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Understanding successive industrial revolutions: A “development block” approach[☆]

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ABSTRACT

This paper provides a reappraisal of the literature on “long waves” and “general purpose technologies”. This approach is still widely used to characterize long run trends of technological change and economic development since the first industrial revolution. Notwithstanding providing some useful insights, it is argued that this approach is rooted in a too rigid historical chronology positing a tight connection between technological change to economic outcomes. On these grounds, the paper suggests that a more flexible interpretative framework based on the notion of successive industrial revolutions and “development blocks” may offer a more accurate historical account and be more useful for providing insights for innovation and sustainability policies.

1. Introduction

This paper provides a reassessment of the neo-Schumpeterian long wave view of capitalism development as originally formulated by Freeman, Louca and Perez and subsequently rehearsed by the more mainstream economic literature on “general purpose technologies”. It is argued that, despite the appeal of the framework, which seems to provide an insightful approach for the study of the interactions between technological transformations, economic development and social change, long-wave periodizations are historically questionable. The key-issue is that the technological systems identified by the neo-schumpeterians as the drivers of the long waves of economic development are actually characterized by extremely prolonged life cycles (spanning in some cases more than 100 years). Hence, it is difficult to link the successive deployment of these technological systems to a pattern of economic growth in terms of Kondratiev waves (of about 50 years).

We suggest that an interpretative framework based on the somewhat more traditional periodization in terms of first, second and third industrial revolutions may provide a more useful characterization of the macro patterns of development since the eighteenth century. Interestingly enough, this framework is still consistent with some of the most important of the basic interpretative conjectures put forward by neo-schumpeterian authors such as Freeman and Perez. However, the framework allows for a greater degree of autonomy between technical change and long run economic performance. The same goes also for the micro-patterns of economic and social change associated with each technological revolution.

As noted by Pearson and Foxon (2012), understanding long run trends of technological change represents an important prerequisite for the formulation of effective innovation, industrial and environmental policies. This paper concurs with their assessment by pointing to the risks inherent in the formulation of policy scenarios characterized by the assumption of a rapid deployment of new technological systems. In fact, the prolonged and lingering nature of the industrial revolutions witnessed so far suggests that the

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breadth and depth of policy interventions needed to tackle in a timely way the ongoing current pressing environmental concerns will be of an unprecedented scale.

2. General purpose technologies (GPTs), steam power and ICTs

During the 1980s many informed observers noted the puzzling concomitance between the rapid rates of innovation and diffusion that were seemingly characterizing the spread of ICT and the sluggish dynamics of aggregate productivity. The phenomenon was eloquently described by Nobel laureate Robert Solow (1987) with the dictum: “you can see the computer age everywhere except in the productivity statistics”. Since then, the discomforting lack of connection between ICT diffusion and productivity growth has been commonly referred to as the “Solow paradox” and the assessment of the contribution of ICT to productivity growth (at various level of analysis: firm, industry, aggregate economy) has become a rapidly expanding research field (see Draca, Sadun and Van Reenen, 2007 for a survey). This is hardly surprising, taking into account the transformative potential that the ICT revolution seem to hold for increasing productivity in almost any sector of the economy. Interestingly enough, the ICT productivity puzzle, besides empirical investigations on the drivers of productivity growth, has also spawned contributions devoted to reconsider the overall connection between technology and economic growth in theoretical perspective.

The outcome of these research efforts has resulted in the elaboration of a new interpretative framework for the study of the innovation/economic growth relationship. This new approach may be labelled as the “general purpose technology” (GPT) view of economic growth, and today it represents one of the most influential “paradigms” in this research field (this is testified by the inclusion in two recent authoritative volumes *Handbook of Economic Growth* and *Handbook of the Economics of Innovation* of chapters devoted to “general purpose technologies”: Jovanovic and Rousseau (2005) and Bresnahan (2010)).

At this point, it is useful to briefly describe the intellectual origins and development of the GPT view of economic growth. On reflection, the GPT interpretive framework of the relationship between technical change and economic growth appears to have been profoundly influenced by the view of economic development that Schumpeter presented in *Business Cycles* (Schumpeter, 1939). As is well known, Schumpeter proposed that the economic history of capitalist economies was characterized by long (Kondratiev) waves of development, that is to say by historical phases in which economic growth is rather robust and sustained, intertwined with periods in which the growth process is relatively sluggish and the overall economic performance (in terms of productivity growth, output growth, unemployment, etc.) of the system is generally poor. In Schumpeter’s view, this cyclical pattern of development was due to the clustering of basic innovations at particular moments of time. In his book, Schumpeter discussed how the uneven appearance of the clusters of basic innovations (reinforced by a bandwagon effect of minor collateral innovations) could generate upswings which became progressively exhausted producing a wave-like pattern of economic growth.

Few exceptions aside, from the 1950s to the mid of the 1970s, Schumpeter’s view of economic development was completely neglected in the mainstream economic literature. Not surprisingly, the long-lasting economic performance (“golden age”) of the post war period led most economists to consider a rather different perspective for the study of economic growth. Accordingly, in the predominant view of the time (epitomized in the Solow model), economic growth proceeded smoothly at a stable growth rate. Furthermore, in the Solow model, technical change was reckoned as the key driver of economic growth, but it was considered to be the outcome of autonomous developments in science and technology and, accordingly, treated as an exogenous factor. Interestingly enough, in stark contrast with the Schumpeterian view of innovation clustering, it was posited that technological progress was characterized by a constant time-drift. In a nutshell, the Solow model illustrated how the constant rate technical progress produced a stable and constant rate of economic growth.

However, since the early 1980s, Schumpeter’s perspective of long waves of economic development fuelled by technical change was revived by Chris Freeman and other economists (Luc Soete, Carlota Perez and Francisco Louca) mostly working in the sub-field of innovation studies (to date Freeman and Louca, 2001 still represents the most articulated treatment of this approach).

Freeman’s theory is based on the notion of “technological system” or “techno-economic paradigm”. With this term, Freeman indicates a “constellation” of innovations characterized by strong technological and economic linkages (mainly between materials, machinery, power systems and final products). One can think as a possible example to the interdependencies and complementarities between machine-tool technology, steam engine and iron production during the British industrial revolution. These “technological systems” are endowed with a high degree of *pervasiveness* in the sense that they affect a wide range of industrial activities. The long term evolution of capitalist economies, according to Freeman, has been characterized by the deployment of a series of these pervasive technological systems. Furthermore, the deployment of each “new technological system” triggers deep changes in the organization of production, determining a fundamental restructuring at the level of the whole production system:

> Such discontinuities have long been familiar to archaeologists with their taxonomies of ‘Stone Age’, ‘Bronze Age’, ‘Iron Age’. We shall argue here that there is justification for a similar approach to the far more rapidly changing and complex technologies of industrial societies…[Accordingly], it has been common parlance for a long time among historians to use such expressions as the ‘age of steam’ or the ‘age of electricity’, even only for convenient descriptive periodization…..[In our view] this type of taxonomy is needed not just for convenience, but because it enables us to develop a better understanding of the successive patterns of change in technology, in industrial structure, and, indeed, in the wider economic and social system (Freeman and Louca, 2001, p. 142).

In other words, Freeman put forward a theory of long waves of economic development formulated in terms of large-scale transitions between different technological systems. This framework of analysis has been employed by Freeman and Louca in an intriguing and lively account of the economic development of capitalist economies since the British industrial revolution (Freeman and Louca, 2001).[1]

Interestingly enough, since the 1990s, also mainstream approaches to the study of economic growth have attempted to move beyond the rather abstract representation of the growth process of the Solow model by formulating models which incorporate some key-ideas of the view of the process of economic growth originally proposed by Freeman and his associates (see the essays collected in Helpman, 1998).

The fundamental building block of this family of new neoclassical models is the notion of "general purpose technology" (GPT), which may be regarded as an attempt of introducing in growth models a more "phenomenological" and less reductionist view of technical change. In the original formulation proposed by Bresnahan and Trajtenberg (1995), GPT are defined as technologies with three salient characteristics:

i) they perform some general function, so they can be employed in a wide range of possible application sectors. Jovanovic and Rousseau (2005) label this characteristic as "pervasiveness".
ii) they have a high technological dynamism, so that the efficiency with which they perform their function is susceptible of being continuously improved. Jovanovic and Rousseau (2005) label this characteristic as "improvement"
iii) they generate "innovation complementarities", that is to say that their adoption stimulates further rapid technical progress in the application sectors. Jovanovivic and Rousseau label this characteristic as "innovation spawning".[2]

Steam power, electricity and information and communication technologies are most frequently put forward as clear-cut examples of GPTs. It is worth noting that most GPT growth models retain the traditional neoclassical micro-foundations based on perfectly rational agents and market equilibrium.[3]

The most innovative aspect of this class of endogenous growth models is that they generate patterns of growth that are characterized by alternating phases of acceleration and deceleration determined by the implementation of successive GPTs, producing, on a long time scale, a wave-like profile. More specifically, these models assume that each new GPT requires a rather long period of "acclimatization" in the economic system. Hence, the initial impact of GPT on productivity growth is typically rather "small". This phase of sluggish dynamics of productivity concludes when the GPT is finally fully "acclimatized" in the economic system. Then, the rapid rate of technological change in the GPT and in the application sectors (due to the innovation complementarities of the GPT) produces an increase in the rate of overall productivity growth. Finally, as the scope for further improvements in the GPT is progressively exhausted, this phase of rapid productivity growth will gradually peter out. In principle, this conceptualization in which the growth dynamics seems therefore able to produce an account of the process of economic growth that can explain why the initial phase of development of radical innovations such as steam and ICT does not lead straightforwardly to productivity growth. At the same time, economic historians have, at least initially, welcomed GPT growth models as a positive development in growth theorizing, on the grounds that they contemplate explicitly the possibility of discontinuities in the patterns of economic growth which is more consistent with the historical record of capitalist economies since the industrial revolution than a stable steady state growth path.

GPT models are intuitively appealing because they hold the promise of providing a simple, albeit insightful account in which the long term dynamic of productivity growth is driven by the diffusion of radical innovations (following the well-known S-shaped paths).[4] However, when moving from the models to their application to economic history, the matter becomes immediately thorny. The first scepticism towards GPT models has been voiced in an important contribution by Field (2011). According to Field, the three criteria used for assessing whether a technology deserves the accolade of "GPT", when looked closely, are far from straightforward. In fact, one of the main directions of the evolution of the GPT literature has consisted in the discovery of more and more GPTs, besides steam, electricity and ICT (from other technologies such as the internal combustion engine and the water wheel to organizational innovations such as the factory system and mass production, to bodies of engineering knowledge such as chemical engineering). This is rather disquieting since it probably indicates that, at least so far, the GPT framework is not really equipped for properly identifying what are the genuine key-technological developments that are underlying the process of long run economic growth.[5]

My contention is that a close reading of the historical evidence shows that the promise of GPT models is largely illusory, even if we decide to limit ourselves to the three most obvious suspects, namely steam, electricity and ICT. Let us consider the example of steam

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[1] Carlota Perez (2002) outlines a chronology of capitalist development in terms of "great surges of development", rather than "long waves".

[2] Lipsey et al. (2005, p. 98) put forward a similar definition: "A GPT is 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.". Bekar et al. (2018) provide a more sophisticated definition, still emphasizing the complementarities with other technologies (both "upstream" and "downstream") and the wide array of applications. Importantly, they also insist that a GPT should not have "close substitutes".

[3] In what follows we will consider the two models proposed by Helpman and Trajtenberg (contained in Helpman, 1998) and Bresnahan (2010) as representative examples of the neoclassical literature on general purpose technologies.

[4] For an example of this approach see Jovanovic and Rousseau (2005).

[5] Also David and Wright (1999, p. 10) have expressed a similar concern with respect to the increasing number of GPTs identified in the literature: "One has only to consider the length of such proposed lists of GPTs to begin to worry that the concept may be getting out of hand. History may not have been long enough to contain this many separate and distinct revolutionary changes. On closer inspection, it may be that some of these sweeping innovations should better be viewed as sub-categories of deeper conceptual breakthrough in a hierarchical structure. Alternatively, particular historical episodes may be fruitfully understood in terms of interactions of one or more GPTs on previously separate historical paths" . See Bekar et al. (2018) for some counterpoints on this issue.

power and the first industrial revolution. A close inspection of the evolution of steam power technology over the period 1700–1850 suggests that it was characterized by two distinct technological paradigms (Nuvolari and Verspagen, 2009). The first one can be labelled as the "low-pressure" paradigm. This paradigm was established by Newcomen and Watt's inventions. The layout of Newcomen's engine (piston/cylinder apparatus coupled with the rocking beam) became almost immediately the "dominant design" in steam power technology. Watt's invention of the separate condenser (and closed cylinder) opened up the possibility of effectively using steam as the driving agent of the engine. In addition, Watt's experiments consolidated the "knowledge base" of the technology providing a number of effective rule of thumbs for the designing of engines of different sizes and for evaluating their performance.

At the beginning of the nineteenth century, it is possible to identify a marked discontinuity in the procedures of innovation in steam engineering. This rupture can be related to the emergence of the "high-pressure" paradigm. Note that the discontinuity is not so much related to the material characteristics of the artefact (the design layout of the low pressure and the high pressure steam engine is indeed very similar), but to the body of knowledge (both in terms of "understanding" and in terms of "practice") underlying the artefact. The fact that the discontinuity was related to the cognitive dimensions of the technology is confirmed by the fact that the delay in the adoption of the high pressure engine in manufacturing applications was indeed determined more by the "intellectual resistance" of different engineering communities to the very idea of employing high pressure steam, rather than by genuine technical difficulties. After the emergence of the high pressure engine, the search for improvements in the different application sectors proceeded "empirically" and semi-autonomously on the basis of rather idiosyncratic sets of engineering heuristics geared to specific sectoral requirements. One can indeed argue that the adoption and diffusion of the high pressure in mining, manufacturing and steam ships followed very different time-paths because was actually the outcome of different search and design heuristics, rather than a process of the diffusion of the same technology across sectors (Nuvolari and Verspagen, 2009). Even when considering the history of the steam engine in the later nineteenth century, one can find a number of examples showing innovations matured in a particular application niche that could not be (successfully) transferred to the other application sectors. In this respect, one could imagine that, after the 1850s, with the rise of scientific thermodynamics, some effective and general design principles could be elaborated. However this was not the case. As noted by Gustave Adolphe Hirn, one of the leading pioneers of scientific thermodynamics, the formulation of a fully-fledged scientific theory of the steam engine had been of little help in actual steam engineering developments, precisely because sector specific functional requirements were already dictating too many features of the engine design (Cardwell, 1994, p. 314).

Once we take into account that the development of steam power technology was punctuated by paradigmatic discontinuities, the task of assessing the precise impact of this technology on economic growth particularly difficult. Endogenous growth models such as those proposed by Helpman and Trajtenberg (Helpman, 1998, ch. 3 and 4) consider the emergence of a *single* GPT which is progressively refined and incorporated in user sectors producing an acceleration of the rate of economic growth. If the development of a specific GPT is instead characterized by major discontinuities, we should actually consider the possibility of a much more complex dynamics relating the evolution of the GPT to spurts of economic growth. Furthermore, it becomes much more difficult to trace the diffusion path of the technology in question (which is a critical task if the GPT framework is going to be applied historical cases).[6] This limitation of the model is explicitly acknowledged by Helpman and Trajtenberg (Helpman, 1998, p. 110). Of course, one could suggest that the high pressure steam engine ought to be considered as a "new" GPT replacing old GPTs (be this water power or low pressure engines).This is indeed the perspective that Rosenberg and Trajtenberg (2009) seems to suggest when they consider the "Corliss" engine as the only type of steam engine which can qualify as GPT for the long term growth of US manufacturing (see also Bresnahan, 2010 and Bekar et al., 2018)

On the other hand, once we allow the possibility of different (successive) vintages of GPT, the framework is going inevitably to lose much of his appeal (or at least the appeal deriving from the simplicity of the basic explanatory mechanism). In fact, in such context, to make the model operational it becomes necessary to work out a precise conceptual definition that would allow a systematic identification of which specific vintages of the technology in question must be treated as genuine GPT and which represents simply improvements (a task so far largely unaccomplished in the GPT literature). Furthermore, in the case of steam, contemplating a framework based on a succession of vintages, would lead us to consider a GPT life cycle of more than one hundred years (from Newcomen to the end of the nineteenth century). Clearly, even when considering only the technology side of the matter, the overall dynamics of productivity growth over such a protracted period is going to be affected by an exceedingly wide array of other innovations (some possibly connected to the GPT, but many others independent from it). In these conditions, the very heuristic efficacy of the GPT concept of generating fruitful insights becomes clearly very doubtful (Ristuccia and Solomou, 2014).

Tables 1 and 2 illustrate the process of diffusion of steam power technology in Britain. Table 1 gives estimates of the share of steam capital in the total capital stock. In particular, I have computed two figures, one for the share of steam in the total capital stock in mining and manufacturing and one by type of asset which considers the share of steam in the "plant, machinery and equipment" stock of the total economy. This can be taken as a rough indication of the relative "weight" of steam technology in the stock of capital. Rather consistently with what we have noticed so far, the share of steam seems to attain a sizable share in the stock of capital of the overall economy only in the very late nineteenth century.

Table 2 collates the available quantitative evidence on the penetration of steam technology across industries in various years. As the table shows, the actual spread of steam technology in British industry remained heavily *concentrated* in a handful of sectors. In all three years considered in Table 2 mining, textiles and metal manufactures account for more than 50% of steam industrial power. In this respect, a hypothetical GPT account of industrialization depicting an economy powered exclusively on steam would be clearly

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[6] Rosenberg and Frischtak (1984) raised similar concerns about the difficulties in identifying reliable periodizations for tracing the diffusion of basic innovations such as the steam engine or the airplane.

Table 1
Share of steam capital in the total capital stock (Britain. 1760–1907).

Year	Steam capital (in millions of current £)	% of steam in the gross stock of capital (Mining and Manufacturing)	% of steam in the gross stock of capital (Plant, machinery and equipment)
1760	0.21	1.17	0.81
1800	1.96	3.44	2.61
1830	9.6	7.22	7.87
1870	51.5	9.77	11.03
1907	144.885	12.26	12.81

Note: Calculated using the data on steam capital cost per HP (replacement costs) from Crafts (2004), the data on total HP installed from Kanefsky (1979, p.338), data on the gross capital stock from Feinstein (1988, pp. 437–440).

Table 2
Steam power by industry, 1800–1907.
Sources: for 1800, Kanefsky and Robey (1980), for 1870 and 1907, Musson (1978) taking into account the adjustments suggested in Kanefsky (1979).

	1800		1870		1907	
	Number of engines	(%)	Steam HP (power in use)	(%)	Steam HP (power capacity)	(%)
Mining	1064	48.56	360,000	26.22	2,415,841	26.49
Textiles	469	21.41	513,335	37.39	1,873,169	20.54
Metal manufactures	263	12.00	329,683	24.01	2,165,243	23.74
Food and drink trades	112	5.11	22,956	1.67	266,299	2.92
Paper manufactures	13	0.59	27,971	2.04	179,762	1.97
Building trades	12	0.55	17,220	1.25	347,647	3.81
Chemicals	18	0.82	21,400	1.56	182,456	2.00
Public utility (waterworks, canals, etc.)	80	3.65	36,000	2.62	1,379,376	15.13
Others	160	7.30	44,375	3.23	309,025	3.39
Total	2191	100	1,372,940	100	9,118,818	100

wide off the mark. [7] In fact, the progress of steam powered mechanization was far from being uniform both across and within industries.[8] Even in sectors that employed steam intensively, a number of critical phases of the production process continued to be carried out using hand tools well up to the late nineteenth century (for a very good overview of the balance between steam power and hand technology in different industries, see Samuel, 1977).

3. Technological systems and development blocks as "engines of growth"

The considerations of the previous section, in our view, indicate that the focus on few key technologies such as the steam, electricity and ICT seems to be a much too narrow perspective for the study of the connection between the long term evolution of technology and economic growth. In fact, economic historians have emphasized that steam technology was the backbone of a broader new technological system of production. The life cycle of this system of production was stretched over a long period of time clearly actually covering the implementation and successive dismantling of different "vintages" of steam engine technology (Von Tunzelmann, 1995). In this respect, Freeman's notion of "technological system" which has seemingly a broader "coverage" - both longitudinally (as it includes a number of interlinked technologies) and temporally - than the one of GPTs seems more appealing and more in tune with received historical accounts of the long term development of industrialized economies.

Yet, even considering the broad concept of "technological system", it must be recognized that the task of thoroughly tracing a connection between the emergence of particular technological systems in the sense of Freeman and Kondratiev waves of economic growth is still largely unfulfilled. Freeman and his associates (see, in particular, Freeman and Louca, 2001) in their appreciative accounts have assembled some highly suggestive evidence in this direction, but it is fair to say that they have not provided any detailed analysis of the large-scale diffusion of the various technological systems in relation with the process of economic growth.[9]

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[7] It is worth citing the conclusions of Crafts and Mills (2004, p. 170) who have attempted, from a broadly sympathetic point of view, to interpret British nineteenth century productivity trends in terms of the diffusion of steam power as a GPT: "seeking to base an account of 19th century British growth primarily on the implications of steam is surely misconceived. The newfound enthusiasm for General Purpose Technology models as a way of conceptualizing long run growth processes should not be taken too far."

[8] As Samuel (1977) as noted, in many production processes, throughout the entire nineteenth century, formidable technical difficulties frustrated the continuous attempts of developing 'self-acting' machines.

[9] To date, the only systematic attempts to assess the contribution of steam power technology to productivity growth (in Britain) are represented by von Tunzelmann (1978) and Crafts (2004).

They have also suggested the existence of a number of mechanisms such as backward and forward linkages, technological spillovers, investment multipliers of particular technologies, etc., that might indeed account for the economy-wide repercussions of the diffusion of these technological systems. However, in their contributions, the actual workings of such mechanisms are never assessed in a systematic quantitative way (Rosenberg and Frischtak, 1984).[10] Furthermore, as noted by Perez (2015), the chronology of technological systems proposed by Freeman and Louca was only partially consistent with the traditional Kondratiev chronology of long waves. Accordingly, Perez (2015) has recently proposed a reformulation of the original framework in which "technological systems" are related to "great surges of development", each characterized by an "installation period" and a "deployment period". Perez's surges of development are not to be interpreted as coherent economic phases in terms of macro-economic indicators, but rather as phases in which the broad production system is rearticulated around the newly emerging technological system. It is worth noting that Perez's (2015) framework still posits a connection between technical change and economic outcomes, in the form of major financial crises that characterize the "exuberance" of investment in the early installation period of the new technological system.

Interestingly enough, when the notion of "technological system" is used in such a way to encompass the entire life-cycle of a broad constellation of technologies (ie, steam power, machinery, iron production techniques) the long term evolution of capitalist economies seems to be better captured by a different chronological scheme, based on the more traditional distinction between the "first industrial revolution", "second industrial revolution" and "third industrial revolution", than by the one based on Kondratiev waves (von Tunzelmann, 1995, pp 97–100).[11] The original neo-Schumpeterian view sketched by Freeman and his associates, by stressing the role of "constellations of major technical innovations" acknowledged the (mutual) interdependencies among major technological trajectories in a much more explicit way than the successive GPT literature which insisted on "a single generic technology" (Lipsey et al., 2005, p. 98). Hence, for the case of the British industrial revolution, Freeman's view is indeed very similar to the classic account sketched by Landes (1969).

Landes considers the industrial revolution as the outcome of a combination of three interrelated streams of technical advances:

1) "mechanization", that is the substitution in a wide range of production process of machines ("rapid, regular, precise, tireless") for human skills
2) adoption of new power sources, most importantly the steam engine which permitted the utilization an almost boundless energy supply
3) extensive use of new raw materials (in particular the substitution of minerals for animal and vegetable substances, most prominently the substitution of iron for wood).

These innovations revolutionized production processes in a wide array of industries determining a marked acceleration in the rate of productivity growth. Furthermore, they "compelled" the adoption of a new mode of production, the factory system.

In more than one sense, Landes' analysis can still be considered as broadly accurate. In particular, the picture emerging from traditional accounts of early industrialization, such as the one provided by Landes, is one in which steam power seems to be one, but it is worth stressing *only one*, of the core driving forces of a wide process of economic transformation. Even, just considering the ambit of technology, Landes suggests that the steam engine was one component of *three* interlinked streams of technological advances. However, at least in our judgment, more recent research findings indicate that a number of qualifications ought to be appended to this ("traditional") account of the British industrial revolution. In particular, the three streams of technical progress outlined by Landes proceeded at rather different paces, both considering the invention and the diffusion phases. Roughly speaking, one can say that "early mechanization" *preceded* the introduction of steam power.[12]

Table 3 attempts to provide a synthetic description of the constellation of the technological advances of the ICT revolution. In our view, this constellation may be regarded as encompassing four main technological clusters: electronic components, computers, software and networking equipment (see for example, Freeman and Louca, 2001; a similar approach is also adopted in the recent account of the ICT revolution of Isaacson, 2014). Table 3 suggests two important points. The first is that also in this case it is very likely that also the streams of technological advances of the ICT revolution are characterized by different paces of progress (compare the proverbial "Moore's law" for components, with the so-called "Whirt's law" arguing that the speed of development in software more the compensates the advances in semiconductors).

The second point emerging from a careful reading of Table 3 is that the "transformative" nature of the constellation of innovations of the ICT revolution is possibly due to the "autocatalytic" nature of the interactions between the four interlinked trajectories described in Table 3. This means that innovations in one domain are, simultaneously, dependent from innovations in other domains, but also capable of inducing further advances in related domains. To identify and to assess the emergence and consolidation of these autocatalytic connections among clusters of technologies is a critical, but still a largely unexplored research issue. In particular, there is an important difference with respect to the activation of the "autocatalytic" linkages between the first industrial revolution and the ICT revolution.[13] In the case of the ICT revolution the activation of these linkages seems to require the formation of "platforms", defined as standardized bundles of components and equipment, often characterized by modular design architecture (Greenstein, 2010).

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[10] See Silverberg (2007) for a perceptive appraisal of the long wave literature.

[11] This is also different from Perez's framework (2002, 2015) that still considers five main technological systems.

[12] The distinction between the expansion of mechanization and the extensive adoption of new power sources was stressed by Marx (1990) in Chapter XV of the first volume of *Capital*.

[13] For a discussion of "autocatalytic" processes and their relevance for understanding production systems, see Padgett et al. (2003).

Table 3
The macro-trajectories of the ICT revolution.

Years	Semiconductors	Computers	Software	Networking
1940-1950	1947: Point contact transistor (Shockley, Brattain, Bardeen; Bell Lab)	1944: Colossus Mark II (Tommy Flowers; Bletchey Park)		
		1945: ENIAC(Eckert & Mauchly; University of Pennsylvania)		
1950-1960	1954: Silicon based transistor (Gordon Teal; Texas Instruments)	1951: UNIVAC I (Remington Rand)	1952: A-0 compiler (Grace Hopper)	
	1958: Integrated circuit (Jack Kilby, Texas Instruments)	1953: IBM 701 (IBM)	1957: FORTRAN	
	1958-9: Silicon oxide insulation in integrated circuit (Jean Hoerni, Robert Noyce; Fairchild)	1954: IBM 650 (IBM)	1960: COBOL	
			1960: LISP (John McCarthy)	
		1958: Solid state 80 (Sperry Rand)	1963: ASCII	
		1959: IBM 1401 (IBM)	1964: BASIC (Thomas Kurz, John Kemeny)	
1960-1970	1965: Moore’s law (Gordon Moore; Fairchild)	1965: PDP 8 (DEC) [first mini-computer]	1964: OS/360 (IBM)	1960: Dataphone (1st commercial modem; AT&T)
	1967: MOS chip (Fairchild)		1969: UNIX (Kenneth Thompson, Dennis Ritchie; AT&T)	
1970-1980	1971: Intel 4004 micro-processor (Federico Faggin, Intel)	1973: Micral	1979: VisiCalc (Daniel Bricklin, Robert Franckston)	1970: ARPANET
	1972: Intel 8008 (Intel)	1975: Altair		1971: ALOHANET (University of Hawaii)
	1976: Zilog Z80	1977: Apple II (Steve Jobs and Steve Wozniak; Apple)		1973: Ethernet (Robert Metcalfe; Xerox PARC)
	1979: Motorola 68000	1979: Atari 800		1975: Telenet
1980-1990	1985: Intel 80386 (Intel)	1981: Osborne I (Adam Osborne)	1981: MS-DOS	
		1981: IBM 5150 (IBM)	1982: Lotus 1-2-3 (Mitch Kapor)	
	1986: optical transistor (David Miller; Bell Lab)	1982: Commodore 64 (Commodore)	1983: GNU (Richard Stallman)	
		1982: ZX Spectrum (Sinclair)		
		1983: Lisa (Apple)	1984: Mac OS (Apple)	
		1984: MacIntosh (Apple)	1985: Windows 1.0 (Microsoft)	
1990-2000	1993: Intel Pentium (Intel)		1990: Windows 3.0 (Microsoft)	1990: HTML (Tim Berners Lee, CERN)
			1991: LINUX (Linus Torvalds)	1993: MOSAIC (Eric Bina, Marc Andreesen; University of Illinois)

The emergence of these autocatalytic connections among clusters of technologies is clearly reminiscent of the notion of "development blocks" introduced by the Swedish economist Erik Dahmen (Carlsson and Henriksson, 1991). Development blocks are constituted by sets of entrepreneurial activities that are linked in complementary way with each other in such way that they mutually stimulate each other by means of both traded and untraded interactions.[14] For the case of the British industrial revolution, a reading of the most recent contributions (Allen, 2009) suggests the emergence and consolidation of a development block constituted by machinery - machine tools - steam engines – coal – iron production techniques. For the ICT revolution the development block may be seen structured around semiconductors – computers – software - networking equipment (see Malerba et al., 2008 for a perceptive analysis of the co-evolution of the semiconductors and the computer industry). Kander et al. (2013) have recently provided an insightful account of long run energy trends in Europe using precisely the "development block" framework. Their emphasis on the energy component of each development block is an important point that deserves further reflection, because it allows an explicit linking of historical trends in technical change with the issue of environmental sustainability.

The perspective outlined so far, stressing the connection between technological systems and development blocks and the critical role of "development blocks" as "engines of growth" during the first, second and third industrial revolutions may be also connected with another fundamental "work horse" of the economics of innovation literature: the Pavitt taxonomy of patterns of innovative activities. As noted by Archibugi (2001), the Pavitt's taxonomy can indeed be connected with the literature on long waves. In this perspective, the taxonomy should be interpreted in a dynamic, rather than in the conventional static-descriptive fashion. According to Archibugi, each Schumpeterian wave described by Freeman and his associates, may be linked with the emergence of a new type of firms (supplier dominated, specialized suppliers, scale intensive, science based, information intensive) whose patterns of innovative activities are described by a specific category of the Pavitt taxonomy. However, as outlined in Table 4, it is also possible to link the emergence of each type of firms to the three industrial revolutions.

Notably, if we take this approach, it becomes clear that in many Schumpeterian accounts, much too emphasis has been put on the notion of "creative destruction". In fact, the constellation of innovations that are at the origins of the three industrial revolutions have led to the emergence of new type of firms characterized by different innovation behaviors, but this does not imply that pre-existing firms have been completely destroyed and superseded. Rather, as noted by Pavitt himself, we can describe this process as "creative accumulation" with the structure of the economic system becoming more articulated and complex (Pavitt, 1986; on "creative accumulation" see also Bergek et al., 2013).

4. Technical change and organizational forms

Freeman and his associates suggested that the process of structural transformation triggered by the gestation and diffusion of a new technological system "is inevitably associated with the combination of organizational changes needed to design, use, produce and distribute [the new products]" (Freeman and Louca, 2001, p. 147).

Certainly, in the context of the first industrial revolution, the most prominent organizational change associated with the extension of mechanization and the diffusion of water and steam power was the rise of the factory. The factory system became the dominant paradigm for the organization of production in manufacturing, in a similar fashion as "mechanization" became the dominant paradigm for the search of innovations. As is well-known, Landes, in his classic account, maintained that mechanization actually "compelled the concentration of production into factories" (Landes, 1969, p. 81).

This traditional view of the rise of the factory has been, however, famously called into question in a paper by Marglin (1974). In Marglin's view, the key factor for the emergence of the factory system, rather than its technological superiority, was the higher degree of discipline and supervision that this organizational form permitted. In the subsequent literature, especially after a famous rebuttal by Landes (1986), Marglin's argument has been usually regarded as unwarranted at least from an historical point of view.[15] Still, it seems useful to reconsider some issues of the Marglin-Landes debate that have been somewhat neglected in the subsequent literature.

In his paper, Marglin is able to refer to several informed contemporary authors explicitly pointing out that the higher degree of discipline and supervision as one of the key-advantages of the factory systems. Additionally, Marglin (1974, pp. 88–90) also shows that, in several branches of the textile industry, such as wool spinning or cotton and wool weaving, the transition to the factory system unfolded even without being prompted by any dramatic technological change (in this trades factories were using the same technologies - spinning jenny, handloom - that were used in cottage production). From this point of view, Marglin's paper has the merit of pointing out to an important set of factors that, in certain contexts, gave, initially, a cost advantage to the factory system with respect to other organizational forms.

However, the core of Landes' rebuttal to Marglin is the existence of a "dynamic" advantage of the factory as incubator of subsequent technological developments. In other words, even if the transition to the factory system was initially determined by the advantages of this organizational form in terms of discipline and supervision and not by any inherent technological superiority, over time, the subsequent development of mechanization provided to the factory a salient technological advantage of other organizational set-ups. This should not be interpreted in the sense that alternative organizational forms became completely unfeasible from an economic point of view, but, rather, that, in the nineteenth century, the large scale-factory became the "core" organizational form of the productive system while other organizational set-ups remained confined only to specific fringes of the industrial landscape.

In fact, it is important to be aware that other forms of small-scale organizations such as artisanal workshops and small producers'

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[14] There is a broad analogy between the notion of "development block" and that of leading sector used by Rostow (1963).

[15] According to Mokyr (2001, p. 18), Marglin's argument was "effectively demolished" by Landes (1986).

Table 4
Pavitt taxonomy and three industrial revolutions.
Source: Archibugi (2001).

Phase of development	FPavitt's category
First industrial revolution (1st phase)	Supplier dominated
First industrial revolution (2nd phase)	Specialized suppliers
Second industrial revolution (1st phase)	Science based
Second industrial revolution (2nd phase	Scale intensive
Third industrial revolution (1st phase)	Information intensive

plants continued to represent a significant part of the industrial landscape throughout the nineteenth century (Berg, 1994, chap. 9). As Maxine Berg has properly noted, any attempt to apply retrospectively Chandler's model of the drive toward large-scale organizational forms to the case of the first industrial revolution would be totally capricious (Berg, 1994, pp. 206–207). In this perspective, it is worth noting that several of the celebrated textile innovations of the first industrial revolution were developed in the context of rural dispersed puttying-out systems (Berg, 1994, p. 196) and most of them were invented to be powered by traditional power sources and not by steam power (Von Tunzelmann, 1978, p. 160). Even the key sector of the first industrial revolution, the cotton industry, remained "vertically disintegrated" and the main trajectory of development at firm level was that of increasing specialization (Berg, 1994, p. 207). Furthermore, it is widely acknowledged today that the shift towards factory production was by no means unidirectional and that, factory production, proceeded alongside with the proliferation small scale plants, innovative artisanal workshops and modernized forms of puttying-out. In sum, the process is better characterized in terms of an evolving "pluralistic" business structure, rather than a clear-cut shift from an old to a new organizational form (Hudson, 2004). In this perspective, a suitable solution of the Marglin-Landes debate on the rise of the factory system has been advanced by Von Tunzelmann (1993). Von Tunzelmann suggests that the key-factor at the root of the rise of the factory system was the *interaction between technology and new organizational forms*. In other words, we should think again in terms of autocatalytic sequences: the development of new systems of machinery permits higher throughput and higher operating speeds, these developments prompt changes in control systems and in the centralization of production which, in turn, stimulate the introduction of new machines with faster operating speeds.

Interestingly enough, one relatively robust finding that is emerging from the quantitative appraisals of the productivity impact of ICT technologies at firm level is that ICT investments are systematically associated with large productivity increases when they are coupled with organizational changes (Draka et al., 2007).

Clearly, the new technologies of the ICT revolution seem to provide tremendous opportunities in terms of the processing and transmission of information in many corporate contexts. On this basis, it has been argued that the progressive diffusion of ICT technologies may, in the long run, be coupled with a dramatic transformation in the organization of production, perhaps as dramatic as the rise of the factory system, but in an opposite direction, that it is towards organizational forms based in a major way on working from home and tele-commuting, in sum, it is not far-fetched to imagine, especially in service sectors, a transition from centralized production to "tele-cottages" (Mokyr, 2001). The positive welfare repercussions of such an organizational shift, amounting to a major reduction in commuting costs and in increase of the flexibility of working time according to the specific workers' needs, defy a precise quantitative assessment, but they may indeed be very significant (Mokyr, 2001). On the other hand, it is also possible to envisage various potential social drawbacks of the increase of adoption of "distributed forms of work", in particular in terms of the proliferation of temporary and unstable work arrangements (Kallinikos, 2007). In this context, as suggested again by Freeman (2007), the final outcome will, by and large, depend on the capacity of the socio-institutional system to put in place appropriate changes in the legal and regulatory system that can counteract the most detrimental developments. Again, on this point, there may be an interesting analogy with the regulation of the factory system during the British industrial revolution (Freeman and Louca, 2001, pp. 171–173).

5. Patents and appropriability during the industrial revolutions

One of the most controversial issues surrounding the current developments of ICT is the role of patents (and of IPRs in general) in affecting the rate of innovation. In this respect, it is interesting to notice that the recent literature on the economic history of the British industrial revolution can provide some interesting insights. Roughly speaking, in the literature on the industrial revolution, the consensus seems to have clearly moved from an optimistic assessment of the role of patents as encapsulated in the contributions by North (North, 1981) to a rather pessimistic interpretation (Mokyr, 2009; MacLeod and Nuvolari, 2016). This new pessimistic outlook concedes that inventors such as James Watt and Richard Arkwright may have been incentivized by the patent system to develop drastic innovations such as the steam engine and the water frame. However, it is also pointed out that a very large bulk of innovative activities remained, throughout this period, outside the coverage of the patent system (a point that has found important corroboration in the evidence collected by Petra Moser (2005). Furthermore, it is also suggested that unduly "broad" patents such as the one granted to James Watt for the separate condenser probably stifled inventive activities in certain sectors. In sum, economic historians studying the role of patents during the industrial revolution have found difficulties in finding a compelling role played by patent incentives.

In a recent paper, Bessen and Nuvolari (2018) point to a simple mechanism that can explain why patents did not play a critical during the industrial revolution (and in general in the early development of new industries). Bessen and Nuvolari's argument is that when technologies are constrained by shortages in people (or in the number of firms) with the practical knowledge and skills to implement the new technology, the excludability provided by patent protection greatly diminishes its competitive relevance.[16] Furthermore, in such context, knowledge sharing and collective invention may greatly foster innovative activities.

As a matter of fact, recent research is confirming the historical importance of knowledge sharing activities among inventors (Bessen and Nuvolari, 2016). Nuvolari (2005) compares knowledge sharing among the steam engineers working in the Cornish copper mines in the period 1800–1870 and the open source software community finding many common features in the way in which these communities organized and managed inventive activities and knowledge sharing. It is worth noting that the limited relevance of patents seems also to be an important characteristic of the early development of other areas of ICT technologies, beyond software. A very often quoted archetypical example is the case of semiconductors where patents did not play a major role for the appropriation of innovations rents until the 1980s (Hall and Ziedonis, 2001). In this respect, the organization of inventive activities outside patent systems may be an important subject of investigation for understanding the early stages of the ICT revolution.

6. Conclusions

The main point of this paper is probably that, despite its appeal, the GPT view of economic growth may not be such a useful analytical framework of inquiry for studying the long run of capitalist economies. The main shortcoming of the GPT view emphasized in this paper is that it relies on a much too simple and narrow interpretative framework of invention and diffusion. In this perspective, the analytical sophistication that one is supposed to gain from moving to the appreciative neo-Schumpeterian accounts of Freeman and his associates to the formalized treatment of GPT growth models may be largely illusory.

At the same time, it is probably fair to point out that also the neo-schumpeterian appreciative accounts of Freeman and his associates are not without limits. Even in the most recent versions, these accounts remain highly impressionistic and descriptive and there is little effort of assessing in a systematic quantitative way the links between the innovation that comprise the “technological system” and those between the evolution of the technological system and the long run fluctuations in aggregate output (the critical assessment of this literature provided by Rosenberg and Frischtak (1984) more than thirty years ago seems still valid). In this respect, on the basis of a comparison of the salient technological features of the first industrial revolution and of the ICT revolution, we have suggested that a fruitful line of research for developing and better articulating the neo-Schumpeterian accounts (also in terms of explicit quantitative assessment of the impact of specific technological developments on productivity growth) could be that of reviving the notion of “development block” and of “leading sector” that were in some vogue during the 1950s and 1960s.

This perspective suggests that many current policy discussions are probably characterized by the adoption of scenarios that do not properly take the historical experience of the three industrial revolutions we have witnessed so far and that are characterized by interpretative frames that are probably, at the same time, both too narrow and too short. They are narrow because they do tend to emphasize the role of specific technologies rather than the broader dimensions of technological systems. They are too short because they tend assume too rapid phases of deployment and diffusion of these new technologies. The recent hype on the fourth industrial revolution is precisely a case in point (Schwab, 2016). All the technologies highlighted in the volume as drivers of this so-called fourth industrial revolution are, at close look, simply recent or possible future developments of ICT technological system. It remains unclear what is to be gained to label these developments as “fourth industrial revolution” when it seems hard to highlight a specific structural discontinuity in terms of technological or economic trends. On the other hand, it is clear that when one considers that the life cycles of the technological systems of the first and second industrial revolution were long drawn-out processes, the current technological trends can be possibly more insightfully characterized as a further advancement of the ICT revolution.

If this is the case, the main lesson from the history of industrial revolutions is that we are facing long term processes involving large-scale technological systems. Accordingly, an effective policy for developing a feasible transition pathway to a low carbon economic system should be based on a twofold approach. [17]On the one hand, there is a need of large-scale “transformative” policy interventions that will shape the development of the newly emerging technological systems. In this case, it is important that this type of intervention will be grounded in a broad, comprehensive perspective of the various components of the technological system and of the actors and stakeholders involved (Weber and Rohracher, 2012; Schot and Kanger, 2018). In this respect, public policies may play an important role in stimulating the “autocatalytic” complementarities between technologies. The activation of this type of complementarities may prompt an acceleration of the rate of innovation in renewable energy technologies such as solar photovoltaic cells and wind turbines. In this context, policies and firm strategies concerning intellectual property may also be important, as testified by Tesla Motors’ decision of opening up completely their patent portfolio in 2014 quickly imitated by Toyota’s release of their patent portfolio of hydrogen fuel cell patents.[18] Both Tesla and Toyota’s decisions are motivated by the notion that an “open” context (even comprising forms of knowledge sharing) may, in the long run, result in an acceleration of the rates of innovation for carbon-free

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[16] In a related contribution, Nuvolari and Sumner (2013) show that, in the case of the brewing industry, trade in technology could emerge even without resorting to patents.

[17] The perspective outline in this paper should be regarded as complementary to the multi-level perspective for the study of the dynamics of technological transitions. The perspective of this paper is obviously more focused on the dynamics of technological change and its economic outcomes, whereas the multi-level perspective is more focused on the socio-economic dimensions of large-scale transitions (for an example, see Foxon et al., 2010)

[18] On Tesla, see https://www.tesla.com/blog/all-our-patent-are-belong-you ; on Toyota, see https://www.ft.com/content/68e00992-9581-11e4-b3a6-00144feabdc0 (both accessed on 29 October 2018).

transport technologies. Interestingly enough, some historical evidence from the first industrial revolution resonate with this notion (Bessen and Nuvolari, 2018).

However, it is important to be aware that the time scale of these interventions must be extended in order to be in tune with the actual prolonged nature of the processes of technological change in a large scale (Pearson and Foxon, 2012). On the other hand, it is also wise to consider policies that will exploit the processes of "creative accumulation" through which the incumbent technological system evolve for tackling environmental issues. Already in 1992, Freeman (1992, pp. 199–202) invited policy makers to consider the opportunities provided by ICT technologies for energy and material savings. More recently, Pearson and Foxon (2012) have pointed the attention to the potentialities of "smart grids" or "smart control systems" for energy-savings (Pearson and Foxon, 2012). Needless to say, it is obviously important that the policies focused on the newly emerging technological systems and those addressing the "creative accumulation" of the incumbent technological system will be undertaken with a sufficient degree of coordination.

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