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Technological revolutions and techno-economic paradigms

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This paper locates the notion of technological revolutions in the neo-Schumpeterian effort to understand innovation and to identify the regularities, continuities and discontinuities in the process of innovation. It looks at the micro- and meso-foundations of the patterns observed in the evolution of technical change and at the interrelations with the context that shape the rhythm and direction of innovation. On this basis it defines technological revolutions, examines their structure and the role that they play in rejuvenating the whole economy through the application of the accompanying techno-economic paradigm. This over-arching meta-paradigm or shared best practice 'common sense' is in turn defined and analysed in its components and its impact, including its influence on institutional and social change.

Key words: Technological change, Technological revolutions, Techno-economic paradigms, Innovation, Neo-Schumpeterian and evolutionary economics
JEL classifications: O3, B520

1. Introduction

Schumpeter is among the few modern economists to put technical change and entrepreneurship at the root of economic growth (Schumpeter, 1911, 1939).[1] Yet, strangely enough, he saw technology as exogenous and—together with institutions and social organisations—'outside the domain of economic theory' (Schumpeter, 1911, p. 11). His focus was the entrepreneur and his goal was to explain the role of innovation in economic growth and on the cyclicality of the system.

It is Schumpeter's followers—the neo-Schumpeterians—who have endeavoured to analyse technical change and innovation as such, with their regularities and evolution; who have delved into the characteristics and dynamics of innovation, from individual technical changes through clusters and systems to technological revolutions. This task has been performed by looking at technology, engineering and business organisation from the perspective of the economist and the social scientist, identifying the common features in the processes of evolution, in the interrelations and in the breakthroughs that occur in the

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[1] In earlier times from Serra (1613) in Renaissance Italy to Friedrich List (1841) in pre-unified Germany, the importance of technology and skills in economic growth was recognised as obvious. See Reinert (2007).

most diverse technical areas. These regularities then inform an understanding of the relationship between technical and organisational change, between these and economic performance as well as the mutual relationships between technology, the economy and the institutional context.

This paper will concentrate on technological revolutions and techno-economic paradigms: their definition, the causal mechanisms that bring them about, their impact on the economy and institutions and their relevance for economic analysis. Yet, since these *macro* phenomena are deeply rooted in the *micro*-foundations of technical change, the following section will refer to some of the basic theoretical advances made at the micro and meso levels.

2. Innovation as the dynamic space for the study of technical change

Schumpeter strongly distinguished *innovation*, seen as the commercial introduction of a new product or a 'new combination', from *invention*, which belongs to the realm of science and technology (Schumpeter, 1911, pp. 132–6).[1] Indeed, the space of the technologically possible is much greater than that of the economically profitable and socially acceptable. It is with profit in mind that entrepreneurs and managers are constantly turning inventions into innovations; technical possibilities and discoveries into economic realities. In turn, through their investment and funding decisions, they can also steer research efforts in particular directions.

The decision processes involved are not random. They are shaped by a context that includes relative prices, regulatory and other institutional factors and, obviously, the perceived market potential of the innovations concerned. They are also path-dependent, because market potential often depends on what the market has already accepted and because the incorporation of technical change requires the coming together of several pre-existing explicit and tacit knowledge bases and various sources of practical experience.

The meaningful space in which technical change needs to be studied, therefore, is that of *innovation*, at the convergence of technology, the economy and the socio-institutional context. That space is essentially dynamic and, in it, the basic concept is that of a *trajectory* or *paradigm* (Dosi, 1982), which represents the rhythm and the direction of change in a given technology.

3. The regularities of technical change: innovation trajectories

Radical individual innovations are usually introduced in a relatively primitive version and, once market acceptance is achieved, they are subjected to a series of incremental innovations following the changing rhythm of a logistic curve (see Figure 1). Changes generally occur slowly at first, while producers, designers, distributors and consumers engage in feedback learning processes; rapidly and intensively once a *dominant design* (Arthur, 1988) has become established in the market; and slowly once again when maturity is reached and Wolf's (1912) law of diminishing returns to investment in innovation sets in.

Besides rhythm, a trajectory also involves directionality within a possibility space. That is what Dosi (1982) emphasised when, with the Kuhnian parallel in mind (Kuhn, 1962), he introduced the term *technical paradigm* to represent the tacit agreement of the agents involved as to what is a valid search direction and what would be considered an improvement or a superior version of a product, service or technology. A paradigm is thus a collectively shared logic at the convergence of technological potential, relative costs,

[1] See the discussion in Nelson and Winter (1982, pp. 263–6).

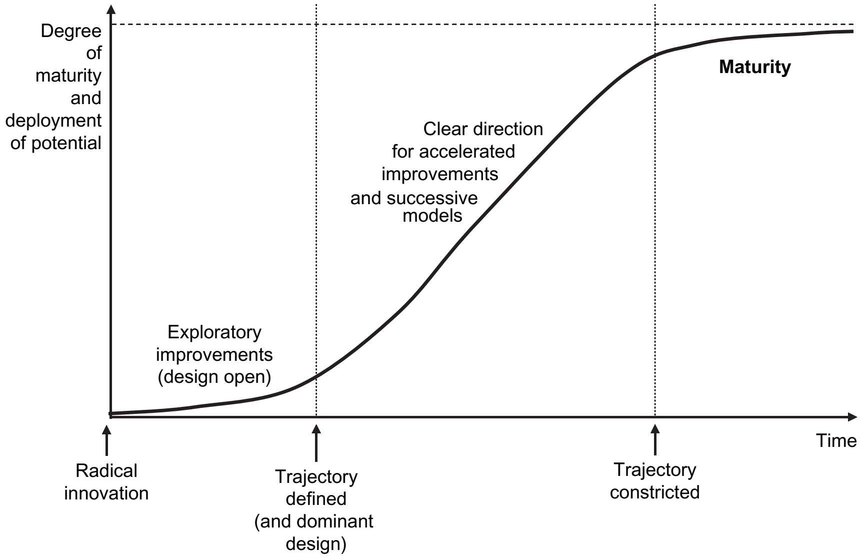

Fig. 1. *The trajectory of an individual technology.*
Source: based on Wolf (1912), Utterback and Abernathy (1975), Nelson and Winter (1977), Metcalfe (1979), Dosi (1982), Arthur (1988), Malerba (1992) etc.

market acceptance, functional coherence and other factors. Microprocessors (and the products based on them), for example, have been expected to become faster, smaller, more powerful, more versatile, relatively cheaper and so on. By contrast, in the 1950s and 1960s, automobiles and airplanes were supposed to become bigger and bigger and, though they were also expected to be faster, versatility was not among the goals.

The notions of trajectory or paradigm highlight the importance of *incremental innovations* in the growth path following each *radical innovation*. Though it is true that major innovations have a central role in determining new investment and economic growth, expansion depends on incremental innovation (Enos, 1962). The numerous minor innovations in product enhancement and process improvement that follow the introduction of any new product have an important impact on productivity increases and market growth. It has been shown that, some time after the take-off, both the number and the importance of incremental process innovations tend to overtake product changes (Utterback and Abernathy, 1975). As production volume and productivity become crucial for market expansion, process innovations drive most of the scaling-up investment.

As will be suggested below, what holds for individual technologies in terms of regularities in the dynamism and direction of technical change occurs also at the *meso* level, in relation to the evolution of all the products in an industry and to that of whole sets of interrelated industries.

Of course these notions and observations represent only the general patterns that characterise the standard dynamics of technical change and there are multiple deviations and exceptions in specific cases.

4. New technology systems and their interactions

The emergence of individual innovations is not random. Technologies interconnect and tend to appear in the neighbourhood of other innovations (Schumpeter, 1939, p. 167).

Neither does their evolution take place in isolation. Innovation is usually a collective process that increasingly involves other agents of change: suppliers, distributors and many others, including consumers. The techno-economic and social interactions between producers and users weave complex dynamic networks that are what Schumpeter referred to as *clusters*. Furthermore, major innovations tend to be inductors of further innovations; they demand complementary ones upstream and downstream and facilitate similar ones, including competing alternatives.

When they are sufficiently radical, innovations stimulate whole industries. Thus the emergence of television led to the growth of industries that manufacture receiving and broadcasting equipment, as well as of multiple specialised supplier industries. At the same time it spurred the transformation of the producing and advertising industries, film, music and other creative sectors, plus new maintenance and distribution activities and so on.

It is this kind of dynamic interrelatedness that is encompassed in the notion of a *technology system* (Freeman, 1974, 1992, p. 81, 1994) in order to describe how Schumpeterian clusters are formed and evolve. At this meso level of analysis, it turns out that the process of diffusion also follows a logistic shape (as Figure 1). Rather than being simple improvements, the incremental innovations along the trajectory are new products, services and even whole industries, building upon the innovative space inaugurated by the initial radical innovation and widened by its followers.

New technology systems not only modify the business space, but also the institutional context and even the culture in which they occur (as disposable plastics did in the past and the internet does now). New rules and regulations are likely to be required, as well as specialised training, norms and other institutional facilitators (sometimes replacing the established ones). These in turn tend to have very strong feedback effects upon the technologies, shaping and guiding the direction they take within the range of the possible.

Maturity is reached when the innovative possibilities of the system begin to wane and the corresponding markets to saturate. The key point here is that individual technologies are not introduced in isolation. They enter into a changing context that strongly influences their potential and is already shaped by previous innovations in the system.

New products appearing in the early phase of a new system are likely to have a more dynamic market life ahead than those introduced at its maturity phase. This happens for two main reasons. The first is the exhaustion of the opportunity space of that particular system, so that the last innovations are likely to be very minor. For example, the long series of home electrical appliances in the early twentieth century began with the refrigerator and the washing machine and petered out with the electric can-opener and the electric carving knife. The second reason is the intense learning that occurs within the system and the externalities that result from it. These tend to reduce the time to market and to ease user acceptance, thus shortening the product life-cycle and cutting down the time for profitability. For instance, it took 24 years, from 1954, to incorporate air conditioning as an improvement in 90% of the automobiles produced in the USA, whereas radial tyres, introduced in 1970, took less than 8 years to reach the same level of market penetration (Grübler, 1990, p. 155).

The complex and changing network of interactions and cooperation among the many agents that contribute to innovations—researchers, engineers, suppliers, producers, users and institutions—as a technology system evolves has been conceptualised as a *national system of innovation* (Freeman, 1987, 1995; Lundvall, 1988), evoking Friedrich List's *national system of political economy* (List, 1841). This idea has led other researchers to the study of *regional* and *sectoral systems of innovation* (Howells, 1999; Arocena and Sutz, 2000;

Malerba, 2002). The interrelatedness of technologies and of the knowledge and experience bases that underlie their development, together with the infrastructures and service networks that complement them and the multiple learning processes that accompany them, provide externalities for all participants and competitive advantages for the economy in which they are embedded.

5. Technological revolutions and techno-economic paradigms

Just as individual innovations are interconnected in technology systems, these are in turn interconnected in technological revolutions. Thus, on a first approximation a *technological revolution* (TR) can be defined as a set of interrelated radical breakthroughs, forming a major constellation of interdependent technologies; a cluster of clusters or a system of systems.

The current information technology revolution, for example, opened an initial technology system around microprocessors (and other integrated semi-conductors), their specialised suppliers and their early uses in calculators, games and in the miniaturising and digitising of control and other instruments for civil and military uses. This system was followed by an overlapping series of other radical innovations, minicomputers and personal computers, software, telecoms and the internet, each of which opened new system trajectories, while being strongly inter-related and inter-dependent. As they appeared, these systems interconnected and continued expanding together with intense feedback loops in both technologies and markets.

It is possible to identify five such systems of systems since the initial 'Industrial Revolution' in England. Each can be seen as inaugurated by an important technological breakthrough acting as the *big-bang* that opens a new universe of opportunity for profitable innovation. Such was the case of the Intel microprocessor, or computer on a chip, initiating the information revolution. Table 1 indicates the five revolutions, their corresponding big-bangs and the core country where the revolution originally takes shape and from which it spreads across the world (sometimes even concentrated in a particular region: Manchester was as much the cradle and the symbol of the Age of Steam as Silicon Valley has been for the microelectronics revolution).

What distinguishes a technological revolution from a random collection of technology systems and justifies conceptualising it as a *revolution* are two basic features.

- The strong interconnectedness and interdependence of the participating systems in their technologies and markets.
- The capacity to transform profoundly the rest of the economy (and eventually society).

The first is the most visible and defines what is popularly understood as 'the revolution'; but it is the second that makes it really warrant the term. The capacity to transform other industries and activities results from the influence of its associated *techno-economic paradigm*,[1] a best practice model for the most effective ways of using the new technologies within and beyond the new industries. While the new sectors expand to become the engines of growth for a long period, the techno-economic paradigm that results from their use guides a vast reorganisation and a widespread rise in productivity across pre-existing industries.

[1] The term was introduced by Perez (1985)—replacing the previous (1983) *technological style*—in order to connect with Dosi's (1982) concept of technical paradigms.

Table 1. *Five successive technological revolutions: 1770s to 2000s*

Technological revolution	Popular name for the period	Big-bang initiating the revolution	Year	Core country or countries
First	The Industrial Revolution	Arkwright's mill opens in Cromford	1771	Britain
Second	Age of Steam and Railways	Test of the *Rocket* steam engine for the Liverpool–Manchester railway	1829	Britain (spreading to Europe and USA)
Third	Age of Steel, Electricity and Heavy Engineering	The Carnegie Bessemer steel plant opens in Pittsburgh, PA	1875	USA and Germany forging ahead and overtaking Britain
Fourth	Age of Oil, the Automobile and Mass Production	First Model-T comes out of the Ford plant in Detroit, MI	1908	USA (with Germany at first vying for world leadership), later spreading to Europe
Fifth	Age of Information and Telecommunications	The Intel microprocessor is announced in Santa Clara, CA	1971	USA (spreading to Europe and Asia)

Source: Perez (2002).

Thus, a technological revolution can be seen more generally as a major upheaval of the wealth-creating potential of the economy, opening a vast innovation opportunity space and providing a new set of associated generic technologies, infrastructures and organisational principles that can significantly increase the efficiency and effectiveness of all industries and activities.

The processes of diffusion of each technological revolution and its techno-economic paradigm—together with their assimilation by the economy and society as well as the resulting increases in productivity and expansion—constitute successive *great surges of development* (Perez, 2002, pp. 20–1).

It should be noted that this concept of great surges represents a break with both Kondratiev's and Schumpeter's notion of *long waves* (Kondratiev, 1935; Schumpeter, 1939).[1] For them, the focus is on the upswings and downswings in economic growth. Although Schumpeter clearly ascribes such waves to technological revolutions while Kondratiev does not commit himself to any particular causal factor, they are both trying to explain long-term variations in gross domestic product (GDP) and other economic aggregates. What this author proposed (Perez, 2002, ch. 6, 2007, pp. 783–6) was to focus instead on explaining the process of diffusion of each technological revolution and on its transformative effects on all aspects of the economy and society, including among them the impact on rhythms of economic growth. This re-orientation has resulted in a different dating of the surges (as opposed to those of the traditional long waves) and in identifying a different set of regularities in the patterns of diffusion, which are the object of the discussion that follows.

[1] For a selection of the main authors on long waves (both from evolutionary economics and from other schools of thought) see Freeman (1996) and for a collection of the more statistical treatments of the same see Louçã and Reijnders (1999).

6. The structure of technological revolutions

The interconnection of the technologies of a revolution takes place at several levels.

- They stem from the same areas of knowledge in science and technology and use similar engineering principles.
- They require similar skills for their design and operation—quite often new ones.
- They stimulate the upstream development of a common network of suppliers of inputs and services as well as interdependent distribution outlets.
- Their dynamism is mutually driven through very strong interlinkages, often being the main market for each other (the more growth and innovation there is in computers, the more growth and innovation there will be in semiconductors and *vice versa*).
- Their diffusion generates coherent patterns of consumption and use so that the learning in one system facilitates the learning in the next and the installation of conditions for the use of one set of products becomes an externality for the next (once electricity comes to the home for lighting and refrigeration, it facilitates the adoption of radios and vacuum cleaners).

A technological revolution basically introduces whole new sections in the input–output table, which gradually become the most dynamic (and end up modifying the rest).

In terms of structure, each revolution includes a significant number of inter-related new products and production technologies, giving rise to important new industries. Among them there tends to be a core all-pervasive low-cost input, often a source of energy, sometimes a crucial material, plus one or more new infrastructures. The latter usually change the frontier and conditions of transportation networks—for products, people, energy and information—extending their reach and increasing their speed and reliability while drastically reducing their cost.

Table 2 indicates the main industries and infrastructures of each of the five technological revolutions that have taken place since the Industrial Revolution at the end of the eighteenth century.

From the point of view of the role they play in driving change, the core industries of each revolution can be ranged into three main categories Perez (1983):

- The *motive branches*, which produce the cheap inputs with pervasive applicability: semiconductors today, oil and plastics in the previous surge, cheap steel in the third, coal in the second and water power (for water wheels and canal transport) in the first.[1]
- The *carrier branches*, which are the most visible and active users of the inputs and represent the paradigmatic products of the revolution, carrying the ‘word’ about the new opportunities: computers, software and mobile phones today, automobiles and electrical appliances in the fourth, steel steam ships in the third, iron steam engines in the second and textile machinery in the first.
- The *infrastructures*, which are part of the revolution in terms of technology and whose impact is felt in shaping and extending the market boundaries for all industries: internet today, roads and electricity in the fourth, the world transport network in the third (transcontinental railways and steamship routes and ports), national railways in the second and canals in the first.

[1] For a discussion of the role of water wheels in the industrial revolution, see Tylecote (1992).

Table 2. *Five technological revolutions: main industries and infrastructures*

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures
First The Industrial Revolution	Mechanised cotton industry Wrought iron Machinery	Canals and waterways Turnpike roads Water power (highly improved water wheels)
Second Age of Steam and Railways	Steam engines and machinery (made in iron; fuelled by coal) Iron and coal mining (now playing a central role in growth)[a] Railway construction Rolling stock production Steam power for many industries (including textiles)	Railways (use of steam engine) Universal postal service Telegraph (mainly nationally along railway lines) Great ports, great depots and worldwide sailing ships City gas
Third Age of Steel, Electricity and Heavy Engineering	Cheap steel (especially Bessemer) Full development of steam engine for steel ships Heavy chemistry and civil engineering Electrical equipment industry Copper and cables Canned and bottled food Paper and packaging	Worldwide shipping in rapid steel steamships (use of Suez Canal) Transcontinental railways (use of cheap steel rails and bolts in standard sizes) Great bridges and tunnels Worldwide telegraph Telephone (mainly nationally) Electrical networks (for illumination and industrial use)
Fourth Age of Oil, the Automobile and Mass Production	Mass-produced automobiles Cheap oil and oil fuels Petrochemicals (synthetics) Internal combustion engine for automobiles, transport, tractors, aeroplanes, war tanks and electricity Home electrical appliances Refrigerated and frozen foods	Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and homes) Worldwide analogue telecommunications (telephone, telex and cablegram) wire and wireless

Table 2. *Continued*

Technological revolution	New technologies and new or redefined industries	New or redefined infrastructures
Fifth Age of Information and Telecommunications	The information revolution Cheap microelectronics Computers, software Telecommunications Control instruments Computer-aided biotechnology and new materials	World digital telecommunications (cable, fibre optics, radio and satellite) Internet/electronic mail and other e-services Multiple source, flexible use, electricity networks High-speed multi-modal physical transport links (by land, air and water)

[a]These traditional industries acquire a new role and a new dynamism when serving as the material and the fuel of the world of railways and machinery
Source: based on Perez (2002, p. 14).

A fourth category of *induced branches* may be added to encompass a set of industries that are not necessarily revolutionary in technological terms but that may be seen as indispensable to facilitate the maximum diffusion of the core industries. They may have existed before but they are modernised and take on a different role. Such was the case of the construction industry that made suburbanisation possible during the mass production surge. The multiplication of housing at the edges of cities constantly expanded the market for automobiles and electrical appliances and created a whole technology system of standardised building materials and several other suppliers of goods and services for suburban construction and living. In the current world of globalised trade and internet shopping, a similar role is being played by the courier services—and all the other systems of transport of goods—that have experienced explosive growth and profound transformations to facilitate complex global and local logistics.

7. The emergence of a techno-economic paradigm

No matter how important and dynamic a set of new technologies may be, it only merits the term *revolution* if it has the power to bring about a transformation across the board. It is the *techno-economic paradigm* (TEP), being articulated through the use of the new technologies as they diffuse, that multiplies their impact across the economy and eventually also modifies the way socio-institutional structures are organised.

A meta-paradigm,[1] then, is the set of the most successful and profitable practices in terms of choice of inputs, methods and technologies, and in terms of organisational structures, business models and strategies. These mutually compatible practices, which turn into implicit principles and criteria for decision-making, develop in the process of using the new technologies, overcoming obstacles and finding more adequate procedures, routines and structures. The emerging heuristic routines and approaches are gradually internalised by engineers and managers, investors and bankers, sales and advertising people, entrepreneurs and consumers. In time, a shared logic is established; a new 'common sense' is accepted for investment decisions as well as for consumer choice. The old ideas are unlearned and the new ones become 'normal'.

Table 3 gives a few of the most salient and general innovation principles that have characterised each of the successive techno-economic paradigms.

The extraordinarily efficient pyramidal structures with clearly defined roles and tasks that facilitated growth and innovation in the mass production paradigm of the 1950s are now seen as bureaucratic dinosaurs next to the dynamic global networks digitally interconnected with multi-skilled personnel and high levels of autonomy of the flexible production paradigm of the current Information Technology revolution. The marvel of the cabled telephone for talking at a distance becomes a museum piece when consumers can normally expect wireless multipurpose devices for all communication, information and entertainment needs.

The construction of a techno-economic paradigm occurs simultaneously in three main areas of practice and perception:

- *In the dynamics of the relative cost structure* of inputs to production where new low- and decreasing-cost elements appear and become the most attractive choice for profitable innovation and investment.

[1] To avoid unpleasant repetitiveness, *meta-paradigm* will be used as a synonym for *techno-economic paradigm* or TEP.

- *In the perceived spaces for innovation*, where entrepreneurial opportunities are increasingly mapped for the further development of the new technologies or for using them advantageously in the existing sectors.
- *In the organisational criteria and principles*, where practice keeps showing the superior performance of particular methods and structures when it comes to taking advantage of the power of the new technologies for maximum efficiency and profits.

In all three areas, the emergence of the paradigm depends on the rhythm of diffusion of the revolutionary products, technologies and infrastructures in self-reinforcing feedback loops. At first the impact is localised and minor, with time it is widespread and all-encompassing. The changes occur in the economy and in the territory, in behaviours and in ideas. The paradigm and its new common sense criteria become ingrained and act as inductors and filters for the pursuit of technical, organisational and strategic innovations as well as for business and consumer decisions. The process is self-reinforcing as the further propagation and adoption of the new technologies confirm in practice the wisdom of the shared principles.

7.1 Changes in the cost structure

The new dynamics introduced in the relative cost structure is an important driver of the emergence of the new techno-economic paradigm. In fact, a crucial element in the articulation of a revolutionary constellation is the appearance of a key input that is (i) obviously cheap and getting cheaper, (ii) inexhaustible in the foreseeable future, (iii) all-pervasive in its applications and (iv) capable of increasing the power and decreasing the cost of capital and labour.

Such was cheap water power for the mills and canals in the first revolution; cheap coal for the steam-powered railways and mills of the second; cheap steel for the worldwide steamships, railways, the giant bridges and structures and the major chemical and electrical equipment of the third; cheap oil for the internal combustion engines of automobiles, trucks, airplanes and ships as well as for the production of electricity for the all-electric home and, finally, cheap microprocessors for the computers and telecom equipment of the current fifth.

The general price profile is also radically modified by the growing cost advantage of the new infrastructure. This occurs in two main ways: directly through decreasing prices (as operational volume decreases the unit cost of transport) and indirectly through increasing the market reach of users and therefore allowing greater economies of scale in production and distribution. So the preferred direction of innovation is already suggested by the relative cost profile of inputs and transport, which become a part of the meta-paradigm.

Wedgewood pottery could not go far without breaking on the backs of mules along uneven turnpike roads; but it could reach the world moving over water going from river to canal and from canal to river and eventually on to the wide seas.

7.2 The perception of opportunity spaces

The second way in which the meta-paradigm signals the best direction for investment and innovation is via the perception of the profitable opportunity spaces. These are ever more clearly defined as the new technologies propagate and multiply. Such spaces are of two main types: those of the producers of the new technologies and those of the users.

At the core of the revolution are the basic scientific and engineering principles that open a whole new universe of possibilities. The dynamism of innovation in these opportunity spaces is internally driven and the contributing industries are mutually-reinforced. However, their evolution constantly creates new spaces for innovation in the rest of the economy due to the generic technologies of ample applicability that each revolution provides. The new infrastructures are the most obvious all-pervasive generic technologies; the others are the new sorts of materials and equipment that penetrate the operational context of every other industry.

In terms of infrastructures, the current role of the internet in the major reshaping of structures and behaviours in finance and trade needs no reminder. In the fourth surge the networks of roads and electricity to the home made widespread suburban living possible.

Equipment such as the steam engine, in the second surge, liberated industry from the need to be near a source of water power. The individual electric motor, in the third, allowed industry to do away with the forest of belts and the simultaneous operation of all machines; it also allowed small scale powered industry.

In materials, the molecular '*lego*' trajectory of innovation in the petrochemical technology system opened a wider and wider range of application opportunities across

Table 3. *The five great surges of development and their techno-economic paradigms*

Technological revolution	Techno-economic paradigm 'Common-sense' innovation principles
First	
The Industrial Revolution	Factory production Mechanisation Productivity: time keeping and time saving Fluidity of movement (as ideal for machines with water-power and for transport through canals and other waterways) Local networks
Second	
Age of Steam and Railways	Economies of agglomeration Industrial cities National markets Power centres with national networks Scale as progress Standard parts: machine-made machines Energy where needed (steam) Interdependent movement (of machines and of means of transport)
Third	
Age of Steel, Electricity and Heavy Engineering	Giant structures (steel) Economies of scale of plant: vertical integration Distributed power for industry (electricity) Science as a productive force Worldwide networks and empires (including cartels) Universal standardisation Cost accounting for control and efficiency Great scale for world market power: 'small' is successful, if local

Table 3. *Continued*

Technological revolution	Techno-economic paradigm 'Common-sense' innovation principles
Fourth	
Age of Oil, the Automobile and Mass Production	Mass production/mass markets Economies of scale (product and market volume): horizontal integration Standardisation of products Energy intensity (oil based) Synthetic materials Functional specialisation: hierarchical pyramids Centralisation: metropolitan centres–suburbanisation National powers, world agreements and confrontations
Fifth	
Age of Information and Telecommunications	Information-intensity (microelectronics-based ICT) Decentralised integration: network structures Knowledge as capital: intangible value added Heterogeneity, diversity, adaptability Segmentation of markets: proliferation of niches Economies of scope and specialisation combined with scale Globalisation: interaction between the global and the local Inward and outward cooperation: clusters Instant contact and action: instant global communications

Source: based on Perez (2002, p. 18).

the economy, from successive plastics for packaging or structures, through textile fibres and fertilisers to detergents and pharmaceuticals during the fourth surge.

7.3 New organisational models

Finally, the TEP incorporates the criteria for best organisational practice. As the new technologies transform work and consumption patterns, they also transform the way factories and businesses are organised. Regular practice in the use of these technologies and in relating to the new conditions in the market contributes to the establishment of new principles of organisation that prove superior to the previous and become part of the new common sense for efficiency and effectiveness.

In the second surge, for instance, the penny post, telegraph and national railways changed the structure of the banking industry from isolated local institutions to national networks of local branches. The railways themselves became very large business structures requiring what were then the most advanced organisational and logistics innovations for the management of complex systems.

In the fourth surge, following Ford's example, the assembly line with Taylorist principles became widely adopted and deeply transformed the organisation of fabricated products. The clear separation between blue- and white-collar workers, between the thinking and the executing, had consequences that went far beyond the factory, and so did the much greater productivity achieved with that organisation. Ford's reduction of the work force and more than doubling the average wage together with his claim that cars would be cheap enough for his workers to buy were a foretaste of the potential for social transformation to come.

In each case, the paradigm shift in organisational and business logic becomes widespread and modifies business models and strategies so that the ones that are more compatible with the general logic of the new paradigm prove to be more successful, become highly visible and are increasingly imitated. Thus the TEP is further enriched and the process is self-reinforced.

Of course, there are also intended propagation processes. In the early surges in Britain there were networks of engineers sharing the new knowledge and experiences (while they also competed for contracts). By the fourth surge, the transmission of the full model with all its principles and practices had become the professional activity of hundreds of consultants in Scientific Management (Taylorism). In the current surge management consultancy has blossomed into a full-fledged economic sector and has been transforming deeply the contents of the MBA courses developed under the previous paradigm.

A techno-economic paradigm is, then, the result of a complex collective learning process articulated in a dynamic mental model of the best economic, technological and organisational practice for the period in which a specific technological revolution is being adopted and assimilated by the economic and social system. Each TEP combines shared perceptions, shared practices and shared directions of change. Its adoption facilitates the achievement of the maximum efficiency and profitability and its diffusion provides a common understanding among the different agents that participate in the economy, from producers to consumers.

8. Diffusion, resistance and assimilation of successive techno-economic paradigms

It should be noted that some of the principles indicated in Table 3 extend beyond the economy into the social and institutional spheres. Suburbanisation in the fourth surge and globalisation in the fifth are two such instances.

In fact, the common sense principles of organisation for maximum efficiency and effectiveness embodied in the techno-economic paradigm gradually spread out of the business world and into government and other non profit institutions. The operations manuals and hierarchical structures of government ministries in the 1960s were fundamentally similar to those of a big mass production corporation. Yet, at present, these two sorts of institutions are very different. The changes that have been occurring in company structures and organisations since the irruption of the information revolution in the 1970s have radically changed them into what are now the flexible networked (increasingly global) corporations. But the processes of incorporating those more effective patterns into public institutions have been slow and are far from fully developed. This is not surprising. Organisational inertia is a well known phenomenon of human and social resistance to change. In the market economy, however, inertia is overcome by competition, which, by showing the direction of success, serves as a guide to best practice and as a survival threat to the laggards. That type of pressure and directionality is not present in most public institutions. Historically, then, these have lagged considerably (typically as much as 20–30 years) and have only imitated the paradigmatic principles developed in firms when forced to respond to political pressures for effectiveness.

Even in the economy, under the pressure of competition, the profound and wide-ranging changes made possible by each technological revolution and its techno-economic paradigm are not easily assimilated; they give rise to intense resistance and require bringing forth even stronger change-inducing mechanisms. It is the younger generation that never learned the practices of the previous paradigm that most naturally adopts and applies the new principles.

Eventually, the new TEP becomes the shared, established and unquestioned 'common sense' both in the economy and in the socio-institutional framework creating a clearly biased context in favour of the trajectories of the technologies of the revolution and their use across the economy. This adaptation generates externalities that operate as an inclusion–exclusion mechanism to encourage compatible innovations and discourage incompatible ones. This is an important part of the explanation of why change occurs by revolutions. Thus, techno-economic paradigms act as context shapers in favour of one revolution and—through over-adaptation—as hindrance and obstacle for the next.

Hence, each *great surge of development* involves a turbulent process of diffusion and assimilation. The major incumbent industries are replaced as engines of growth by new emerging ones; the established technologies and the prevailing paradigm are made obsolete and transformed by the new ones; many of the working and management skills that had been successful in the past become outdated and inefficient, demanding unlearning, learning and relearning processes. Such changes in the economy are very disturbing of the social status-quo and have each time accompanied the explosive growth of new wealth with strong polarising trends in the income distribution. These and other imbalances and tensions resulting from the technological upheaval—including a major financial bubble and its collapse (Perez, 2009)—end up creating conditions that require an equally deep transformation of the whole institutional framework. It is only when this is achieved and the enabling context is in place that the full wealth-creating potential of each revolution can be deployed.[1]

9. Putting everything together: Regularities, continuities and discontinuities in technical change

Within the neo-Schumpeterian lines of inquiry, innovation occupies an important space, including its dynamics, its clustering and interrelations. Studies of innovation have shown that the introduction of technical change is not random but path dependent and interdependent with other innovations clustered in systems, which are in turn interconnected in revolutions.

Although innovation is constant in the market economy, it is not always continuous. There are changes in rhythm that tend to follow a logistic curve and are influenced by the cycle of the technology system in which they are embedded. There are discontinuities often stimulated by the exhaustion of possibilities along a particular trajectory, where productivity and markets are approaching exhaustion. To capture these combinations of regularities and discontinuities the neo-Schumpeterians have introduced the concepts of

[1] See Perez (2002) for an extended discussion of the processes of diffusion and assimilation of technological revolutions and TEPs as well as for the crucial role of the two complementary agents of innovation and growth: financial and production capital.

technological trajectories, technology systems, technological revolutions, techno-economic paradigms and *great surges of development*.

The *technological trajectories* of individual products are grouped in *technology systems* that are in turn grouped in technological revolutions; the system trajectories overlap generating externalities and markets for each other, thus influencing the direction of further innovation. *Technological revolutions* are clusters of interrelated technology systems that only merit the term 'revolution' because their impact extends far beyond the boundaries of the new industries they introduce. The transformations eventually encompass the whole economy, raise the expected productivity level across the board, rejuvenate mature industries and open new innovation trajectories, not only within the new technologies, but also through their application to rejuvenate all the other industries and activities. The process of diffusion of these massive changes and of their economic and social effects constitutes a *great surge of development.*

The vehicle of that wide-ranging change of direction in innovation is the techno-economic paradigm, which is a best practice model gradually emerging from practical experience in applying the new technologies. It indicates the optimal, most effective and most profitable way of making use of the new innovative potential. Each TEP articulates a basic set of principles that serves as an envelope encompassing the trajectories of individual technologies and shaping their preferred direction. The TEP propagates together with the new technologies producing the surge of development. Its influence extends from the business sphere to institutions and society so that, as its adoption advances, it becomes the shared common sense for decision making in management, engineering, finance, trade and consumption. This new logic and its capacity to increase effectiveness and efficiency eventually also shape institutional and social organisations, expectations and behaviours.

The mutual adaptation of technology and society through the social learning of the paradigm and the adaptive redesign of the institutional framework enables reaping the maximum benefit from the wealth creating potential contained in each great surge. But, when this potential is exhausted and a new revolution begins to emerge, those embedded habits and institutions act as a powerful inertial force and must be transformed to enable the next surge.

This understanding of the influence of technical change on long term economic growth is one of the key contributions of evolutionary economics to the comprehension of macroeconomics as dynamic and historically shaped. It is no longer possible to ignore the specific technological revolution being diffused and its stage of deployment.

The level of abstraction at which growth processes are studied need not—and indeed should not—ignore the nature of the particular set of technologies being propagated. Suburbanisation would not have been possible without mass production and without the switch to the automobile as means of transport; globalisation could not have happened without transoceanic fibre optics, satellites and internet.

On the view being described here, the notions of long run equilibrium and continuous progress are rejected in favour of more complex processes of overcoming multiple disequilibria originated in massive innovation, in internal differentiation within and between sectors, of creative destruction, assimilation, learning and unlearning successive technological spaces and best practice models and of reaching and overcoming maturity through successive surges of change. The changing rhythms of growth and the processes of structural change and increasing productivity in the economy can now be understood as driven by identifiable technical change and as shaped by the diffusion of successive technological revolutions.

Taken together, the micro, meso and macro views of how technologies evolve show that it is possible to recognise the nature of technology, its forms of evolution and its interrelations as an object for social science analysis and as a way of embedding economic theory in the dynamics of its interaction with technology and institutions in a changing historical context.

Ignoring the potent role and influence of technical and institutional change in shaping the economy reduces the analytic capacity of economics. Incorporating them in a historically dynamic approach is an important task in order to enhance the explanatory and predictive power of economic science. Evolutionary economists and neo-Schumpeterians have pioneered in exploring and mapping that new territory.

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