The Journey of Innovation

From Incremental to Radical Innovation and High-Tech Innovation Cascades: The Case of Biotechnology

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Abstract This paper argues that innovation has itself evolved, from the slow, path-dependent, and foreseeable world of technological trajectories, to the less predictable world of innovation cascades, after incorporating the analysis of radical innovation in the last three decades. Innovation cascades are long series of radical innovations in one or in related technological domains. Two types of innovation cascades are distinguished in the paper: those emerging before the Industrial Revolution and the modern high-tech ones. The previous innovation cascades usually petered out fairly soon by lack of institutional support, as inventors and innovators were individuals or companies trying out their luck in the market place in a less than friendly environment. Present day innovation cascades benefit from numerous innovating firms, research universities and government laboratories, science, technology and innovation policies, increasing numbers of countries investing in R&D and innovation, as well as reduced costs of access to information, communication and transportation. Today's innovation cascades tend to be more extended through time and space. Their systemic effects are also more widely diffused in global terms.

Innovation is the engine of economic growth. It is thus critical to understand how it proceeds. For several decades, evolutionary theories using the biological model were applied to innovation (Basalla 1988; Petroski 1994; McKelvey 1996): innovation was supposed to proceed in a leisurely way, over the centuries if not the millennia, one step at a time, in an incremental process. Similarly, organisations and institutions evolved clearly from one form to the next. The founding book of this current is that of Richard Nelson and Sid Winter (1982). Industries also evolve and several models have been advanced to explain this evolution (Malerba 2006). For most authors, including the author of this paper, this type of technological

A previous version of this paper was presented to the International Schumpeter Society conference, Jena, Germany, 25–30 September 2014. I gratefully acknowledge the many comments I received in that session.

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A. Pyka, U. Cantner (eds.), *Foundations of Economic Change*, Economic Complexity and Evolution, DOI 10.1007/978-3-319-62009-1_12

change is the most frequent. Arthur (2009) calls 'standard engineering' this evolutionary technical change. Bessant et al. (1994) underlined the fact that continuous innovation is sometimes difficult. Yet the vast majority of authors find evolutionary innovation is ubiquitous. Companies and governments alike abhor rapid technological change that may devalue their assets and sunk costs, and cannibalize their products (Christensen 1997).

Radical innovation (already identified by Schumpeter in his 1939 book *Business Cycles*) appeared and, again, it was deemed analogous to biological change, where saltation (Gould 1977) and short periods of rapid structural change interrupted long periods of stasis and incremental change. Both in biology and management, radical innovation and saltation were difficult to accept. In biology, the neo-Darwinian synthesis wiped out most ideas about saltation. They came back slowly since the 1950s and 1960s through the work of B. McClintock (Nobel Prize in physiology 1983). The idea was developed and popularized by S.J. Gould and N. Eldridge. How the markets accept these complex modifications of product and/or process? In the postwar period, radical innovation appeared in Britain in the works of Gibbons and Littler (1979), Rothwell (1980) and others. A few years later, several authors were discussing the multifarious dynamics between radical innovation, organizations and industry structure (Souder 1983; Achilladelis et al. 1990; Christensen and Bower 1996) as well as the importance of the necessary infrastructure for radical innovation to be adopted (McIntyre 1988).

Much more recently, innovation seems to be accelerating; new scientific disciplines appear. Thus, it cannot be properly depicted as a smooth path, punctuated by occasional changes in direction. It looks much more like a river where fast-moving water evolves from rapids to waterfalls, splits into several diverging flows that sometimes merge with other flows to form new estuaries. The concept of innovation cascades circumscribes evolutionary change (Antonelli 2008, 2009; Berkers and Geels 2011; Delapierre and Mytelka 2003; Lane 2012). Rothwell and Wissema (1986) had suggested that radical innovations arrive in clusters, much in line with the Schumpeterian view of business cycles. This paper suggests that **innovation cascades** are becoming much more frequent today for several reasons: because of the rise of science-based industries (Pavitt 1984), the increasing number of research universities in a growing number of emerging countries, more linkages between these loci of knowledge creation, and faster technology diffusion. Fastest imitation also increases the probability of new combinations between different strands of knowledge. Cascades have a definite Schumpeterian flavour.

The paper will bring some aggregate figures about the rise of science-based industries, and then it will illustrate one of the major (if not the major) present-day innovation cascade with the growth of biotechnology and the arrival in rapid succession of genetic engineering, monoclonal antibodies, genomics, epigenetics, proteomics, bioinformatics, gene therapy, pharmacogenomics, nanobiotechnology, metabolomics, stem cell technology, and other related disciplines. The growth of biotechnology publication and patenting by countries such as China, Japan, Singapore and South Korea is also presented (nbt. 2384). A table with the different disciplines, application and key companies will help.

1 Evolutionary Innovation: Natura Non Facit Saltum

Evolutionary or incremental innovation (small, continuous improvements in technology and organisation) is the most abundant type of innovation. Its predominance over other forms of innovation is easy to accept. Companies and individuals tinker on what they know best. Such behaviour reduces the risk associated with big jumps. Evolutionary product and process and organizational innovation is less expensive, because it requires minor adaption of marketing, and operations strategy and infrastructures. Markets recognize, and sometimes even trigger such slow changes. Many organizations almost continuously produce such small adaptations to environmental changes of their output and/or their structure. Large changes, both in biology and economics would produce monsters, which the environment often rejects as such, and do not survive. The organisation produces variety (at the level of technology, product, process, strategy and structure) in a bounded rational way, and the environment selects. Such slow process drives the organisation and its technologies to local optima. "Artifacts, like plant and animal life forms, can be arranged in continuous, chronological sequences./. . ./Butler, Pitt-Rivers, Gilfillan, Ogburn and Usher all stressed the accumulation over time of small variations that finally yielded novel artifacts." (Basalla 1988, p. 24) Yet, the author recognizes that short periods of rapid change may exist between long periods of slow change and stasis. However, the vast majority of authors on technology have adhered to an evolutionary perspective (Fig. 1).

In economics, Nelson and Winter (1982) have identified the sources of slow change: the firm's routines, which are the genes of organizations. Over time, organisations have developed ways of solving their search, production and marketing problems; such a learning process has been long and costly, and has been

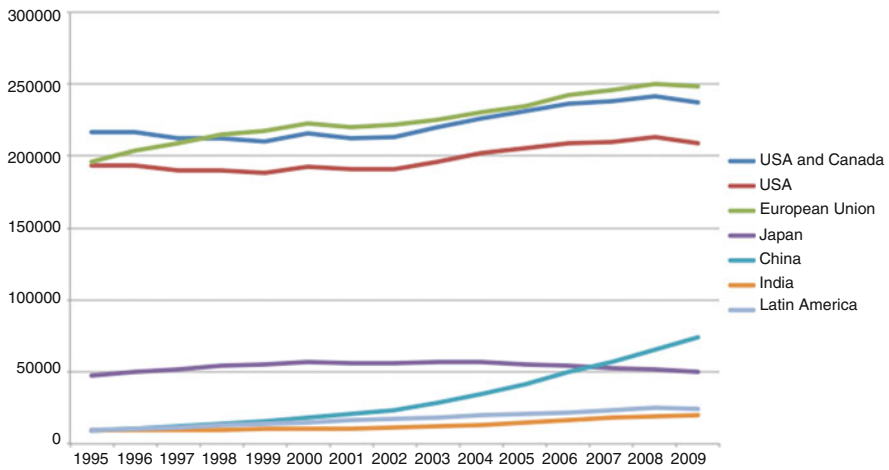

Fig. 1 The rise of scientific publication (1995–2009)

reinforced by the building of complementary infrastructures and practices. Maureen McKelvey (1996) has presented the basic principles of evolutionary innovation in biotechnology. They include variation (generation of novelty); selection; transmission and retention of certain traits over time; and non-optimization but adaptation to local environments. Like Basalla (1988), McKelvey argues that biological evolution cannot be deemed identical to economic evolution. Nelson (2006) has also adopted this perspective: biological evolution and human culture share a few major unifying themes, such as variation, selection and retention, but are split apart by major differences, including the speed of change and the goal-oriented action of humans in cultural evolution. Also, within cultural dynamics there are large differences between fields, such as linguistic and policy evolution.

A lively debate among evolutionary economists and management theorists is linked to the amount of inertia that organizations carry. At one extreme one finds the organisational ecology perspective, with such authors as Michael Hannan, John Freeman, and Glenn Carroll, for which organisational inertia is predominant, and firm level adaptation is limit. Populations of firms change by the birth and death of organizations; those that survive have usually from the start, the right genes. Organizational ecology is more Darwinian, while Nelson and Winter (1982) are more Lamarckian. The more the evolutionary approaches put the emphasis on the importance of strategy, including Nelson and Winter, the farther they are away from the organizational ecology perspective. Whatever the case, it is clear that most companies live and die with their original routines, technologies and strategies. These are the traditional small and medium-sized firms that Bhidé (2000) has shown to be the vast majority of firms. A few of them usually medium-sized and large ones, tend to change from time to time their range of technologies, strategies and structures. This paper adopts a mixed perspective: studies on firm mortality in all OECD countries show that the vast majority of firms disappear a few years after they were founded. A few of them manage to change and adapt to the environment. Even among those that adapt and change, many sometimes err in their choice of new routines, technologies and markets, and also disappear. The roads of industrial change of the latest years are littered with the remains of such companies as Blackberry and Nokia.

In this world of evolutionary innovation, technological trajectories abound, and technological discontinuities are amenable to modelling (Dosi 1982). New technological paradigms (discontinuities) are linked to the emergence of Schumpeterian companies and the process of innovation stabilises. The process is fairly structured:

> . . .a technological paradigm (or research programme) embodies strong prescriptions on the directions of technical change to pursue and those to neglect. (Dosi 1982: 152).

Also, evolutionary innovation is the world of path dependency. Institutions, routines, technologies persist over time, even when they have outlived the social matrix in which they were born

2 Radical Innovation

Before turning to present day work about ***radical innovation***, let us recall that Schumpeter (1939: 90) had already made the distinction between major and minor innovations. By the way, his debate about new forms and innovation has a very deep organizational ecology flavour (ibid: 90–93). Very often new firms are founded to launch a major innovation, Schumpeter adds, and they cease to exist when the previous novelty is not new anymore.

The notion of radical innovation is also labelled **discontinuous** or ***disruptive innovation***. Radical innovation, when successful, has a much larger effect on firm's profitability, market share, and entire industries (Sainio et al. 2012). Key dimensions of radical innovation include technology novelty (clear advances in frontier technology, as in the I-Pad), and market novelty (products that address themselves to new markets, or to markets that were served by other products, such as MABs). Even if it often the special activity of entrepreneurial firms, it also occurs in large established companies (O'Connor and McDermott 2004).

Compared to the PC or even the portable computer, the I-Pad is a disruptive innovation, where large firms are bringing high technical novelty. The I-Pad is lighter (1.5 pounds), has a long life battery (up to 10 h), a powerful camera, a GPS, and fingers are used to tape and swipe the contents of the screen. The I-Pad corresponds to what Sainio et al. (2012) call radical innovation: launched in April 2010, it had sold over 100 million units by October 2012. In addition, other large manufacturers quickly entered the market; they include Google, Lenovo, Microsoft, Samsung and Sony. By the end of 2013, Apple remained the market leader in the tablet segment of the computer industry, and tablets contributed enormously to its profitability. Experts expect that in 2015, tablets sales will be larger than PC shipments (Table 1).

Biopharmaceuticals medicines represent radical innovations compared to traditional chemical-based drugs. Monoclonal antibodies (MABS) that bind to specific forms of cancer bring at the same time market novelty and technological novelty. Up to a few years ago, the only ways to treat cancer were early detection followed by surgery and/or chemotherapy. Ten years ago, in 2004, the first monoclonal antibody, i.e. bevacizumab, against breast cancer, made its appearance in the market. It was surrounded (and still is, like most radical innovations) by strong market uncertainty. The drug inhibits the growth of blood vessels that feed cancer tumours, but not on all patients; its high cost added to market uncertainty, as price inhibited the growth of demand. Many other MABS followed for treatment of different types of cancer.[1] All of them are still suffering from similar market uncertainty, due to high cost, and different effects on different patients.

Table 2 presents the most usual dimensions of radical innovation compared with incremental ones. Note the fact that all these characteristics of radical innovation

[1] See http://en.wikipedia.org/wiki/Category:Monoclonal_antibodies_for_tumors, the list of 71 antibodies approved or being developed against tumours.

Table 1 The biotechnology innovation cascade

Year	Discipline	Landmark event	Definition	Key organizations
1953	Biology	Drs. F. Crick and J. D. Watson (UK) discover the structure of DNA	NA	University of Cambridge, UK
1970	Bioinformatics	E. A. Kabat (USA) pioneer computer methods for biological sequence analysis	"The application of computer technology to the storage, management, and analysis of biological data."[a]	Genomodel, Integromics, Rosetta, SymBioSys
1972	Biotechnology: genetic engineering	Drs. H. Boyer and S. Cohen (USA) develop methods to combine and transplant genes	"Any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use." (UN)[b]	Amgen, Biogen, Genentech, Gilead, Serono, Vertex, UCSF and Stanford U.
1975	Monoclonal antibodies (MABS)	Drs. C. Milstein and G. Kohler (UK) develop hybridoma techniques to produce MABS	The development of monospecific antibodies made by identical immune cells, cloned from a unique parent cell. They bind to any organic substance, that they can detect, purify or destroy	Abbott, Amgen, Biogen, Eli Lilly, Genentech Genzyme, Glaxo, Novartis
1977	Genomics	Dr. F. Sanger (UK) publishes a key method to sequence DNA	Genomics is a discipline in genetics that applies recombinant DNA, DNA sequencing methods, and bioinformatics to sequence, assemble, and analyze the function and structure of genomes (the *complete* set of DNA within a single cell of an organism)	Agilent, Illumina, Life Technologies, Myriad Genetics, Pacific Biosciences[c]
1994	Proteomics	Dr. R. Nelson (USA) develops the use of mass spectrometry in immunoassays	The large scale study of proteins, their structure and functions	Applied Biomics, Biacore, Proteome Sciences. . .[d]
1998	Stem cell therapy	Drs. Thompson and Gearhart (USA) develop stem cells	Introduction of adult stem cell in damaged tissue in order to treat disease or injury, I.e. bone marrow transplantation	Mostly experimental in hospitals and research universities

(continued)

Table 1 (continued)

Year	Discipline	Landmark event	Definition	Key organizations
2002	Gene therapy	Dr. Claudio Bordignon (Italy) publishes the first successful gene therapy treatment	Use of DNA as therapeutic agent to treat genetic diseases (replace mutated genes)	Ark Therapeutics Group, Ceregene (US) Glybera (Netherlands), Shenzen SiBiono GeneTech (China), Oxford BioMedica (UK)
2003	Pharmaco-genomics	Completion of the Human Genome Project (international)	The application of genomics concepts and technologies to the study of drug activity and metabolism, including gene expression, or inactivation and SNP association studies	AnyGenes, DeCode Genetics, Gentris, Glaxo, Jackson Library[e]

[a]European Bioinformatics Institute (EBI)(2012): *In a Nutshell*, Cambridge, UK
[b]UN (1992): The Convention on biological diversity. (http://www.cbd.int/convention/articles/default.shtml?a=cbd-02)
[c]http://www.marketwatch.com/story/genomics-companies-ripe-for-flurry-of-mergers-2013-04-16
[d]http://www.proteinscience.com/companies.html
[e]http://www.jazdlifesciences.com/pharmatech/leaf/Drug-Discovery/Clinical-Research-Services/Pharmacogenomics.htm

Table 2 Incremental and radical innovation defined

Dimension of radicalness	Incremental	Radical
Impact on the industry	Low	High
Source of subsequent innovation	No	Yes
Older technology remains substitute for new	Yes	No
Cost reductions	Low	High
Competitive advantage to adopters	Low	High
Benefits brought if successful	Low	High
Adoption risks	Low	High
Technical uncertainty levels	Low	High
Market uncertainty levels	Low	High
Resource uncertainty levels	Low	High
Organizational uncertainty levels	Low	High

are difficult if not impossible to distinguish at the moment where the new product or service is launched. The impacts on the industry, future benefits and cost curves, risk and uncertainties are unknown at the beginnings of the market introduction, as are the subsequent innovations that may follow piggyback on the original radical

one. Such phenomenon explains why the very innovators in all these science-based radical technologies are often confounded about the future adoption of the novelty. Radical innovation appears wrapped either under the look of incremental one, or as a monster that the market will reject. We know that an innovation was radical only when it is accepted by the market, and generates benefits, cost reductions, competitive advantages to adopters, and when major uncertainties and risks have been dealt with.

3 Innovation Cascades

Innovation cascades are streams of radical innovations usually concentrated in one industry or in contiguous industries. The idea of innovation cascades is already present in Schumpeter:

> First, that innovations do not remain isolated events, and are not evenly distributed in time, but that on the contrary they tend to cluster, to come about in bunches, simply because first some, and then most, firms follow in the wake of successful innovation; second, that innovations are not at any time distributed over the whole economic system at random, but tend to concentrate in certain sectors and their surroundings. (Schumpeter 1939, p. 98)

More recently, a few authors have explored the subject without arriving to a satisfactory explanation of the dynamics of the development of cascades. Delapierre and Mytelka (2003) link innovation cascades to the oligopolistic behaviour of large firms. Competition among large diversified corporations generates the exploration of new technological domains, and the creation of new technologies and new industrial sectors. They do not make any link between their work and Schumpeter's, in spite of the obvious similarities. Antonelli (2008, 2009) explains innovation cascades by the interplay of Marshall and Jacob externalities within clusters. Cascades would appear in regional innovation systems, not necessarily in concentrated industries, as in Delapierre and Mytelka (2003). Explains innovation cascades by a phenomenon called "exaptive bootstrapping". In biology, exaptation is the use of structure or feature for a function other than that for which it was developed originally through natural selection. "Exaption is a change in the function of a trait during evolution. "Bootstrapping," means to help oneself by one's own means and efforts. Thus, in the two previous explanations, the conscious efforts of economic agents launch a cascade; in Lane's approach, some agents would launch a cascade without even noticing it, just trying to solve a local specific problem. His example is Gutenberg's re-invention of the printing press by the introduction of the movable metal type around 1452–1854. Such innovation launched a cascade where new organizational forms (printing companies), new technical novelties (new ink, paper), new markets (for printed books), new types of printing characters (the *italics*) and new functionalities emerged, imitation from other economic agents increased both the market and the innovative activities, in a positive feedback dynamics that eventually extend over decades.

Once it is launched, the self-reinforcing dynamics is difficult to control or predict, even for those that actively involved in the process (Lane and Maxfield 1996). Under such conditions, optimization and strategy making become difficult, if not impossible. And predicting technological trajectories is highly improbable. Finally, Berkers and Geels (2011) use the same notion of innovation cascades to describe a positive feedback innovation mechanism that has taken place among traditional small and medium-sized enterprises using innovations generated elsewhere (mostly equipment suppliers, but also government laboratories and universities). The authors make a passing remark on the fact that these cascades are different from those studies in scale-intensive and science-based industries and/or government utilities (ibid, p. 243), but they do not cite any of the above mentioned papers on innovation cascades. They contribute to the theory of technological transitions.

Technological transitions are major long-term technological changes. These technological transitions come along through several mechanisms: niche-accumulation, technological add-on and hybridisation (Geels 2002). His idea of technological transitions is close to Schumpeter approach of innovation cascades. Technological transitions occur in all different types of industries, from science-based to scale intensive to government-supported sectors. However, "transitions are characterised by one major, radical innovation or discontinuity" (Berkers and Geels 2011, p. 230), while innovation cascades are more characterised by a stream of radical innovations.

In this paper I contend, following Mokyr (2002) that innovation cascades in Western economies before the Industrial Revolution, such as the printing press, failed to promote sustained economic growth. They are different from present day high-tech (information technology and biotechnology) cascades. The reasons why innovation cascades before 1800 where short lived are many. First, the institutional environment did not contribute to its adoption but blocked the diffusion of innovation and the emergence of new radical ones: indexes of prohibited books and censorship were widespread. Also, universities and private companies did not conduct R&D, and there were no public research laboratories to push the cascade further. Radical innovation depended on the individual efforts of remarkable luminaries like Galileo or Watt in physics, Dalton and Lavoisier en chemistry. Before 1800, the innovation centres of the world were just a few cities such as Amsterdam, London, Paris, and Venice, and within them there were few innovating organizations. Also, communications between those centres were slow and costly, and the scientific and technical knowledge of the times was scanty. Innovation came through serendipity, and was not the routine activity of thousands of organizations as it is today.

After the Industrial Revolution innovation cascades became more frequent. One can find several of them associated with the rapid improvements in steel-making technology, the railway, the internal combustion engine, and chemicals to name some of the most important in the nineteenth and early twentieth centuries.

Postwar innovation cascades are increasingly frequent in Western countries. The reasons are many. For one, the stock of knowledge grows by bounds and leaps. As a result, innovation, as measured by the number of patents and scientific publications increases continuously. So the scientific and engineering raw material for innovation is today much more abundant (Kortum and Lerner 1999; Larsen and von Ins 2010). Second, the rise of scientific collaboration (Grene 2007) and particularly of international scientific collaboration increases the number of new combinations that may be produced on the basis of this new knowledge. The growth of international scientific collaboration may be explained by the diffusion of scientific capacity both within industrial countries and among emerging countries (Wagner and Leydersdorff 2005). Also, rapid advances in communication and transportation technology increase today the chances that new combinations emerge from international and inter-regional collaboration. Third, the institutional landscape has enormously changed: in each advanced industrial and emerging country, thousands of innovative firms and hundreds of research universities, as well as public laboratories are now able to amplify and develop many technological trends in a way that was impossible to occur 200 years ago. Thus, all these elements launch positive and self-reinforcing feedback processes that are increasingly unstoppable. Other key innovation institutions contribute today that did not exist in the fifteenth or sixteenth centuries, namely policy incentives, such as those aiming to the commercialization of university research, policies increase the likelihood that scientific novelty is used in industry and launch an innovation cascade.

The previous world was one were technological trajectories and path dependencies were the name of the game. They still are numerous today, but innovation cascades, a world of self-reinforcing mechanisms, non-linear dynamics with many possible short-term equilibrium situations, make that technological trajectories are less evident than 50 years ago. Who could foresee the rise of Internet, or the advances in computational genomics 30 years ago? Technological path dependencies also seem to be often interrupted by these innovation cascades. The dictum "Natura non facit saltum" does not apply to these unpredictable cascades.

4 Biotechnology Innovation Cascade

Today two major innovation cascades are dominating the industrial landscape: information and communication technologies, and biotechnology. This paper will confine to biotechnology.

The discovery of the structure of DNA by Crick and Watson, in 1953 launched one of the most astounding innovation cascades in human history, only comparable with those that are taking place in information and communication technologies.

In a rapid succession, from the discovery of the structure of DNA by Crick and Watson in 1953, followed the development of methods to cut, transplant and

recombine genes by Boyer and Cohen in the United states (1972), the development of bioinformatics in the 1970s, methods to produce monoclonal antibodies (UK, 1970s), and genomics and proteomics and pharmacogenomics, followed by stem cell and genomic therapies. While genetic engineering and MABS are already revolutionising the way biopharmaceutical companies operate and the drug market is organised, bioinformatics, genomics and proteomics are starting to produce new results that allow companies to identify the reasons why some drugs are effective on some people and not on others, and to improve them consequently. Between 2000 and 2009 US applicants filed 116,145 international biotechnology patent applications, against Japanese applicants with 37,754, Chinese applicants with 24,135 and Germans with 23,818.[2]

Any innovation cascade is punctuated by many intersections where the very people involved in the dynamics could not understand the nature of what was going on. In the late 1990s, gene or stem cell therapies were considered impossible. Today they are being experimented everywhere and the first successes take place in both bone marrow transplantation and cornea regeneration, among others.

It is important to underline the fact that today the biotechnology innovation cascade takes place essentially in North America and Western Europe. The United States are the cradle of some 80% of all biological drugs, with Britain, France, Germany and Switzerland following. Such a finding suggests that innovation cascades occur within innovation systems in advanced countries. Yet, several Asian countries, most prominently China, Japan and South Korea are entering this field at great speed, through massive public subsidies and through the hiring of hundreds of Chinese scientists trained in North America and Western Europe. The rise of stem cell research in China is just one of them (Dennis 2002). Similarly, Indian pharmaceutical companies are starting to innovate and patent in several advanced fields of biopharmaceuticals (Mueller 2006). And Brazil is now among the top countries in terms of biotechnology publication.

Also, the biotech innovation cascade, as the ICT one, is bringing forward a cornucopia of new business models, a big bang of new business organizations (Bourreau et al. 2012). The reason is that biotechnology firms operate in an environment of high uncertainty due to rapid technological change.

4.1 The Genomics Revolution and Sequencing Technology

A major part of the biotechnology revolution is linked to the fast improvement that took place in sequencing technology (Heather and Chain 2016). The following insert summarizes the main steps in the sequencing technical support of the revolution.

[2] http://www.uspto.gov/web/offices/ac/ido/oeip/taf/tecstc/classes_clstc_gd.htm (for US patents)

Date	Main inventor	Country	Contribution
First generation sequencing milestones			
1965	Robert Holley	USA	Describing the structure of tRNA
1977	Frederick Sanger	UK	Chain-termination sequencing technique
1983	Kary Mullis	USA	Polymerase chain reaction improved
	Kary Mullis	USA	Polymerase chain reaction improved
Second generation sequencing milestones			
1983	Kary Mullis	USA	Polymerase chain reaction (PCR) improved
2000	454 Life Sciences (in 2007, Roche acquired it)	USA	Mass parallelisation of sequencing reactions reducing cost and increasing ease of DNA sequencing through large scale pyrosequencing
Third generation sequencing milestones			
2003	Stephen Quake	USA	Single molecule sequencing
2004	Illumina	USA	Bridge PCR; ligation of fragmented DNA to a chip
2005	Complete Genomics	USA	DNA nanoballs and unchained sequencing by ligation

The performance of DNA sequencers has increased at a rate faster than Moore's law in computers, and allowed the biotechnology revolution to enter in a new era. Sequencer's applications include evolutionary biology (evolution of plants and animals), genetic tests, forensics, paternity tests, metagenomics (identification of organisms present in air or water), pharmacogenomics (identification of genes that may favour or block the efficacy of medicines in patients) and many others. The biotechnology innovation cascade would have never unfolded in so short period of time if not for the contribution of DNA sequencers.

5 Conclusion

For centuries, evolutionary innovation has taken place in Western countries at its own slow pace. Radical innovation, conversely, has taken place most often in advanced scientific and industrial nations, and occasionally in emergent nations. Innovation cascades of today exist in affluent (Europe, North America, and Japan) and emergent capitalist nations, China and South Korea.

We are not aware of innovation cascades taking place in developing countries, but occasionally such countries produce a radical innovation. Mokyr (1990) suggested that many Chinese innovations (silk, porcelain, gunpowder, clocks, printing, iron suspension bridges, advanced ships, etc.) were either suppressed or controlled by bureaucratic restraint of the Ming dynasty (1368–1644), and their diffusion was sometimes forbidden by the central government. In Europe, instead, political divisions favoured the diffusion of advanced scientific or technical ideas from one country to others. No autocratic European ruler or the Catholic Church could completely suppress technical and scientific advancement in Europe, thus leaving free course to innovation cascades.

Innovation cascades are taking place even more frequently within different sectors of the advanced economies. Up to now most of them, if not all, from those that occurred before the Industrial Revolution to modern times high-tech ones, have taken place in industrial advanced nations. To impact economic growth, such cascades require an ecosystem of institutions, one that is only provided by the national systems of innovation in those countries.

Innovation cascades seem not so much linked to regional knowledge spillovers, as argued by Antonelli, even if at the origins there may be a hub or several ones of knowledge creation. They are not either linked to large firm behaviour in oligopolistic markets, like Delapierre and Mytelka suggested. They are more often determined by a rapid increase in knowledge production in a rising number of countries and organisations. They are also linked to increasing international scientific and technical collaboration.

Innovation cascades are such that their technological trajectories are difficult to foresee. They have their own dynamics, and often confound their own main agents. By nature, radical innovation is difficult to foresee. Streams of radical innovation are even more so.

This paper suggest that innovation cascades have become more frequent in the past half century and will become more so in the years to come, as the frontiers of science advance very fast, the number of loci of knowledge creation increases, and international research collaboration soars multiplying the chances of radical recombination, and brand new novelty.

Also, innovation cascades force us to revise our evolutionary models including concepts such as path dependency, technological trajectories, and lock-in. Some room must be left to path creation, technological uncertainty and radical novelty.

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