growth, radical novelty, and coherence, and *future-oriented technology analysis* to select emerging technologies, including its impact, uncertainty and ambiguity. At the end of this chapter, we consider possible emerging technologies including nanotechnology, biotechnology, quantum computing, and AI, and what role they might play in the next technology revolution (or Kondratiev long wave).

In this chapter we review four concepts essential for understanding radical and disruptive technological change: long waves, techno-economic paradigms, general purpose technologies (GPTs), and disruptive technologies. This chapter draws its inspiration from Schumpeter's vision of long waves (1939) and developed further by Knell (2010, 2013, 2021) and Cantner and Vannuccini (2012). Our focus is on technology, but we rule out a reading based on technological determinism. In line with Heilbroner (1967), we are aware that technology influences but does not exclusively decide the socioeconomic order. The following section introduces early long wave theory and the Kondratiev long cycle. Section three summarises Schumpeter's three cycle model, emphasising the Kondratiev long wave. We summarize long waves modelling methods after Schumpeter in section four. Section five describes the theory behind the techno-economic paradigm and section six presents a brief historical narrative supporting the theory. We then cover GPTs in section seven and disruptive technologies in section eight. Section nine considers the range between discontinuous and continuous innovation. The concluding section covers the emerging technologies.

On the origin of long waves

Schumpeter (1939: 252) regarded Kondratiev as the first economist to provide a “reasonably clear statistical description” of the long wave. Several economists had noticed them previously, namely Hyde Clarke, W.S. Jevons, and Clement Juglar in the nineteenth century, and John Bates Clark, Knut Wicksell, Vilfredo Pareto and Mikhail Tugan-Baranovsky in the early twentieth century.² Using long-term price data, they found climate, demographics, land speculation, sunspots and famines, secular stagnation, and the possibility of crisis were all plausible explanations of the long cycle. Marx and Engels were not direct precursors to long

wave theory, they had experienced frequent periods of unrest, especially the global crisis of 1857-58, secular stagnation, and extreme inequality in their lifetime.

An active participant in the *Soviet Industrialization Policy Debate* of the 1920s, Nikolai Kondratiev published several papers on long wave cycles before his death in 1938 during the Great Purge. Two English translations had an immediate impact followed by two all-inclusive versions published posthumously in 1979 and 1984 as well as his collected works in 1999. Inspiration originated in Marshall's approach to competitive equilibrium, Marx's periodic renewal of fixed capital, and Tugan-Baranovsky's endogenous theory of the business cycle.³ Kondratiev used the term long wave cycle to stress their cyclical character (Garvy 1943, Louçã 1999), but others named them long waves, long cycles, or long swings (Tylecote 1994). These papers received much criticism in his lifetime for his use of statistical and econometric techniques. Kondratiev (1925, 1928) addressed some of these concerns in a methodological paper on reversible dynamic processes. Trotsky (1973: 273) believed that the downward phase of a Kondratiev cycle implied the decline of capitalism, harshly criticizing Kondratiev's interpretation of equilibrium and self-reinforcing mechanisms in economic development.⁴

Kondratiev (1979, 1984) named three phases in the cycle, i.e., expansion, stagnation, and recession. Using statistics on price behaviour, including wages, interest rates, raw material (wholesale) prices, production and consumption of coal and pig iron, foreign trade, and bank deposits, Kondratiev dated two long cycles of expansion and decline, one upswing from 1789 to 1814 and a downward swing from 1814 to 1849 (first Industrial Revolution), and a second wave that including one upswing from 1849 to 1873 and a second downswing from 1873 to 1896 (age of railroads, steam, and steel). A third wave began in 1896 and ended in 1920 (electricity, chemistry, and motors). He applied the method of least squares (linear trend and third-order nonlinear trend) to estimate the theoretical curve.

In his model, Kondratiev distinguished between normal cycles of fixed capital replacement and extraordinary waves of investment in infrastructure, including large plants and buildings, railways, canals, etc., that could last 50 years.⁵ His main belief was that long swings reflect spurts in the reinvestment of fixed capital. Kondratiev modified Marx's idea that periodic reinvestment of fixed capital produced business cycles by introducing diverse types of capital (investment) goods with different degrees of durability (Garvy 1943). There is an endogenous mechanism in the theory, but not all variables are endogenous to the system, interpreting them

in consequence rather than a cause of its rhythm (Rostow 1975). Radical technological change, wars and revolutions, and changes in gold production and monetary circulation appear exogenous to the long cycle (Tylecote 1992). Yet Kondratiev believed that technological changes happened as a response to endogenous forces within capitalism (Rosenberg and Frischtak 1984). He recognized that profound changes in society take place before the beginning of a long upswing.

Schumpeter on long waves

Schumpeter (1935, 1939) developed a theory of long waves within his three-cycle scheme or model. Bunching or clustering of radical innovations propelled the endogenous long-investment cycle in the model (Silverberg 2003). The model became a “convenient descriptive device” with its main purpose to explain cyclical behaviour over time (Schumpeter (1939: 177). Modelling of this kind build on oscillations generated by the capital-goods, investment bunching, and self-reinforcing behaviour. His historical narrative focused on cotton textiles, railroads, steel, automobiles, and electric power in the United States, Britain, and Germany from 1790 to 1920 (McCraw 2007).⁶ In this narrative there was an uneven distribution of innovative activities across countries, industries, and time. The broadly defined technology that characterized the period dated the cycle.

Schumpeter named the three cycles for prominent business-cycle theorists: a short-term ‘Kitchin’ inventory cycle of about 40 months duration that captured information asymmetries, a medium-term investment or ‘Juglar’ cycle that captured the dynamics of both the monetary or financial markets over an eight-to-ten-year period,⁷ and a long-term ‘Kondratiev’ cycle capturing the evolution of major technological innovations over a fifty-to-sixty-year period. Integral to each long wave are shorter cycles: six Juglars to each Kondratiev and three Kitchins to each Juglar. Both the Juglar and Kitchin cycles could generate financial crisis and economic recessions at regular intervals, depending on the timing of each cycle. Schumpeter believed that the demand for capital and credit would generate cyclical fluctuations as Juglar reasoned, but he also understood them to be a consequence of innovative behaviour rather than excessive speculative behaviour.

Business Cycles laid the foundation for a post-Schumpeterian cyclical approach to radical innovation, clusters, long waves, and technological revolutions. Schumpeter (1939: 31) called

these the “tools of analysis”. The scheme developed by Schumpeter (1935, 1939) provided the building blocks to define, date, and weight inventions and innovations, as well as a sound theoretical basis for modelling long waves with different underlying mechanisms and different periodicity (Kurz et al. 2018).

Long waves after Schumpeter

After a hiatus of academic interest, long waves returned to the theoretical discourse in the 1980s. Mensch (1979) started the discussion by arguing that basic innovations occur in groups or swarms, that appear toward the end of the long wave downswing, resembling a “depression-induced accelerator”, which then stimulates inventive activity and kickstarts a new long wave. Clark et al. (1981) rejected the depression trigger hypothesis and found weak evidence for a bunching of innovation. They also questioned the timing of the innovations in the long wave, giving diffusion a more prominent role in the cycle. Tinbergen (1981) noticed this idea, suggesting that the system dynamics perspective was ideal for modelling long waves. Forrester (1977) developed a two-sector system dynamics model with capital accumulation and depreciation that simulates successive long waves of overexpansion and collapse in the capital producing sector. While the long wave tends to be a self-sustaining cycle, innovation and clustering are not fully endogenous in the model. This spawned a discussion and debate on the nature and existence of long waves that included SPRU (Science Policy Research Unit) (Freeman, et al. 1982, Freeman 1984, Freeman and Perez, 1988), IIASA (International Institute for Applied Systems Analysis) (Bianchi 1985, Vasko 1987, Di Matteo et al 1989, Vasko et al 1990) and several heterodox economists.

The revival of classical and Marxian political economy gave impetus to long wave theory. Mandel (1964) sought early on to combine Marx’s crisis theory with long waves. Mandel (1980) viewed long waves as a unity of endogenous economic mechanisms and exogenous social and political factors which combine to define the path of capitalist development. The falling tendency in the profit rate appeared as a mirror image of a technological revolution and where the starting point and turning point appear in the cycle.⁸ Mandel (1980) as well as Wallerstein (1984) and Shaikh (1992), accepted profitability drives accumulation and that long cycles are waves of capital accumulation, not only price waves, but innovation appears absent in the approach. Gordon (1991) introduced the social structure of accumulation (SSA) approach to explain tensions between the forces of production, relations of production,

institutional arrangements, and the technical superstructure.⁹ In the model, the long-swing upturn depends on a complex process of institutional transformation including "exogenous" forces and stage-theoretic considerations.

A conference session on long waves and economic growth organized for the *American Economic Association* in December 1982 was pivotal in the understanding the debate on long waves.¹⁰ In this session, Mansfield (1983: 141) found, "There are enormous difficulties in defining, dating, and weighting inventions and innovations, . . . [which limit] the extent to which they cluster together and whether these clusters (if they exist) occur about forty to sixty years apart". Rosenberg and Frischtak (1983: 150) supposed long waves "repeat over time, either because the wave-generating factors in the form of innovation clusters are themselves cyclical (or at least recur with a certain regularity), or because there is an endogenous mechanism in the economic system which necessarily and regularly brings a succession of turning points". In their view, *causality, timing, economy-wide repercussions, and recurrence* are necessary conditions to generate long waves. Gordon, et al. (1983) applied the SSA approach to long swing expansion (reproductive cycle) and crisis (nonreproductive cycle) to stimulate profitability, investment, and growth.

There are many different descriptions of long waves in more recent debates. Nelson (2001) called long waves "a succession of eras (Hobsbawm 1968), phases (Maddison 1991), accumulation regimes . . . [and] a succession of socio-institutional systems built on a cluster of technologies". Gordon (1991: 271) named them different tendencies or schools, "bunched investments, traditional Schumpeterian, neo-Schumpeterian, modified Trotskyist, traditional Marxist, world-systems, economic/warfare interactions, and French regulationist approach". Freeman and Louçã (2001: 97) named three modelling methodologies: (1) traditional statistical methods, (2) simulation of formal models and (3) historical narratives. Kondratiev and Schumpeter used a historical and narrative approach and early econometric techniques. Gordon (1991), Freeman and Louçã (2001), Reati and Toporowski (2009), Silverberg (2003), and Scherrer (2016) review some of the models and tools used to conceptualise long waves.

Freeman and Louçã (2001), Louçã (1997, 2007, 2019) and Metz (2011) raised serious concerns about the statistical and econometric analyses of long waves. Strong and unrealistic assumptions underlying the trend-cycle make it difficult to separate growth and fluctuations in the general equilibrium theory. Researchers used a wide variety of statistical tools to study long waves. Some, including Kondratiev (1979, 1984), Kuznets (1940),¹¹ and van Duijn (1983) used

moving-average smoothing techniques and the trend-deviation computation to obtain the trend-cycle.¹² Others, such as Goldstein (1988) and Solomou (1988) used correlation analysis. Another group, including Mandel (1980), Gordon (1991), and Kleinknecht (1987, 1992), transform the growth rate and then separate the analysis of long fluctuations from the behaviour of shorter ones. A third group, including van Ewijk (1981, 1982), Beenstock (1983), Kleinknecht (1992, part 1), and Reijnders (1990), used spectral and cross-spectral analysis, but found little or no empirical support for the Kondratiev cycle, while Korotayev and Tsirel (2010), Grinin et al. (2016), and Ozouni et al. (2018) found support for it. Van Duijn (1983) found compelling evidence of a global long cycle. Diebolt (2014) detected Kuznets cycles and no Kondratiev cycles. Limitations of spectral methods led Gallegati et al. (2017) and Gallegati (2019) to develop a wavelet method for dating long waves based on the phase difference between a representation in growth rates, which is consistent with the findings of Korotayev and Tsirel (2010). Using a similar method, Staccioli and Virgillito (2020) confirm Freeman and Louçã's (2001) dating of the cycle. Silverberg and Verspagen (2003) suggest non-deterministic processes limit the possibilities for forecasting and the explanatory power of the long wave theory.

Contributions from the field of complexity and chaos theory offer the most sophisticated models of long waves. Goodwin (1990) extended Schumpeter's three-cycle scheme to show how investment in innovative activities produces both the short and the long wave, and implicitly assumes that the two are independent. While there is no obvious solution to the problem, Goodwin integrates effective demand and complexity (self-reinforcing mechanism) to produce non-linear dynamics in his theory. This results in limit cycle behaviour with an unstable Juglar cycle and stable Kondratiev cycle.¹³ The self-reinforcing mechanism in the model, however, only oscillates within a given long wave and requires an exogenous shock to move between revolutions. Fatás-Villafranca et al. (2012) develop a Goodwin model that generates endogenous cyclical growth as a disequilibrium process that partly captures the succession of long waves.¹⁴

Strohmaier et al. (2019) propose a new way to capture the systemic transformations induced by technological discontinuities by tracking the spread of technological change through networked socio-economic structures. Their approach is not explicitly based on long waves but builds on the structuralist-evolutionary framework of Lipsey et al. (2005). A two-mode network connects a variety of indicators to the macro-components of an economy to map its

structure. Indicators' values change over time, and the authors use this information to measure economies' evolution given their structure. They interpret the resulting mapping as an absorbing Markov chain. This allows to use measurements from network theory to assess how performance indicators (e.g. productivity or employment growth) “absorb” shocks initiated in any part of the economy.

Freeman's et al. (1982) commentary of Mensch (1979) is the starting point for the post-Schumpeterian theory of long waves. This study led to several publications on long waves, which we discuss in the following two sections. Freeman (1995) adopts a “reasoned history” approach to long waves. Nelson (2020) defined the method to include “qualitative verbal descriptions and narratives, spliced by numbers, and structured in a ‘reasoned’ but not formal way” (Nelson 2020) and resembles the “appreciative theory” approach of Nelson and Winter (1982). In a reasoned history approach, radical innovation depends on the interplay between institutional set-ups and technical change.

Long-waves, technological revolutions, techno-economic paradigms, and great surges of development

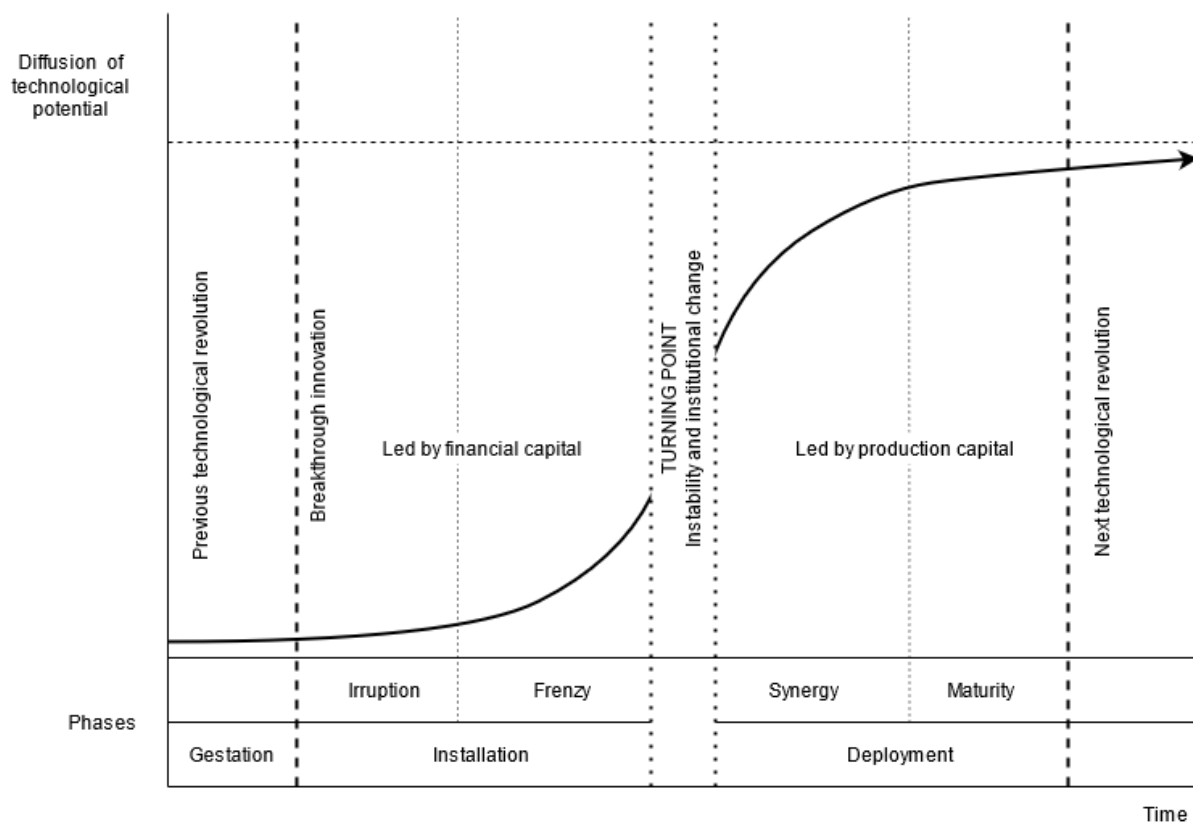
One shortcoming in Schumpeter (1939) was his “use of an a-historical theory of entrepreneurship in place of theories of the firm and of technical change” (Perez 2015: 70). This limitation inspired Freeman and Perez to introduce the techno-economic paradigm as a conceptual tool in the 1980s. Perez (1983) and Freeman and Perez (1988) focused on (macro) techno-economic paradigms that connect cyclical theories of technological evolution with path dependence and structural and institutional changes (Freeman, 1994). Prior to this, Dosi (1982, 1988) proposed an analogy between Kuhnian scientific paradigms and (micro) technological paradigms, where the evolution of technologies follows identifiable trajectories. The evolution of specific technological trajectories underlying (micro) technological paradigm must be consistent with a (macro) techno-economic paradigm. Perez (1985: 443) defines a techno-economic paradigm as “a set of common-sense guidelines for technological and investment decisions” which guides the actor's choices. Freeman (2019) grounded this idea in the historical approach, which recognizes “institutional diversity and of path dependence for firms, industries, national economies and technologies”. By taking this approach, Schumpeter's long waves appear as a succession of techno-economic paradigms. Freeman and Louçã (2001) called them long-waves, while Perez (2002, 2015) called them great surges of development.¹⁵

Perez (1983, 1985) argued that each great surge has its own all-pervasive low-cost key or leading sector(s).¹⁶ These usually include a new source of energy or a new material, technologies, products and processes, and unique organization (Perez 2010; Knell 2013). A key sector in a techno-economic paradigm must satisfy four conditions: 1) low and declining relative cost; 2) unlimited supply; 3) pervasiveness of low-cost core input; and 4) reduce the cost and improve the quality of labour, capital equipment, and intermediate products. There is an increasing mismatch between the techno-economic and the socio-institutional spheres during the first half of the techno-economic paradigm (Perez 1983, 2002).¹⁷

Freeman and Perez (1988) associated the Kondratiev long wave with technological revolutions. They use the term *techno-economic paradigm* to describe the systemic transformation following a technological revolution. Techno-economic paradigms introduce a more complex perspective into the long wave debate through the interplay between technology, the economic structure, management, social institutions, and the way people relate to the technology.¹⁸ Perez (2002: 8) defined a technological revolution as “a powerful and highly visible cluster of new and dynamic technologies, products and industries, capable of bringing about an upheaval in the whole fabric of the economy”. It is also “a set of interrelated radical breakthroughs, forming a major constellation of interdependent technologies”, namely “a cluster of clusters or a system of systems” (Perez 2010: 189).

Every revolution has its own logic that shapes a specific techno-economic paradigm. This involves not only the appearance and evolution of certain core inputs and physical technologies, but also a change in the way people relate to the technology (Nelson 2005). The microprocessor, for example, not only transformed the way economic system generates economic growth, but also, through its applications, how people interact. The same holds with mechanisation of production, the emergence of the chemical industry, and mass production, just to name a few of the ‘big bang’ innovation kick-starting technological revolutions. There will be one or more core technologies in each revolution. A core technology may appear as a cluster of interrelated radical breakthroughs and form a core constellation of interdependent technologies that will drive down the cost of production over time. Long-term economic growth is not only causally related to the major technological innovations, but also their diffusion throughout the economy.

Figure 4.1: Phases of the techno-economic paradigm



Source: Based on Perez (2002: 48)

Economists already understood the idea of S-shaped (sigmoid function) growth curves (Nelson and Winter 1982). The diffusion of radical technologies appears S-shaped as they spawn novel ideas and new combinations until exhaustion of the paradigm. Perez (2002) interpreted the growth curve as a S-shaped diffusion curve or technology life cycle to describe a technology revolution or great surge. Diffusion involves a learning process in which there are leaders and followers that evolves over the course of the techno-economic paradigm.¹⁹ Once a particular paradigm becomes dominant, the breakthrough technology will define the evolution of the technology life cycle. Figure 1 shows the four phases in each techno-economic paradigm: (1) irruption phase, when the latest technology supplants old technology; (2) frenzy phase, or the period of intense exploration; (3) synergy phase, when the new technology is diffused throughout the economy; and (4) maturity phase, as the diffusion process becomes complete. There is also has a gestation period at the beginning of the technology life cycle, in which a laboratory-invention phase, with prototypes, patents, and early applications will develop. This

phase challenges the dominant technology system, and can last for decades, culminating in the new paradigm.

Freeman and Louçã (2001) name six phases in each long wave, implying two technology systems may coexist, with the laboratory phase foreseeing the new paradigm. In this instance, the diffusion of each revolution may last more than a century. They take a systemic perspective on long waves, focusing on macro processes of technological diffusion. By contrast, Perez (2002, 2015) emphasized the diffusion process of each technological revolution and on its transformative effects on all aspects of the economy and society. But Perez then asserts, “great surges are about the rhythm and path of assimilation of each technological revolution and its paradigm”. This changed the focus of analysis and Schumpeter’s dating of the cycle (called great surge in table 1). The diffusion of the mass production revolution or the digital revolution are good examples.

A novel feature of Perez (2002) is that there is a turning point in the middle of each technological revolution where production capital supplants financial capital.²⁰ This idea follows from Schumpeter’s recognition that the entrepreneur and financier are two independent economic agents that drive the innovation process.²¹ Perez then argues that the financier dominates in the first two phases of the cycle, and the entrepreneur dominates in the second two phases.²² There can be significant and turbulent changes to industrial structure and the regulatory regime during the first phase. Increasing financial instability will culminate in frenzy and one or more major technology (financial) bubbles might appear as the phase progresses. Financial bubbles are most common just before the turning point as confidence in the financial system becomes more turbulent but support for the latest technology gains momentum. Substantial political unrest can also take place near the turning point. The instability should be powerful enough to weaken the power of finance and restore the long-term interests of production capital and the regulatory power of the State (Perez 2013). Dynamic expansion, economies of scale, and diffusion are most common during the synergy phase, when producers tend to dominate, and economic growth is balanced. In the last phase complacency appears as the technology reaches maturity and diffuses through the economy, and diminishing returns begins to set in.

From the industrial revolution to the digital revolution

Freeman and Perez (1988: 50) give a brief overview of the main characteristic of successive long waves or techno-economic paradigms. In their sketch, there have been five technological revolutions since Richard Arkwright introduced the first mechanical spinning machine, or water-frame, in a Cromford water-powered mill in 1771. Precise dating of the first industrial revolution may be arguable, but Schumpeter (1939), Freeman and Louçã (2001), and Perez (2002) recognize Richard Arkwright's patent on the water-frame in 1769. Table 1 summarizes the five technological revolutions and follows the dating of Perez (2002). The first column names the key energy source in each revolution. Renewable energy sources become crucial for the digitalization of energy systems in the last half of the fifth techno-economic paradigm. Column two shows the first breakthrough in each revolution. Columns three and four condenses the key physical and social technologies in each paradigm, following the broad distinction made by Nelson (2005). Physical technologies include the core technologies and leading (or carrier) industries (e.g. Arthur 2009) and social technologies are the institutional arrangements of the economy, which include "changing modes of division of labour, and new ways or organizing and governing work" (Nelson 2005: 195, e.g. von Tunzelmann 1995). Finally, the fifth column names the key networks in each revolution.

Innovation in the machine tool industry and in precision engineering gradually led to the design of smaller high-pressure steam engines. The Rainhill Locomotive trials and the opening of the Liverpool-Manchester railway between 1825 and 1825 marked the *Second Technological Revolution*. As resource prices fell, steam-powered mechanization of industry became the key technology (Chandler 1977). Agglomeration, standardization, and specialization accelerated productivity growth during this time. Railways, telegraphs, transatlantic steamship navigation and a universal postal service also made it possible to network the economy. Timesaving management and specialization in tasks within the enterprise drove labour productivity during this paradigm.²³

The *Third Technological Revolution* started the electrification of industry, transport, and a new electrical equipment industry from 1875. Innovative technology also made steel inexpensive. Steel, chemicals, copper, and other metal alloys were key for the development of shipping, railways, bridges, tunnels, and other large civil engineering projects. Thomas Edison created

Table 4.1. Summary of great surges (technological revolutions)

	Key energy source	Initial breakthrough	Physical technologies	Social technologies	Networks
First (1771)	<i>Water-powered industry</i>	Arkwright's water-frame	Iron, raw cotton, coal, machine tools	Factory system vs. domestic system, shift-work, entrepreneurs, interchangeable parts	Canals, roads, sailing ships, local networks
Second (1829)	<i>Steam-powered industry</i>	Manchester Liverpool railway, Brunel's steam ship	Iron, coal, Railways, Steamships,	Factory system and capital process, worker loss of control, professional management, joint stock companies	Railways, steam ships, telegraph networks, national power networks
Third (1875)	<i>Electrification of industry</i>	The Carnegie Bessemer steel plant, Edison's electric power	Steel, copper, metal alloys, internal combustion engine, electricity	American system, key machine tools, vertical integration, horizontal integration, management, R&D lab	Transport, communication, and electricity networks
Fourth (1908)	<i>Fossil fuel driven industry</i>	Ford moving assembly line; Burton oil cracking process	Oil, gas, synthetic materials, automobiles, aerospace	Mass production, managerial control (scientific management), multinational corporations	Production networks, radio, television, motorways, airports
Fifth (1971)	<i>Digitalization of energy systems</i>	Intel Micro-processor	Integrated circuits, computers, robots, software, AI, e-services, satellites	Factory and workplace automation, flexible specialization, integrative management	Global innovation networks, Internet, mobile connectivity networks

Source: Own summary based on Freeman and Perez (1988), Perez (2002), and von Tunzelmann (1995).

the first professional research and development (R&D) laboratory, with the explicit aim to provide the market with steady stream of new products, which later included the phonograph, microphones, electric lighting, and a system for electrical distribution, as well as other goods (Israel 1998). This made it easier to recombine old ideas in new ways and to encourage the creation of social networks both within and outside the laboratory.

Declining oil prices combined with the moving assembly line (to produce Ford's Model T) in 1913 made it possible to produce inexpensive motorised vehicles. This application of mass production techniques was essential to the *Fourth Technological Revolution*, including making use of machines and presses to stamp out parts and ensure interchangeability, led to the relative cheapness of large-scale production and the emergence of mass consumption (Hounshell 1984). Many industries appeared using mass production techniques, including automotive components, tractors, aircraft, consumer durables, and synthetic materials, and to ensure that mass consumption continued (Freeman and Louçã 2001). After the Second World War, the US and Europe experienced extended periods of high growth, innovative product design, and intensive positive feedback effects. This led to the creation of even larger corporations that needed new ways of managing diverse operations (Chandler 1977).

The digital revolution was bubbling underneath the fourth industrial revolution. Advances in the vacuum-tube (1935) and transistor (1947), followed by many prototypes, patents, and early applications at Bell Labs anticipated the digital revolution. A vibrant electronic cluster then appeared in the Santa Clara (Silicon) Valley (Lécuyer 2006). Intel announced plans to make the first commercially practical microprocessor (known as the Intel 4004) out of silicon in 1969 (realized in November 1971), the same year the US department of defence installed the first computers on the Advanced Research Projects Agency Network (ARPANET) (which became the Internet). This microprocessor made it possible to incorporate all the functions of a central processing unit (CPU) onto a single integrated circuit. The Apollo Guidance Computer was the first silicon integrated circuit-based computer, which led to the microprocessor. Nevertheless, news about Apollo 11 mission completely drowned out the announcement by Intel (Isaacson 2014).

The microprocessor was a revolutionary breakthrough. Advances in photolithography (and planar) techniques increased the number of transistors in an integrated circuit doubled about every two years (the so-called Moore's Law).²⁴ Soon afterwards several new technological trajectories appeared within the digital techno-economic paradigm, which evolved into clusters of new and dynamic technologies, products, and industries that rippled through the entire economy and society. New enterprises appeared and interacted with each other in complex networks. This led to the development of a global digital telecommunications network and the internet, together with electronic mail and other e-services.

We are now in the second phase of the digital revolution (Perez 2013, Reati and Toporowski 2009). The financial collapse of 2008 marked the turning point, as power shifted away from financiers to entrepreneurs and enterprises, and currently we should be in the period of high economic growth, or the golden age. Here diffusion is key, as is the complete digitalization of everyday objects and activities, or what we might refer to as ubiquitous computing (Weiser 1991). The blending of the digital and real world has opened room to the creation of digital twins, as well as for the appearance of cyber-physical systems (Lombardi and Vannuccini 2021). A wide array of new products dependent on computing devices have appeared in recent decades, including situated robotics, artificial intelligence (AI) technologies and smart energy networks (Perez 2013; Knell 2013). Modern robots can be autonomous or semi-autonomous, appearing human-like at times, but most often they are just a sophisticated industrial (and numerical control) machine with little guiding intelligence. These included industrial robots, warehouse robots, agricultural robots, autonomous vehicles, caring robots, medical robots, and robots in education. A few robots embed AI in the sense of (statistical) learning algorithms, but these are narrow and limited by the inability to deal with common sense solutions to everyday problems (Mitchell 2019).

General purpose technologies

General Purpose Technologies (GPTs) are a particular type of radical technology. They are a valuable tool for understanding technological change. Bresnahan and Trajtenberg (1995: 84) define GPTs as key technologies that have, “the potential for pervasive use in a wide range of sectors and by their technological dynamism”. Rosenberg and Trajtenberg (2004) called them ‘epochal innovations’.²⁵ Analyses of GPTs originally focused on industries’ interdependence in innovation,²⁶ and are narrower in scope than the techno-economic paradigm. However, industrial change at scale results in economic growth. Economists have since embedded GPTs into endogenous growth models, as their diffusion process offered fruitful way to explain growth cycles (Cantner and Vannuccini 2012, Faccarello and Kurz 2016).

Lipsey et al. (2005: 98) defined a GPT as “a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects”. GPTs are a distinct class of technologies by virtue of three features characterising them. For Bresnahan and Trajtenberg (1995), these are “pervasiveness, inherent potential for technical improvements,

and ‘innovational complementarities’, giving rise to increasing returns-to-scale” (see also Bresnahan 2010; Cantner and Vannuccini, 2012). General applicability suggests that a technology is pervasive in scale and scope, that is, economic actors use the technology in a large array of different economic activities (scope) and in sizeable quantity (scale). Technological dynamism captures the very steep learning curve of these technologies. Complementarities in innovative activity describe the push that a GPT gives to innovation in user sectors (and vice versa): adopting this radical technology makes innovation downstream easier by raising the returns of investing in R&D (downstream R&D and GPT quality are supermodular).

Mainstream economists tried to model long waves (Jovanovic and Rob 1990) and technological revolutions (Shy 1996). But GPTs strip the historical nuances out of long wave theory while keeping the central abstract mechanism stimulating the diffusion of radical technologies. The approach is a response to the critical view of long waves as “ex-post rationalization of historic events” (Lipsey et al., 2005). Dosi and Nuvolari (2020) called them “long waves for neoclassical economists”. This explains why few economists link the two concepts, although the mechanisms they aim to capture are similar (Nuvolari 2019). Bresnahan (2010: 763) summarised the goals of GPT research programme:

One goal lies in growth macroeconomics, to provide an explanation of the close link between whole eras of economic growth and the innovative application of certain technologies, called GPTs, such as the steam engine, the electric motor, or computers. Another goal is in the microeconomics of technical change and proceeds by differentiating between innovations of different types.

From the growth macroeconomics perspective, GPT-driven growth theory builds on the endogenous growth models with expanding product variety (Romer 1990; Grossman and Helpman 1991) and the Schumpeterian growth model of Aghion and Howitt (1992, 2009). GPT models also extend the models of Lucas (1988) and Romer (1986, 1990) by explicitly considering the interaction between technology breakthroughs and complementary technologies (Faccarello and Kurz 2016).²⁷ Helpman (2004) suggests a significant difference between GPTs, and endogenous growth models is that radical innovation drives the former, while incremental innovation drives the latter.

Long cycles derived from GPT-driven growth models are different from long wave theory. In GPT models, radical innovation can appear deterministically or stochastically but is usually exogenous to the system (Helpman 1998, Cantner and Vannuccini 2012). It also sparks a

growth phase in long wave models while GPT-driven growth models initially display a slump (in productivity and output) because of the reallocation of resources needed to guarantee the implementation of the novel technology. The economy shifts to a new, higher, equilibrium growth path only after implementation lags. Shocks produced by radical innovations such as those kickstarting a new technological revolution should appear in the patterns of industrial growth. This produces what Harberger (1989) labelled a synchronous “yeast” process, as compared to the “mushroom” process of idiosyncratic, localised growth. In practice, the elasticity of growth to technological shocks can vary across sectors of economic activities because of a complex array of reasons that range from the very microeconomic (e.g. firms incentives and competition) to meso- and macroeconomic one (e.g. the structure of inter-industry demand of intermediate goods, or retardation effects in industrial growth that are not uniformly distributed across economic activities). Even a synchronous technological shock can produce asynchronous effect, and more problematic, non-revolutionary asynchronous and localised shocks can average out pre-existing sectoral differences. This makes it exceedingly difficult to show empirically the pushes deriving purely by radical innovations such as GPTs (Napoletano et al. 2006).

From the microeconomics of technical change perspective, GPTs set in motion a key mechanism that Bresnahan and Trajtenberg (1995) label “dual inducement”. The dual inducement captures the interdependence in innovation incentives between GPT-producing and GPT-using sectors. When a dispersed set of application (downstream) sectors use a GPT as a core technology in their innovative activities, the improvement in the core technology is a function of user sectors' innovation decision. Yet, innovation in GPT-user sectors depends on the GPT-producer's decision about its own innovation intensity. The underlying implication of the incentive structure is not the generation of long wave patterns, but a less ambitious (though more abstract) coordination problem. Adoption may not happen when a radical innovation is not ‘good enough’. The coordination failure associated with GPTs provide room for technology policy intervention. Public procurement policies aimed at creating enough critical mass of downstream demand to start a dual inducement feedback loop and, thus, the diffusion of a GPT throughout the economy. Without this, a potential GPT might never become pervasive (Cantner and Vannuccini 2017).

The idea of GPT appears at the intersection of three major trajectories of research in the economics of technological change. It features in models of industrial organisation (e.g.

Bresnahan and Trajtenberg 1995), endogenous growth (e.g. Helpman 1998), and economic history (e.g. Rosenberg and Trajtenberg 2004). And it is the cornerstone of recent industrial and innovation policy designs such a smart specialisation (Foray 2015, 2018). The essential hub-and-spoke network structure between a core, radical technology and its user application domains that underlies the GPT concept is an agile representation of the interdependencies at work in a system or cluster of technologies (Bresnahan and Yin 2010). Furthermore, the mechanism captured by GPTs approximates the dynamics that Rosenberg (1963) explored in his study of the innovation and industry dynamics at work in the machine tool industry at the turn of the 20th Century. Rosenberg uncovered the process of “technological convergence”, namely the emergence of a new upstream industry as the result of a growing similarity in the knowledge base between different downstream industries. The novel industry that takes over the task of supplying technologies for a large set of user sectors, is likely to rely on a GPT.

Lipsey and colleagues (Lipsey et al. 2005; Bekar et al 2018) link the GPT approach used in industrial organisation and endogenous growth models with the historical, appreciative, structuralist, and evolutionary approaches. They developed several multi-sectoral growth models that introduce uncertainty on the arrival of a new GPT as well as inter-industry spillovers (Carlaw and Lipsey 2011). Many economists consider the non-linear path of GPTs diffusion and their lengthy implementation lags as an explanation for productivity slowdowns and booms (Jovanovic and Rousseau, 2005; Brynjolfsson, Syverson and Rock, 2021). Lipsey and co-authors (Carlaw and Lipsey 2002, Bekar et al. 2018) stress, instead, how technological revolutions of sort like those induced by the adoption of GPTs can occur through forms of technological replacement that fundamentally change the fabric, working logic and infrastructure of economic systems without necessarily displaying reverberations on macroeconomic performance such as productivity.

GPT models rely on diverse assumptions about the nature of technological and economic change. As a conceptual tool, GPTs have become the object of several academic disputes as the research programme builds on many conflicting ideas (Bekar et al. 2018). Bresnahan and Yin (2010) expanded the list of GPTs to include the succession of different computer platforms. Nevertheless, economic historians willing to capture the nature of technological revolutions with a more operational conceptual tool have been disappointed by the abstraction. For example, Field (2008) characterised GPTs as a “meme” in the field of economic history, while David and Wright (1999) suggest that the concept “may be getting out of hand” given its

ambiguous use. Because of their heuristic power, GPTs can be the bridging concept between economic history and the microeconomics of technological change (Cantner and Vannuccini 2012). For this reason, they remain one of the most important tools for understanding radical technological change after Schumpeter.

Disruptive technologies

Disruptive innovation is a predictive tool to that helps understand innovative technology. It is a theory about why businesses fail, but it does not explain technological change (Lepore 2014). So, it quickly became a catchphrase and rhetorical narrative in the management and strategy literature, often misused and misunderstood. Bower and Christensen (1995) introduced the term *disruptive technology*, which Christensen (1997) developed further in “The Innovator’s Dilemma”. Christensen and Raynor (2003) then used the term *disruptive innovations* to emphasize the idea that technologies only become disruptive once they are part of a company’s business model. Although they changed the terminology, its meaning has remained the same, that is, to explain a paradoxical pattern of industrial evolution where smaller competitors that supply low-range niche products come to replace leading companies. Christensen et al. (2015) defined disruption as “a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses” (see Christensen, et al. 2018). The innovator dilemma is the one that hits incumbent firms. By doing precisely what has made them successful, dominant firms overlook market segments from which disruptors can enter and progressively conquer the market.

Christensen and Raynor (2003) found this pattern repeated in industries, such as hard disks, steel mills and earthmovers and began to investigate whether this pattern appeared because the industry leaders did not innovate or respond to customers’ needs. On the contrary, they discovered that being innovative and sensitive to their customers’ needs were the reason these industry leaders failed. They found that by catering to the needs of the mainstream customers, the leading companies tend to ignore downmarket opportunities for cheaper and lower performing products. These markets tended to be smaller and less profitable and often left to newcomers which supplied products that were cheap and tawdry, but often offered an added advantage, such as “portability” (for the first transistor-based radios) or smaller size (for successive generations of hard disks).

Gans (2016) distinguishes between demand side and supply side disruption, with the former being the ‘classic’ process. Disruption can appear on the supply side, when “new innovations are especially difficult for incumbents to adopt and offer competitively because they involve changes in the entire architecture of a product (that is, how components link together) rather than in the components themselves”. Gans associate this type of disruption to the theory of architectural innovation (Henderson and Clark 1990). Here a reconfiguration in the structure of interdependence among the components of a product or technology presents added challenges to incumbent companies that can count less on the complementary assets they accumulated before the architectural innovation arrives.

Utterback and Akee (2005) provide a useful extension that links disruptive innovation with Schumpeterian ‘destruction’. They place disruption in context by highlighting how the “attack from below” typical of Christensen accounts is just one type of discontinuous innovations. Different drivers can trigger discontinuous change, not just niche demand. Most of the sources of change tend to come from the outside of a given industry. Still, they suggest the true (societal) impact of discontinuous types of technological change may not displace incumbents or established technologies but lie in the market expansion they generate.

Both the supply and demand side theories of disruption offer a useful tool to understand the impact of technological change. However, compared with the grand view of long waves and technological revolutions, or with the economic mechanisms at work in the diffusion of GPTs, disruptive innovation describes a specific path to market dominance and offers insights for strategic management of enterprises. Firms exploiting disruptive innovation to gain market leadership can certainly have a broader societal impact, stretching out until the working of the whole economy (the role played by current technical giants is a case in point). Yet the level of analysis they influence is that of the organisational and market structure, rather than the whole sociotechnical “envelope”.

Between discontinuous and continuous innovation

Schumpeter and post-Schumpeterians characterize innovations as either being radical or incremental. But many other possibilities lie between these two extremes. This requires defining the extent of innovation according to the extent of change or degree of novelty. Real novelty and increasing complexity were of interest to Schumpeter (1934; 1939), but he never

fully embraced these concepts. In a paper written in 1932, Schumpeter (2005: 115) defined novelty as the “transition from one norm of the economic system to another norm in such a way that this transition cannot be decomposed into infinitesimal steps”. One consequence of genuine novelty is increasing societal complexity. The most novel innovations appear as discontinuities through time, while the less novel innovations appear as imitations and gradual improvements on the original innovation.

Novelty also is originality, and as such can distinguish between the creation of new knowledge and the adoption and use of existing knowledge. Originality often involves greater risk and uncertainty (Rosenberg 1976), but it can also lead to greater diffusion as other enterprises try to replicate the innovation. Diffusion does not play a vital role in Schumpeter’s theory, he does recognize the importance of copying, imitating and gradually improving on the original “induced” innovation. Some enterprises follow an offensive strategy and introduce highly novel products onto the market, while others follow a defensive and imitative strategy and introduce fewer novel innovations (Freeman and Soete 1997). The commodity, enterprise and entrepreneur are the units of analysis that are important for Schumpeter, which makes it possible to discuss some of the issues important to the degree of novelty.

Every commercial innovation displays a degree of novelty (and risk). The degree of novelty (degree of newness) is a conceptual and measurement problem. It shows whether the innovation is “new for the industry” or “new for the firm” (reflecting adoption rather than innovation in the narrow sense) or “new to the world”. These distinctions suggest that replication matters for the degree of novelty to redesign and adapt existing products (Winter and Szulanski 2001, Becker et al. 2006). Replication is complex, requiring adaptive behaviour as it is not possible to replicate new knowledge, but discover it. The OECD (2018: 78-79) asserts that disruptive or radical innovations are difficult to find and measure. They assert a world-first product innovation implies a qualitatively greater degree of novelty than a new-to-market innovation.²⁸

The discrete view on innovation is mostly a representational issue. Various approaches to the study of technology understand innovations exist in a spectrum that has radical and incremental as extremes. For example, the multi-level perspective on socio-technical transitions and the more recent theory of deep transitions (Schot and Kanger 2018) stress how innovation occurs within a multi-layered landscape that goes from single rules to meta-rules, regimes, meta-

regimes, and socio-technical systems. The complexity approach to technology highlighted the recursive nature of technology that “builds itself out of itself” (Arthur and Polak 2006). Radical innovation is a complex process that requires a series of smaller complementary advances that makes the final innovation possible, which Silverberg and Verspagen (2005) approximate as a percolation process through a technology lattice. In sum, the radicalness of innovation is a matter of degree rather than clearly separable categories.

Emerging technologies in the sixth techno-economic paradigm

Today it is fashionable to write about Industry 4.0 and the Fourth Industrial Revolution. The idea of Industry 4.0 began as a marketing-style promotion during a press conference at the Hannover Messe, a fair in Germany, in 2011. Institutions took up the concept and two years later, the Federal Academy of Science and Engineering, with the support of the Federal Ministry of Research (BMBF), presented a research agenda and implementation recommendations (Kagermann et al. 2013). This agenda became part of a specialized discourse meant to promote the digitalization of production and innovation networks that integrate machinery, warehousing systems, and production facilities through cyber-physical systems (Pfeiffer 2017). Since then, the term Industry 4.0 has stimulated a lively, ongoing debates about the future of work and society.

The motto of the 2016 World Economic Forum meeting in Davos was “Mastering the Fourth Industrial Revolution”. Schwab (2016) associated it with the diffusion of digital technologies and emerging breakthrough technologies such as biotechnology, nanotechnology, artificial intelligence, robotics, 3D printing, the Internet of Things, and quantum computing. He named four revolutions, broadly corresponding to long waves: 1) water- and steam-powered mechanical manufacturing (first two long waves); 2) electricity-powered mass production (second two long waves); 3) digitalisation (fifth long wave); and 4) cyber-physical systems (sixth long wave). However, in this framework there is no discussion of nor reference to long-waves, technological revolutions, and techno-economic paradigms. The discussion resembles the crafting of a strategic narrative rather than a solid conceptual scheme to interpret techno-economic dynamics. Schiølin (2019: 4) labels the Fourth Industrial Revolution as an act of ‘Future essentialism’, or the “discourses, narratives or visions that (...) produce and promote an imaginary of a fixed and scripted, indeed inevitable, future, and that can be desirable if harnessed in an appropriate and timely fashion but is likewise dangerous if humanity fails to

grasp its dynamics”. Compared to this, the concepts, and tools we highlight in this Chapter are not ‘imaginaries’, but patterns derived from historical or analytical analysis.

Similar discourses on digitalization and automation technologies have taken place over the past decade, often re-igniting decades-old debates between techno-optimists and techno-pessimists (Mokyr et al 2015). Our concepts and tools will help to understand these discussions and debates. For example, Rifkin (2011) claims “green” technologies, such as wind, solar photovoltaic, hydropower, and wave and tidal power, will encourage a new industrial revolution. Brynjolfsson and McAfee (2014) believe we are in the second machine age where productivity gains from intangible assets and digitalization of the economy intensified changes in skills, organizations, and institutions. They believe earlier technology-driven revolutions, such as the steam engine and electrification, took longer to diffuse through the economy. Schot and Kanger (2018) grouped the first four technological revolutions into what they call “industrial modernity”, or the first deep transition. Their framework builds on the concepts we describe, as for them Deep Transitions describe “an evolutionary multi-level model of surges”. Labour and machines were complementary during the first transition. The second deep transition began with the digital revolution and involves the automation of cognitive tasks (especially symbol processing) that make humans and software-driven machines substitutes, rather than complements. Brynjolfsson et al. (2021) suggested that productivity growth may have “paused” in the first decades of the digital revolution but might surge again as the novel wave of digital technologies deploy its effect, resembling the way ICTs pushed productivity growth in the Nineties after the puzzling slowdown in the Eighties. These narratives confirm Perez’s (2013) idea that we are now in the golden age of the digital revolution.

Can we envisage the future and the sixth technological revolution through the tools and concepts we outlined? Possible emerging technologies include nanotechnology, biotechnology, quantum computing, and AI. This is where the physical, digital, and biological worlds could converge in what Lombardi and Vannuccini (2021) call a “cyber-physical universe”. Inspiration for the idea originates in Richard Feynman’s 1959 lecture, “There's Plenty of Room at the Bottom”. Here Feynman described a process in which scientists would be able to manipulate and control individual atoms and DNA molecules. The idea of the transistor and the microprocessor triggered the process of miniaturization. Feynman anticipated nanoscience and nanotechnology, which influenced other science fields, including chemistry, biology, physics, materials science, and engineering. We might call Feynman’s idea the

Quantum Technological Revolution, which would blend the digital revolution and its informational basis and the sixth technological revolution, much like Brynjolfsson and McAfee (2014) and Schot and Kanger (2018) might suggest.

It is possible that two or three independent technological systems could converge into one system (or a system of systems, to use Perez's expression), which would then trigger the explosive take-off into the sixth technological revolution (Roco and Bainbridge 2003, Knell 2010). Atoms, DNA, bits, and synapses will supply the basic elements and foundational tools that will make it possible to integrate several emerging technologies, including nanotechnology, biotechnology, quantum biology, information technology, and the latest cognitive technologies, into multifunctional systems. It is a long way from Kondratiev and Schumpeter's contributions, but the tools we illustrated remain the cornerstone of a useful theory of innovation and change even in our current complex socio-technical landscape.

Notes

1. Following Schumpeter, Arthur (2009: 18-19) argues that the evolution of technology is due to combinatorial evolution or fresh combinations of what already exists. Arthur also highlights the *problem-solving* nature of technological innovation.
2. See Schumpeter (1954), Barr (1979), van Duijn (1983, chapter 4), Barnett (1998) and Freeman and Louçã (2001, part 1).
3. Tugan-Baranovsky ([1894] 1954) found long-term patterns underlying the normal business cycle, related to prolong periods of rising and falling commodity prices and the expansion and contraction of trade that fluctuates at fifty-year intervals (Barnett 2001).
4. *On June 23, 1921*, Trotsky (1945, 227) wrote “Capitalist equilibrium is an extremely complex phenomenon. Capitalism produces this equilibrium, disrupts it, restores it anew in order to disrupt it anew, concurrently extending the limits of its domination. In the economic sphere these constant disruptions and restorations of the equilibrium take the shape of crises and booms”.
5. The length of a cycle depends on the economic lifespan of durable fixed capital (machinery and factories).
6. In *Economic Development* Schumpeter (1934: 229) writes “every normal boom starts in one or a few branches of industry (railway building, electrical, and chemical industries, and so forth), and that it derives its character from the innovations in the industry where it begins”.
7. Juglar’s (1862) analysis of business cycles based on easy credit and speculative behavior was different from Schumpeter’s so-called Juglar cycle, driven by investment and technological innovation (Legrand and Hagemann 2007). Schumpeter described the Juglar cycle as a fixed investment cycles that average a decade.
8. Shaikh (1992, 189) argues, “The falling tendency in the rate of profit chokes off the initial acceleration in the mass of profit, which then decelerates and eventually stagnates. The point of stagnation in the mass of profit, which Marx called the ‘point of absolute overaccumulation’, signals the turning point in the long wave”. Shaikh (2016) suggests wholesale price index divided (normalized) by the price of gold displays long fluctuations.
9. The SSA approach is about the institutional arrangements “that regulate the accumulation process and establish the conditions for profitability” (Gordon, et al. 1983). It is closely related to the French Regulation School.
10. Papers and Proceedings of the Ninety-Fifth Annual Meeting of the American Economic Association, New York, New York, December 29-30, 1982. Session on Long Waves and Economic Growth: A Critical Appraisal. In the American Economic Review, May 1983, Vol. 73, No. 2.
11. Kuznets (1930) found infrastructural investment cycles, of between 15 and 25 years, before Schumpeter.
12. Evidence of long waves appeared when the average growth rate over a lengthy period was either above or below the long-term trend.
13. See Goodwin (1990: 44). Goodwin (1985) also introduced nonlinear dissipative systems into Schumpeter’s long wave, which acts like a ‘frequency converter’. The model produces a non-linear, long term evolution of the economy.
14. Using a Goodwin model, Silverberg and Lehnert (1993) showed that clustering was not necessary to produce long-period cyclical behavior.

15. Perez (2015: 74) stressed that long waves are about statistical testing of long time series, while great surges are a historical narrative.
16. These “key” or “leading” sectors of the economy or “basic industries” as Sraffa (1960) put it, are commodities that enter directly or indirectly in the production of all commodities, which then spread novelty throughout the economy. Pasinetti (1981) extends the multi-sectoral conceptual framework to handle leading sectors and creative destruction.
17. This mismatch also appears between physical and social technology Beinhocker (2006).
18. The *techno-economic paradigm* is more than the sum of its parts – it is a coordination mechanism that evolves as a *conditio sine qua non* alongside a new technological regime. This theory goes from single innovation and their technological trajectories and build up hierarchically to the whole technological ‘envelope’ of an economy.
19. Diffusion is not prominent in *Economic Development* and only appears as a process by which firms copy, imitate, and gradually improve on the original innovation, or what he described as ‘induced innovations’.
20. At the turning point, stagnation combined with financial fragility will become an acute problem, as what happened during the canal mania, when Britain invested huge sums in canal building in the 1790s, during the speculative frenzy or railway mania in the mid-1840s in the UK, the panic of 1893 in the US, the great US stock market crash of 1929 and finally the internet mania of 2000 and financial collapse of 2007 in the US.
21. Schumpeter (1912) emphasized the role of banks and bank credit in financing investment and radical innovation (see also Knell 2015).
22. This suggests that there is a break in the great surge over two periods.
23. Large joint stock companies appeared during this time, creating the need for principled management. Repression of the working class and inequality was extreme at the time (von Tunzelmann 1995).
24. Today Apple Notebooks, iPads and telephones use a processor with 11.8 billion transistors (5nm technology node). The original Intel microprocessor had only 2,250 transistors.
25. Rosenberg and Trajtenberg (2004) show how the adoption of the Corliss steam engine produced what they call “a relaxation of geographical constraints”. Adopting the new technology, economic activities were not anymore bound to water as source of power and could relocate, boosting agglomeration and urbanisation processes as other social transformations. This historical account of GPTs demonstrate their far-reaching impact and shows the similarities with the literature on techno-economic paradigms.
26. Bresnahan and Trajtenberg (1995) introduced GPTs after they realized that their research agendas on digitalisation in the workplace were dependent on technological advances in and the wide availability of common input technologies (Bresnahan 2010).
27. A GPT appears as a productivity parameter in the model and excludes technology and innovation. Emphasis on new technical (efficient) solutions of the GPT implies a simple view of the complex process of adoption of a radically different technology across heterogeneous agents. (see Faccarello and Kurz 2016: 549).
28. Dahlin and Behrens (2005) suggest a measure of radicalness for patents.

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Friedrich Schiller University Jena

Faculty of Economics and Business Administration

Carl-Zeiss-Str. 3

D-07743 Jena, Germany

Email: office.jerp@uni-jena.de

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