Radical Innovations: Indicators, Origins, and Processes

by

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PRELIMINARIES AND OBJECTIVES OF THE DISSERTATION

There is a vast and sprawling literature on radical innovations, covering (among others) historical, sociological, managerial perspectives, as well as a large body of economic research. The fil rouge connecting all these perspectives lead us to a un understanding of Radical Innovations as innovations which introduce new concepts that depart significantly from past practices, have the potential to generate new markets, and through a mix of competitive and cooperative interactions, trigger follow-up innovations and growth in other firms. All in all, they can be considered Critical building blocks of nations' creative destruction capacity and their long-term economic growth.

However, given their unquestionable importance, how can we define Radical Innovations?

Although a number of definitions have been advanced both in the management literature (Henderson and Clark 1990; Chandy and Tellis 2000; Tushman and Anderson 1986; Utterback 1994; Fleming 2001; Ahuja and Lampert 2001) and evolutionary economics literature (Dosi 1982; Freeman 1992), all these scholars have used the notion of radical innovation in at least two distinct ways. The only common feature of these two uses is that in both cases something big and exceptional happens.

According to Murmann and Frenken (2006), Radical innovations have been defined either in terms of their antecedents (the scope of new knowledge required) or in terms of their consequences (the increased performance they make possible). Given these two different dimensions of radicalness, an innovation could be incremental in terms of the new knowledge required but radical in terms of the additional performance achieved, and vice versa. The extreme case concerns innovations requiring large amounts of new knowledge and creating large performance improvements clearly having a particular potential to transform industrial structures.

In this sense we have a blurry meaning to cope with. Indeed, what complicates the picture is that most scholars do not distinguish between these two meanings, which makes it difficult to interpret in what sense they see an innovation as being radical.

From these few lines, someone can easily realize that what lays at the basis of the distinction between radical and incremental is easier to intuit than to define or measure (Dewar and Dutton 1986).

Indeed, even going beyond defining this construct with all the related context dependence, disentangling the variety of indicators developed so far to get the gist of radicalness, provides us with a faint and incomplete landscape. Our effort in that sense pointed out to the validation of such a set of patent-based indicators in the Biotechnology domain, by taking into account the difference between ex-ante and ex-post measurements and perspectives; the former, reflecting at least partially the nature and novelty of the patented inventions (Ahuja and Lampert 2001; Dahlin and Behrens 2005; Trajtenberg et al. 1997; Fleming et al. 2007); the latter, concerning at least partially the impact and value of inventions (Gambardella et al. 2008; Dahlin and Behrens 2005; Albert et al. 1991; Carpenter et al. 1993; Jaffe et al. 2000; Trajtenberg 1990; Harhoff et al. 1999; Hall et al. 2005; Singh and Fleming 2010). While the results concerning the ex-post patent-based indicators were quite satisfactory both in terms of recall (67%) and precision (79%), when it comes to consider the ex-ante patent-based indicators the figures are less comforting. Recall and precision get 21% (less than 1 out of 4) and 61% respectively. Notwithstanding the fact that the model with both ex-ante and ex-post patent-based indicators works well (Recall = 69%, Precision = 84%). This signals four future challenges: 1) in terms of novelty, a great potential for seeking to identify the nature of inventions more accurately emerges; 2) in terms of impact, the deployment of more sophisticated, network-oriented indicators could enhance the prospect of added value; 3) in terms of developing novel, complementary indicators calls for text mining algorithms to take

into account the content of the inventions; 4) the role of non-patent references, as well as the number of claims, would appear to deserve further attention: when included as a control variable, they tend to consistently predict important contributions in a positive manner.

To be informative on the novelty side, trying to provide more insights on the antecedents of radicalness, a longitudinal case studies methodology has been applied. Specifically, the innovative path to the discovery of the structure of DNA on one hand, and the path to the invention of DSL on the other hand, have been gone through. Withing the frame of the novelty construct, the socio-technical dynamics have been also explored in order to be informative on the key factors influencing the rate and direction of innovativeness. By relying on the notions of Ludwik Fleck's Thought Collective (Denkkollektiv) and Thought Style (Denkstil), developed late in the 1930s, in conjunction with the role of the Experimental Systems (Rehinberger 1994/1996) and the concept of Prematurity in the background (Stent 1972), some preliminary and interesting insights popped up. What we did was to first make a systematic collection of those common aspects characterizing both inventive paths,in the attempt to generate propositions. These common factors can be easily characterized as follows: Systematic discovery (the struggle between rigour and logic, and the moderating role of intuition), Fruitfulness of discovery (investigating the role of associated discoveries, and complex chains of discoveries), Simplicity and Brevity, Flashes of Thought, Role of Chance (to distinguish between psychological and external chance), Role of Errors (oversimplifications, false problems, discrepancies between theory and experiments), Originality (problems of precursors and quarrels about priority, forgotten and/or unpublished discoveries, coincidence of discoveries, rediscoveries, simultaneous discoveries), Missed Discoveries, Struggle against Routine, Inventor's personality (role of vanity, ambition, rewards, love of science, discipline). If so far we have insisted on the individual aspect of discoveries, nevertheless our examples have brought out the part played by collective factors.

The importance of instruments in observation and experiment is such that the technical level has direct repercussions on that of the experimental sciences, and the latter in turn is reflected in the theoretical sciences. The reverse process also is equally clear. Thus the levels attained in the fields of scientific knowledge are always more or less interdependent, their interrelations being largely determined by political and economic factors. The set of these 'individual and collective' factors leads to the prematurity of what in German is called Zeitgeist (the spirit of time). Indeed, failure to initially recognize the arrival of a breakthough concept is not uncommon in science, as in any human endeavor. The most important implications stemming from this study pertain to the fact that ex-post radical innovations seem to be nothing more than the last incremental advancement of a long and complex chain of events, being them objectifications of a radical event occurred years before, sometimes neglected, sometimes unpublished, with the help of more converging results made possible by more sophisticated technological and scientific tools. Another important conclusion concerns the concept of knowledge recombination, stimulated by inter- and intra-collective socio-technical dynamics; and as the invention materializes at the end of a collective act, the question 'who invented what' looses importance: our study, on the contrary, signals the necessity to emphasize the 'how was invented what', the process.

By delving into the innovation process perspective, from the angle of the collective dynamics, we noticed that a preminent role was played by multiple-heterogeneous agents engaging in collaborative strategies with the aim of getting some degree of radicalness. A theoretical framework was then advanced by considering two dimensions: 1) partners' non-spatial proximity, which can be briefly characterized as the set of cognitive, technological, organizational, social, cultural, institutional characteristics (Aguiléra, Lethiais, and Rallet 2012; Knoben and Oerlemans 2006) basically shaping their knowledge base; 2) collaborative development strategy, in terms of the number of partners involved in the collaboration setting

(one-to-one, or one-to-many). What is important about the second dimension is the meaning of the term ‘collaborative’: it entails a joint work (e.g. R&D cooperatives), not simply shared positions (e.g. industry association, lobbying group), to leverage the differences, in terms of knowledge, skills, and resources, so as to develop innovative, synergistic solutions to complex problems companies cannot solve on their own (Hardy, Lawrence, and Grant 2005; Deck 2004; Doz and Hamel 1998; Verganti 2009). According to Hardy, Lawrence, and Grant (2005), collaboration represents a complex set of ongoing communicative processes among individuals who act as members of the still separate organizational hierarchies. There is also a collective identity, a concept grounded in a variety of traditional sociological concepts, ranging from Durkheim's "collective conscious" to Marx's "class consciousness." It "addresses the 'we-ness' of a group, stressing the similarities or shared attributes around which group members coalesce“ but also leveraging their diversity. Three probabilistic paths emerge, being them potential ways by means of which companies can get radical innovations, conditional to the configuration of knowledge about likelihoods, knowledge about outcomes, and time frames that each path requires. Also, a more fine grained differentiation between antecendents and consequences of radicalness was implemented. The most interesting implications concerned the kind of Search strategy such companies undertake, being it ‘local’ in cases of collaboration settings involve very similar partners, and ‘discoursive’ in cases of collaborative developments among very diverse partners. What emerged was that such a Discursive Search is an effective way of improving the chances of getting radicalness both in terms of new knowledge recombinations and innovation outcomes. However, this collaborative capability requires to carefully go through the Conversation-Consensus-Collaboration circle, to consider the role of knowledge about outcomes vs knowledge about likelihoods in order to cope with ‘incertitude’, the role of extended time frames, the dissemination of local optima in between the two search strategies, and the expectation that relationship between the overall strategy and

the degree of radicalness which is aimed to, is an inverted-U shape: too much diversity becomes detrimental even for any (collaborative) conversation to start.

The three chapters which follow, will further illuminate the aforementioned peculiarities of radical innovations.

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Contents

CHAPTER 1

Inventions shaping technological trajectories: do existing patent indicators provide a comprehensive picture?[1]

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Abstract

Since Schumpeter's seminal work on economic development (Schumpeter 1934), innovation is considered as one of the main drivers of firm performance and economic growth. At the same time, technological innovations vary considerably in terms of impact with only a minority of new inventions contributing significantly to technological progress and economic growth. More recently a number of indicators derived from patent documents have been advanced to capture the nature and impact of technological inventions. In this paper, we compare and validate these indicators within the field of biotechnology. An extensive analysis of the recent history of biotechnology allows us to identify the most important inventions (n=214) that shaped the field of biotechnology in the time period 1976-2001. A considerable number of these inventions have been patented between 1976 and 2001 (n= 117, 55%). For all USPTO biotech patents filed between 1976 and 2001 (n= 84,119), relevant indicators have been calculated. In a subsequent step, we assess which indicators allow us to distinguish between the most important patented inventions and their less influential counterparts by means of logistic regression models. Our findings show that the use of multiple, complementary indicators provides the most comprehensive picture. In addition, it is clear that

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ex-post indicators reflecting impact and value outperform ex-ante indicators reflecting the nature and novelty of the invention in terms of precision and recall.
Keywords: patent indicators, important technological inventions, validation, biotechnology.
JEL codes: 033, 034

Introduction: Some technological inventions are more influential than others

While the importance of technological innovation is widely acknowledged in terms of value creation on the level of firms and economies as a whole, the nature and impact of technological inventions vary widely. Some new technologies imply a relatively small extension of prior art (i.e. prior technological inventions), while others are highly novel and disrupt or reshape the technological landscape. A large number of new technologies never reach the commercialization phase whereas others allow companies to grow at impressive rates or even stimulate the creation of new industries. For instance, Scherer and Harhoff (2000) found, in the case of eight samples of company and university owned patents, that 10% of the patents in the sample generated 48% to 93% of the total returns. A variety of concepts have been advanced to delineate important technological inventions ranging from radical, revolutionary and breakthrough to discontinuous and disruptive. Technological breakthroughs or radical inventions introduce new concepts that depart significantly from past practices, have the potential to disrupt existing markets, generate new markets, and elicit follow-up innovations. Thus, they can be seen as critical building blocks of a company's or a nation's creative destruction capacity and as a key determinant of long-term economic growth.

In general, the definitions used in the management literature tend to characterize the differential nature of inventions both in technological and in economic/financial terms. Adopting a technological perspective, radical inventions rely on a different set of science and engineering principles than previously existing technologies (Henderson and Clark 1990),

and/or incorporate substantially different core technologies (Chandy and Tellis 2000). Incremental inventions, in contrast, improve and extend existing technology. Henderson and Clark (1990) introduced the notion of architectural innovation in which core components remain unchanged but are linked differently in a new architecture. Radical innovations, according to their classification, are those where not only the concepts are linked together differently but the core concepts themselves are overturned. Along the economic and financial dimension, technological breakthroughs are listed as adding significant new value to the marketplace or through their impact on competitive dynamics. For example, Tushman and Anderson (1986) defined a technological breakthrough as an order-of-magnitude improvement in the maximum achievable price versus performance frontier of an industry. Finally, breakthroughs have been defined in terms of the profound impact they have on firms, industries and markets. Utterback (1994) defined radical innovations or discontinuous change as "change that sweeps away much of a firm's existing investments in technical skills and knowledge, designs, production technique, plant and equipment," and Henderson (1993) described an innovation as being radical when it renders a firm's information filters and organizational procedures (partially) obsolete. In addition, a number of concepts closely related to radical innovations are popular in the management literature. Tushman and Anderson (1986) classified technological breakthroughs as either competence-enhancing or competence-destroying, depending on whether they either reinforce or destroy established firms' existing competencies, skills, and knowledge. Technological breakthroughs are also described as inventions that serve as the basis for many subsequent technological developments (Fleming 2001; Ahuja and Lampert 2001) and, as such, shape the development of fields and related industries. Christensen (2003) focuses on disruptive technologies and their implications for established firms in an industry. A disruptive technology will have features that initially only a fringe market segment will value. It redefines the performance

trajectory (e.g. in the case of the disk drive industry, shrinking the size of disks). These disruptive technologies need not be radical in nature: in fact, Christensen notes that, in general, disruptive innovations are technologically straightforward.

In the evolutionary economics tradition, radical innovation is commonly evoked in typologies that attempt to characterize the degree of innovativeness of a product's or process's (Dosi 1982). Freeman (1992) proposed a taxonomy for technological innovation involving four levels of change: incremental innovation, radical innovation, changes of technical systems, and changes of techno-economic paradigms. Radical innovations, according to Freeman, are discontinuous as they introduce far-reaching changes in technology and affect different parts of the economy, ultimately leading to entirely new sectors.

In the last two decades, we have not only witnessed the introduction of a variety of definitions, but a number of patent-based indicators have been advanced to assess the nature and value of patented technological inventions. Patents contain detailed information on the nature of the technology and leave a trail of patent citations, backward citations (i.e. the citations made to prior patents) and forward citations (i.e. the citations received from future patents). This information allows us to trace elements of the origin of technologies as well as their influence on future generations of technologies (when they directly or indirectly serve as prior art). In addition, patent citations provide indications of the economic value of patents (Griliches 1984; Jaffe & Trajtenberg 2002). Our contribution builds on the most notable patent-based indicators used in the literature to assess the nature and value of patents, and aims to assess which indicators allow us to identify the most important inventions that shape the development of a technological field. In order to do so, we identified major contributions within the field of biotechnology (time period: 1976-2001). In a subsequent step, the different indicators used in the literature are calculated for all granted USPTO biotech patents (time period 1976-2001). Finally, we rely on logistic regression models to assess which indicators are able to identify

the most influential patented technologies. Our findings reveal that combining available indicators results in recall rates exceeding 68% while precision amounts to 84%. Ex-post indicators measuring technological impact and economic value clearly outperform ex-ante indicators reflecting the nature and novelty of an invention.

The remainder of the paper is outlined as follows. First, we introduce the data and indicators used in this analysis. Next, we discuss the descriptive statistics and results from multivariate analysis. We conclude with a discussion of the implications as well as the directions for further research.

Patent indicators that assess the nature and value of technological inventions: an overview

Different indicators relying on patent data have been used in the literature to assess the nature and impact of patented inventions.

Patent-indicators to assess the nature and novelty of technological inventions

To assess the nature of an invention, patents can be compared in terms of backward citations, technology classes or both. Patents without backward citations to technical prior art have been labeled 'pioneering' (Ahuja and Lampert 2001) while dissimilar patents have been defined as having backward citations that are different compared to prior patents in the same field (Dahlin and Behrens 2005). The originality of a patent can be identified through a patent's backward citations with original patents relying on prior art from a broad range of technology fields (Trajtenberg et al. 1997). Finally, more creative inventions have been identified as displaying novel pairwise combinations of technology subclasses or components at the patent level (Fleming et al. 2007).

Dissimilar and unique backward citations

A first method of identifying technologically radical inventions was developed by Dahlin and Behrens (2005) using backward patent citations to other patents. By calculating the overlap scores between the backward citations of each patent P granted in year t with all other granted patents[2] in the same field, and averaging these overlap scores within each year relative to the grant year t, one can identify which patents have a dissimilar citation structure with respect to prior art and a unique citation structure with respect to patents granted in year t. Those patents that have low overlapping scores compared to prior art in the field are considered more inventive and unusual. Note that patents without backward citations have the lowest possible overlap score and, as such, are considered more revolutionary or pioneering (Ahuja & Lampert 2001).

New pairwise combination of technology subclasses

New technological inventions originate from recombining and extending pre-existing technological inventions (Nelson and Winter 1982; Basalla 1988). Fleming (2001) conceptualizes technological invention as a recombinant search process across the technology landscape in which inventors experiment with the recombination of technological components. He argues that a patent's technology subclasses capture the different components used to develop the technology. Using patent data, Fleming (2001) empirically shows that breakthroughs, i.e. patents with the highest variability in forward citations (i.e. the citations received by a patent from future patents), most likely originate from the recombination of familiar technological subclasses, i.e. subclasses with, in relative terms, progressively more recent prior patents. Nevertheless, the findings show that patents re-using the same combination of subclasses as prior patents are less likely to be breakthroughs. Thus,

[2] To calculate the overlap score between patents A and B, the number of overlapping backward citations of A and B is divided by the total number of backward citations of A and/or B. Only citations to patents granted in a year before the minimum grant year of A and B are taken into account.

breakthroughs most likely materialize from recombining disconnected but pre-existing technology subclasses. To identify particularly original contributions with a potentially high impact on future technology development, Fleming et al. (2007) sought to look at patents that were the first in history to recombine at least two previously disconnected technology subclasses[3].

Originality

Trajtenberg et al. (1997) developed a backward-looking measure charachterizing the antecedents an invention based on patent references. Originality captures the extent to which the nature of the research underlying the patent is closely related to technical prior art stemming from a variety of technology fields.

Patent indicators to assess the impact and value of technological inventions

To assess the impact and value of the patent, scholars have primarily used forward citations, backward citations and technology classes. The number of citations a patent receives reflects its direct impact on future technological inventions as well as its private and social value (Gambardella et al. 2008). A similar backward citation structure between a patent and later patents reflects adoption by future generations of technological inventions (Dahlin and Behrens 2005). Patents that are cited by patents from different technology fields are considered to have a more general purpose or impact (Trajtenberg et al. 1997). Finally, technologies with a novel combination of technology subclasses are adopted by future generations of inventions so that the same combination of subclasses is frequently used by future patents (Fleming et al. 2007).

[3] A patent with three technology subclasses A, B and C has three pairwise subclass combinations AB, AC and BC. A novel pairwise subclass combination is identified as the first patent in history with the particular pairwise combination of technology subclasses.

Indicators relying on the count of forward citations

The most popular indicator of patent impact or value is the number of forward citations received from future patents. The number of forward citations that a patent receives is related to its technological importance (Albert et al. 1991; Carpenter et al. 1993; Jaffe et al. 2000) as well as its social (Trajtenberg 1990) and private value (Harhoff et al. 1999; Hall et al. 2005; Gambardella et al. 2008). The distribution of forward citations is very skewed, with a large share of patents receiving no citations and a small minority of patents obtaining a large number of forward citations. This pattern resembles the distribution of the actual value of inventions. Hence, it is likely that outliers in the distribution of forward citations pertain to more important inventions. Prior research has typically identified breakthrough patents as the top 1% or 5% in terms of citations received compared to patents with the same application year and technology class (Ahuja and Lampert 2001; Singh and Fleming 2010).

Adoption of backward citations

Besides having a dissimilar and unique backward citation structure, technologically radical patents should also have a backward citation structure that is adopted by future patents in the same field (Dahlin and Behrens 2005). The more similar the backward citations of a patent and future patents in the field, the more influence the patent has on future technological progress.

Adoption of a novel pairwise combination of technology subclasses

To assess the diffusion or adoption of a patented invention that recombines two disconnected technology subclasses, Fleming et al. (2007) look at the number of future patents that use the same pairwise combination of technology subclasses. The larger the number of future patents re-using the same combination of subclasses, the greater impact the patent has on future technological progress.

Generality

Trajtenberg et al. (1997) develop a measure of generality, capturing the extent to which the patented invention serves as prior art for a broad range of technology fields. So, while originality measures the broadness of the prior art of the invention (based on backward citations), generality captures the extent to which an invention directly serves as prior art for different technological fields (based on forward citations, i.e. citations received).

Biotechnology

Definition and short history

According to Bud (1993), the term biotechnology was coined as long ago as 1917, the year of the Russian revolution. Today, the best known definition is perhaps the one spelled out by the Organization for Economic Co-operation and Development (OECD 2005): "Biotechnology is the application of scientific and engineering principles to the processing of materials by biological agents to provide goods and services." Biotechnology is a field that emerged from agriculture and animal husbandry in ancient times through the empirical use of plants and animals that could be used as food or dyes (McGloughlin and Edward 2010). Moreover, contrary to its name, biotechnology is not a single technology. Rather, it is a group of technologies that share two characteristics: working with living cells and their molecules, and having a wide range of practical uses that can improve our lives (Keener et al. 2012).

According to Buchholz and Collins (2010), four periods can be discerned in the history of biotechnology (before 1850, 1850 to 1890, 1890 to 1950, and the period from 1950 onwards). This paper focuses on the later period, more particularly, the period from 1976 to 2001. By the 1950s, large-scale production of, for example, beer, cheese, citric acid, pharmaceuticals and other products of social and economic relevance such as antibiotics had become well established. During that time, biotechnology benefited from major public funding and made an increasing economic impact. Major technological progress was achieved during the late 1970s

and 1980s, most notably due to genetic research and recombinant technologies. A milestone was the model of DNA providing the molecular basis of heredity derived by Watson and Crick with the aid of data provided by Rosalind Franklin who worked in Maurice Wilkin's X-ray crystallography laboratory in 1953 (Watson and Crick 1953). However, the DNA revolution, as Hotchkiss (1979) termed it, penetrated slowly into technology, initially having little effect on traditional processes and products. A significant change was triggered by the introduction of recombinant DNA (Cohen, Chang and Hsu 1972; Cohen and Boyer 1979; Cohen and Boyer 1980). The emergence of molecular biology and biochemical engineering coincided with a growing industrial interest and the range of products expanded significantly. The field's progress is reflected in the exponential rise in the number of journals devoted to biotech established in the late 1970s and early 1980s (Buchholz and Collins, 2010).

The integration of applied microbiology, biochemical engineering and molecular biology led to the creation of biotechnology as a scientific discipline in its own right, with a common paradigm at the level of molecular research. Sub-disciplines such as genomics, transcriptomics, proteomics, metabolic flux analysis with quantitative analysis of complex metabolic pathways and, finally, biochemical engineering and bioinformatics have merged to create bio-systems engineering (Sinskey 1999; Stephanopoulos 1999; Reuss 2001).

Identification of major contributions that shape the field of biotechnology

In order to identify the most important technological developments that have shaped the evolution of biotechnology, we relied on secondary sources including books, journal articles, websites of inventors, academics, companies and research institutes, and expert reports. Amongst those sources, we principally relied on scientific books providing a consistent and exhaustive overview of major technological accomplishments in biotechnology or a particular subfield of biotechnology. Appendix 1 provides an overview of the major sources used in this respect. We verified multiple secondary sources to strengthen the overall consistency of our

list of important inventions, since any account may well be conditioned by the personal interests or values of the authors. We concentrated initially on events labeled as discontinuous, pioneering, important, breakthrough, revolutionary, radical, drastic, cutting edge, fundamental, groundbreaking, dramatic, leap forward and original, among others. In particular, we searched for those inventions that were described as contributing to the evolution of biotechnology, highlighting fundamental leaps on certain key research trajectories or establishing new ones that were clearly stated by authors.

Relating important contributions to patents

After carrying out a comprehensive screening and assessment of technological inventions that shaped the field of biotechnology, we systematically searched for patents and publications associated with those inventions. Using information on the description and timing of the invention, the associated researchers, institutions and/or companies, we searched for corresponding patents and publications in the USPTO patent database and the ISI Web of Science (WOS), respectively. In some cases, we found more than one corresponding patent and/or more than one corresponding publication, whereas we were unable to find publications or patents for a minority of important inventions. Of the 214 important inventions identified, for 117 (55%) we found patent documents in the USPTO patent database while 153 (71%) were found in the WOS database as scientific publications. For 37 (17%) of the events, we found at least one corresponding patent, for 72 (33%), we found only one publication while for 81 (38%), we found patent-paper pairs. For eight events, we found multiple corresponding patents. Note that in these cases, we only include the patent document with the earliest priority date. For 25 contributions, neither a patent document nor a scientific publication (present in the Web of Science) has been identified. Appendix 2 provides the reader with a detailed list of all major inventions considered in this analysis as well as the related USPTO patents. Notice that a number of inventions resulted in multiple USPTO patent documents. All patents that fall

within the relevant time window (application before 2001 and granted before 2003) and are situated within the biotechnology domain (see infra) have been included in the subsequent analysis (n= 122).

Data and findings

Sample Selection

To identify all USPTO biotechnology patents, we made use of the OECD classification scheme that relies on IPC codes (OECD 2005). Data have been extracted from the Patstat patent database (version October 2011) and include all patents filed at the USPTO between 1976 and 2001 and granted before 2004, which fall into at least one of the IPC classes. The final sample used for analysis consists of 84,119 patents. From the 84,119 patents, 117 have been identified as important inventions that shaped the field of biotechnology, resulting in a total of 122 patented inventions (within the USPTO system and situated within the field of biotechnology according to the OECD classification scheme). For the calculation of citation-related indicators, we employed the updated NBER patent database[4].

Variables

Dissimilar, unique and adopted backward citations

We follow the methodology of Dahlin and Behrens (2005) and calculate, for each patent P granted in year t, the average annual overlap scores between the backward citations of P with, respectively, all other patents filed in the same field (3-digit US technology class) within a time window of five years before and five years after the grant year of P (i.e. patents granted between t-n and t+n with 0<=n<=5). We extend their methodology by comparing a patent to all other US granted patents with, at least, one similar technology class. So, for each of a patent's 3-digit technology classes, we follow the methodology outlined in Dahlin and

[4] see https://sites.google.com/site/patentdataproject/Home

Behrens (2005). First, we label P as dissimilar compared to prior art when the average annual overlap score is 0 or the average standardized annual overlap score is smaller than or equal to the 10th percentile of all patents for each year t-n with n>0 and n<=5. Due to truncation, not all patents have a time window of five years before (and after) grant. For patents that we can only observe three or four years before grant, we require the patent's average overlap score to be 0 or its standardized average annual overlap score to be equal to or smaller than the 10th percentile threshold for each of the observed years before grant. Patents that cannot be observed at least three years before and after the grant are not taken into account during the analysis. Following this methodology, 47% of the patents in our sample have a dissimilar citation structure. Second, a patent is labeled 'unique' when the average standardized overlap score in the year of grant is below or equal to the 10th percentile threshold. We take 67% as the threshold to pass the uniqueness criteria. Third, a patent is labeled 'adopted' when the annual overlap score passes the 90th percentile threshold for each year after grant. 8% of the patents in our sample pass the adoption criteria. Finally, 2.2% of the patents pass all three criteria.

New and adopted pairwise combination of technology subclasses

To identify patents that recombine two technology subclasses for the first time in history, we use the 2008 US technology subclass concordance to investigate all technology subclass assignments of all US-granted patents in order to identify all first pairwise subclass combinations. For each new subclass combination, we count the number of future patents re-using the same pairwise combination. In our sample of biotech patents, we find 45% of all patents displaying a new combination of technology subclasses with, on average, 49 future patents re-using the same combination.

Originality and generality

In line with Trajtenberg et al. (1997) and Hall et al. (2001), we calculate originality and generality using a measure reflecting the concentration of backward and forward citations, respectively, within technology classes. Originality is calculated as 1−bias-corrected[5] Herfindahl index of the technological classes (main) of all cited patents. Generality is calculated as 1−bias-corrected Herfindahl index of technological classes (main) of all citing patents. The average originality score of the biotech patents in our sample is 0.52 while the average generality score is 0.51.

Indicators relying on the distribution of forward citation counts

To identify patents with the largest impact on future technologies, we calculate, for all granted US patents, the count of forward citations as the number of US patents citing the patent (citations from patents granted until 2006 inclusive) and the truncated count of forward citations as the number of citations received within five years of application. Prior research has typically identified breakthrough patents as the top 1% or 5% in terms of citations received compared to patents within the same application year and technology class (e.g. Ahuja and Lampert 2001; Singh and Fleming 2010). This definition assumes that each technology field has a fixed share of high impact inventions each year and does not compare patents across years. To avoid a definition that forces a fixed proportion of breakthroughs every year into each class while allowing similar patents to be compared across years, we follow the methodology of Arts (2012) and consider the distribution of both forward citations received within five years and the distribution of forward citations received from all future patents. We use the full count of forward citations to compare all patents sharing at least one 3-digit US technology class filed in the same year and the truncated citation count to compare all patents sharing at least one technology class irrespective of time of filing. For each of the

[5] A bias correction is necessary because not all patents have the same number of technology classes.

distributions, we calculate the mean and standard deviation of (truncated) forward citation counts. A patent is labeled as having a high impact on future generations of inventions when both its truncated and full count of forward citations are larger than the mean plus n times the standard deviation in at least one of its technology classes. So, for each patent's technology class, the patent is compared with two distributions: the distributions of full and truncated forward citation counts. Using a 1, 2, 5 and 10 standard deviation rule to identify outliers in the distribution of forward citations, we find that, respectively, 7%, 3%, 0.5% and 0.1% of biotechnology patents in our sample are labeled as having a disproportionate impact on future patents.

For all USPTO patent documents under study we calculate the abovementioned indicators. Appendix 3 provides an illustrative example for the inventions related to recombinant DNA and polymerase chain reaction. As a close inspection of both patent documents and the implied indicators reveal, not all indicators signal distinctive values for these important contributions. Whether this is also the case when engaging in a more systematic, multivariate, analysis will become clear in section 4.4.

Descriptive statistics

Table 1 gives an overview of descriptive statistics for the set of major technological inventions and for the control patents including a mean-comparison T-test between the two groups.

--- Table 1 around here ---

In terms of indicators reflecting the nature of the patented invention, we do not observe significant differences in the proportion of patents without citations to technical prior art. By contrast, most important inventions seem to more frequently cite other patents compared to the control group (10 backward patent citations compared to 6 on average). Furthermore, major inventions have more dissimilar backward citations (55% of dissimilar patents compared to 47% for the control group) and rely on more recent technical prior art with an average

backward citation lag of 6.1 years versus 7.5 years for the control group. Both groups are not different in terms of originality indicating that important biotech patents do not rely on prior art stemming from a broader range of technology fields. Nevertheless, patent documents associated with important technological inventions contain a larger number of technology main classes and subclasses, so they seem to cover a larger part of the technology landscape (2.5 main classes and 8.0 subclasses on average compared to 2.2 and 6.2 for the control group, respectively). Finally, important inventions display a much larger number of citations to non-patent literature (44 versus 22 on average), are more likely to have a novel pairwise combination of technology subclasses (66% versus 45% on average) and contain a larger number of claims (23 versus 15 on average). In conclusion, patents associated with major technological inventions cite more patents, cite more recent technical prior art, contain more references to non-patent literature, and have dissimilar backward citations compared to prior art in the same field but do not rely on prior art from a broader range of technology fields. Nonetheless, major patents seem to be more novel and serve a more general purpose by covering more technology fields, subfields and claims, and are more likely to combine previously disconnected technology subfields.

Besides being based on a different set of science and engineering principles and/or incorporating substantially different core technologies, the most important technological contributions are expected to have a higher and broader impact on future technology trajectories. In line with expectations, patents associated with important contributions receive significantly more forward citations on average (146 forward citations and 36 forward citations within five years compared to 7 forward citations and 3 forward citations within five years for the control group). Accordingly, looking at outliers in the distributions of forward citations we observe that 74% of the important patents are 1 standard deviation outliers compared to 7% for non-radical patents, and 29% are 10 standard deviation outliers compared

to only 0.1% for the control group. Besides serving more extensively as prior art for future generations of inventions, they also tend to remain cited for a longer time with an average forward citation lag of 7.6 years compared to 5.9 for the control group. Furthermore, patents associated with important inventions seem to serve as prior art for a broader range of technology fields, reflected by an average generality score of 0.74 (compared to 0.51 for the control group). Likewise, for patents that make at least one new pairwise combination of previously disconnected technology subfields, the pairwise combination of important contributions is adopted by a much larger number of future patents. On average, 1,526 future patents will use the same component configuration compared to 46 future patents for the control group. Also, the backward citations of major patents are more likely to be adopted by future patents with 36% of important inventions having adopted backward citations compared to only 8% for the control group.

Finally, Dahlin and Behrens (2005) suggest the use of a composite measure to identify technologically radical inventions. Besides having a backward citation structure that is dissimilar to prior art and becomes adopted by future patents, they add an additional uniqueness criteria, i.e. having backward citations different from patents granted in the same year in the same technology field. We find important contributions that display a backward citation structure that is less unique with 59% of the important patents satisfying the uniqueness criteria compared to 67% for the control patents. According to the authors, technologically radical inventions should satisfy all three criteria. We find that 14% of the most important inventions satisfy all three criteria compared to 2% for the control group.

Table 2 presents the correlation coefficients between the most notable indicators. The dummies representing outliers in the distribution of forward citations correspond most with being an important contribution to the field, particularly 5 and 10 standard deviation outliers.

Furthermore, the number of future patents re-using the same pairwise combination of subclasses displays a strong correlation.

--- Table 2 around here ---

In conclusion, the descriptive results suggest that both backward-looking measures reflecting novelty with respect to prior art, as well as forward-looking measures of value and impact, signal important inventions within a field. In particular, measures reflecting an impact on future technological progress seem to reveal discriminatory power.

Multivariate analysis

Given that our dependent variable, indicating whether the patent was identified as being a major contribution to the field, is binary (0/1), we use logit models to assess the discriminatory power of the different indicators. All models include technology dummies for each of a patent's main technology classes (3-digit) as well as a set of additional control variables including the number of assignees, the number of inventors, and patent age. Note that patents in a main technology class without important contributions are dropped from the analysis during estimation. To assess the discriminatory power of the different indicators, we provide a number of statistics below each regression model in Table 3. We are particularly interested in the recall, i.e. the percentage of externally identified major patented inventions that are predicted as such, as well as in the precision, i.e. the percentage of patents that are predicted to be very important and that actually prove to be so.

Table 3 presents the results obtained for the full set of patents. Note that important contributions only represent 0.15% of the total sample, which seriously hampers the assessment of precision and recall rates of the different models (any model that would predict all patents as not important would classify over 99% of all patents correctly). Therefore, we present parallel results for a reduced sample of matched patents in Table 4. We generate a more balanced sample of patents by only retaining control patents with exactly the same

combination of technology main classes (3-digit), application year, and grant year as, at least, one of the patents associated with a major technological invention. Treatment and control patents for which no proper matches are found are excluded from the analysis. For each of the 92 remaining major patents, we randomly sample 4 control patents among those that match and rerun the model on the reduced sample.

--- Table 3 around here ---

Marginal effects are calculated as the percentage change with respect to the average likelihood of being an important invention, i.e. 0.15%. In terms of the indicators capturing the nature and novelty of the patented invention, we find recombining previously disconnected technology subclasses makes a patent 47% more likely to be a major invention (Table 3, Column 3). Column 4 (Table 3) presents the findings for the different measures suggested by Dahlin and Behrens (2005). We find that patents dissimilar to prior art in terms of backward citations are 67% more likely to be a major contribution to the field. Surprisingly, the uniqueness dummy has a negative impact, suggesting that important contributions have more similar backward citations to patents filed in the same year and field. Patents with unique backward patent citations are 73% less likely to associated with major inventions. This might indicate that similar and parallel inventions building on the same set of technical prior art are conducted during the same time period. Furthermore, we find major patents are not more original, i.e. they do not rely on technical prior art from a broad range of technology fields. In fact, in Column 8 of Table 3, originality is negative and significant. A standard deviation increase in originality reduces the likelihood of a major invention with 23% compared to the average likelihood.

However, in line with the descriptive statistics, the number of citations in non-patent literature and the number of claims have a positive and significant impact. Surprisingly, the number of

main technology classes has a negative and significant effect while the number of backward patent citations is insignificant.

For the indicators reflecting impact and value, we find that the dummies indicative of outliers in the distribution of forward citations have the most predictive power of all indicators. In Column 2 of Table 3, we find patents that are 1 standard deviation outliers in the distribution of forward citations are 173% more likely to be of major importance for the evolution of biotechnology, 2 standard deviation outliers are 313% more likely while 10 standard deviation outliers are 693% more likely. The stricter the criteria of being an outlier, the better the discriminative performance[6]. While a new pairwise subclass combination makes a patent 47% more likely to be a major invention, the number of future patents adopting the same pairwise subclass combination is also positive and significant (Table 3, Column 3). A standard deviation increase in the number of future patents adopting the same pairwise combination is associated with a predicted increase of 9% in the likelihood of being a major invention. Also, important contributions have backward patent citations that become adopted by future patents. This effect is strong; patents whose backward citations strongly overlap with future patents are predicted to be 146% more likely to become breakthroughs, whilst we find no support for a significant impact of combining dissimilarity, uniqueness and adoption (Table 3, Column 4). Column 5 of Table 3 presents results for the originality and generality measures. While important contributions clearly serve a general purpose as technical prior art, they themselves do not seem to rely on technical prior art from a broad range of fields. A standard deviation increase in generality is associated with an expected increase of 303% in terms of the likelihood of being a very important invention. Finally, we present the results for all ex-ante indicators reflecting dissimilarity or novelty with respect to prior art (Table 3, Column 6), ex-post indicators reflecting impact (Table 3, Column 7) and both combined (Table 3, Column 8).

[6] Note that more conservatively defined outliers are also less conservatively defined outliers. For instance, a patent which is a 5 standard deviation outlier is also a 1 and 2 standard deviation outlier.

The results clearly signal the superior performance of ex-post indicators. Measures reflecting direct use as prior art through forward citations, indirectly reflecting adoption through subclass combination and backward citations, display considerably more predictive power. The full model (Table 3, Column 8) combining all indicators is able to identify 25% of the major patents (recall) while 70% of the patents predicted to be important are indeed important (precision). Note that ex-post indicators account for the recall and precision. The model with only the ex-ante indicators has a recall of 0% (Table 3, Column 6).

--- Table 4 around here ---

Table 4 presents the regression results for the matched sample of patents. Note that being a 10 standard deviation outlier in the distribution of forward citations is a perfect predictor of importance; not a single control patent belongs to this category. Therefore, we dropped it from the regression analysis. Thus, the calculated recall and precision are an underestimation. The obtained results are in line with the results on the full sample of patents in Table 3. In contrast to the results for the full sample, having dissimilar or unique backward citations is no longer significant. Moreover, the adoption of backward citations by future patents becomes insignificant in Columns 7 and 8. The full model (Table 4, Column 8) combining all indicators is able to identify 69% of the important patents (recall) while 84% of the patents predicted to be of high importance are indeed important (precision). Note again that ex-post indicators account for the lion's share of both recall and precision.

Discussion and conclusion

Technological innovation is an important constituent of economic growth. At the same time, technological inventions vary widely in terms of nature and impact. While there has been a great interest in the development of new technologies and their commercialization, only a minority of these new technologies will contribute significantly to private and social welfare in the future. Consequently, analyzing and understanding both the discovery and the

exploitation phases of technological inventions, including their differentiated nature and impact, is important for companies and countries alike. While there has been great interest in the competitive dynamics following the commercialization of inventions, large-scale empirical research on the actual discovery of important technological contributions is scarce. As noted by Dahlin and Behrens (2005), this is mainly due to the lack of reliable indicators that allow such a large-scale quantitative assessment.

In this contribution, we rely on secondary sources to identify the most important technological inventions in the field of biotechnology and relate these to US patent data. Thus, it becomes feasible to examine whether, and to what extent, patent-based indicators advanced in the literature are able to identify these distinctive technological inventions. Indicators advanced so far can be labeled 'ex ante' to the extent that the indicator can be calculated as soon as the invention appears as a patent publication (e.g. novelty of backward citation patterns, new technology subclass combination). Available ex-ante indictors reflect – at least partly – the nature and novelty of the patented invention. At the same time, a number of indicators can only be assessed ex post, i.e. after an invention's impact becomes visible (e.g. the number of received citations, the number of patents displaying similar citation patterns afterwards). Available ex-post indicators reflect – at least in part – the impact and value of inventions. Our results show that relying on ex-post indicators allows us to identify patents associated with the most important inventions on a much larger scale (67% are correctly identified) and more accurately (79% of the patents that are predicted to be of major importance are correctly classified) compared to ex-ante indictors (21% and 61% respectively in the matched sample). The 'ex-post' indictors clearly outperform the 'ex-ante' indicators in terms of precision and recall. In consequence, some of the recent proposed indicators, which rely heavily on novelty, do not qualify as accurate predictors of important contributions to the field. In addition, our findings clearly signal potential for future research seeking to identify the nature of inventions

more precisely. As currently available indicators do not directly take into account the technical content of the inventions under study (e.g. by engaging in a textual analysis of the abstracts or claims), novel, complementary indicators relying on text mining algorithms may well achieve better results (e.g. Magerman, Song & Van Looy 2010; Kaplan & Vakili 2012). In terms of impact, the deployment of more sophisticated, network-oriented indicators could enhance the prospect of added value. Finally, the role of non-patent references, as well as the number of claims, would appear to deserve further attention. When included as a control variable, they tend to consistently predict important contributions in a positive manner. While precision and recall rates for the control variables only are modest, it seems worthwhile to further investigate the nature of this relationship and to assess the relevance of additional indicators based on claims and non-patent references, respectively. We hope our contributions inspire colleagues to engage in such endeavors.

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Table 1. Descriptive Statistics

		Final sample 122 Important Contributions (0.15%)			
	Important Contribution	n	Mean	SD	Pr(|T| > |t|)
Forward Citation Count	0	83997	6.932	14.146	0.0000
	1	122	146.082	218.402	
Forward Citation Count 5y	0	83997	2.813	5.461	0.0000
	1	122	36.230	45.135	
Outlier 1SD class & class year	0	83997	0.068	0.252	0.0000
	1	122	0.738	0.442	
Outlier 2SD class & class year	0	83997	0.028	0.166	0.0000
	1	122	0.648	0.480	
Outlier 5SD class & class year	0	83997	0.005	0.069	0.0000
	1	122	0.385	0.489	
Outlier 10SD class & class year	0	83997	0.001	0.025	0.0000
	1	122	0.287	0.454	
No Forward Citations	0	83997	0.258	0.438	0.0000
	1	122	0.008	0.091	
Forward Citation Lag	0	62299	5.874	3.542	0.0000
	1	121	7.575	3.666	
Generality	0	83997	0.510	0.276	0.0000
	1	122	0.735	0.066	
Count Claims	0	83970	15.421	15.182	0.0000
	1	122	23.336	20.511	
Count main technology classes	0	83997	2.195	1.042	0.0030
	1	122	2.475	1.201	
Count technology subclasses	0	83997	6.248	4.418	0.0000
	1	122	8.016	7.337	
First Subclass Combi Dummy	0	83997	0.452	0.498	0.0000
	1	122	0.656	0.477	
First Subclass Combi Count Re-use	0	37976	45.677	248.231	0.0000
	1	80	1525.700	4754.776	
Count Backward Citations	0	83997	5.879	12.859	0.0006
	1	122	9.861	15.280	
No Backward Citations	0	83997	0.193	0.395	0.5610
	1	122	0.172	0.379	
Backward Citation Lag	0	67581	7.506	4.047	0.0003
	1	101	6.063	2.837	
Originality	0	83997	0.516	0.269	0.8924
	1	122	0.513	0.316	
Count Non-Patent References	0	83997	22.439	39.464	0.0000
	1	122	43.836	47.297	
Dahlin and Behrens dissimilarity (before grant)	0	82969	0.465	0.499	0.0625
	1	122	0.549	0.500	
Dahlin and Behrens uniqueness (year grant)	0	83997	0.668	0.471	0.0699
	1	122	0.590	0.494	
Dahlin and Behrens adoption (after grant)	0	83997	0.076	0.265	0.0000
	1	122	0.361	0.482	
Dahlin and Behrens composite	0	82969	0.022	0.145	0.0000
	1	122	0.139	0.348	

Table 2. Correlation Matrix

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1)	Important Contribution	1												
(2)	Outlier 1SD class & class year	0.1005*	1											
(3)	Outlier 2SD class & class year	0.1396*	0.6384*	1										
(4)	Outlier 5SD class & class year	0.1994*	0.2680*	0.4198*	1									
(5)	Outlier 10SD class & class year	0.3409*	0.1174*	0.1840*	0.4382*	1								
(6)	First Subclass Combi Dummy	0.0156*	0.0868*	0.0668*	0.0343*	0.0210*	1							
(7)	First Subclass Combi Count Re-use	0.1640*	0.0640*	0.0652*	0.0603*	0.1010*	0.1068*	1						
(8)	D&B dissimilarity (before grant)	0.0065	0.0006	-0.0015	0.0003	0.0007	0.1222*	0.0477*	1					
(9)	D&B uniqueness (year grant)	-0.0062	-0.0455*	-0.0357*	-0.0180*	-0.0082	0.1191*	0.0314*	0.5293*	1				
(10)	D&B adoption (after grant)	0.0408*	0.1136*	0.0959*	0.0542*	0.0328*	-0.0095*	0.0432*	-0.0895*	-0.1543*	1			
(11)	D&B composite	0.0310*	0.0540*	0.0448*	0.0185*	0.0158*	0.0634*	0.0804*	0.1597*	0.1054*	0.5145*	1		
(12)	Generality	0.0310*	0.1651*	0.1120*	0.0549*	0.0299*	0.1078*	0.0410*	0.0507*	-0.0473*	0.0725*	0.0431*	1	
(13)	Originality	-0.0005	0.0727*	0.0549*	0.0294*	0.0179*	0.0375*	-0.0257*	-0.2769*	-0.2256*	0.0923*	-0.0168*	0.1345*	1

* $p<0.01$

Table 3. Identifying Important Contributions: Full Sample USPTO Biotechnology Patents

VARIABLES Model	(1) BT Logit	(2) BT Logit	(3) BT Logit	(4) BT Logit	(5) BT Logit	(6) BT Logit Ex ante	(7) BT Logit Ex post	(8) BT Logit
outlier FC 1SD		2.1788***					1.7515***	1.7598***
		[0.375]					[0.370]	[0.371]
outlier FC 2SD		1.7081***					1.5563***	1.5491***
		[0.359]					[0.362]	[0.361]
outlier FC 5SD		0.9558***					0.8302**	0.8339**
		[0.370]					[0.364]	[0.372]
outlier FC 10SD		3.6892***					3.5345***	3.5716***
		[0.461]					[0.458]	[0.471]
First Subclass Combi Dummy			0.4561**			0.4531**		0.2251
			[0.220]			[0.211]		[0.259]
First Subclass Combi Count Re-Use			0.0004**				0.0003***	0.0003***
			[0.000]				[0.000]	[0.000]
D&B dissimilarity				0.6188**		0.4843**		0.2160
				[0.243]		[0.216]		[0.337]
D&B uniqueness				-0.6838***		-0.8888***		-0.2029
				[0.252]		[0.237]		[0.319]
D&B adoption				1.3450***			0.5778**	0.6334*
				[0.300]			[0.253]	[0.355]
D&B composite				0.0990				0.1313
				[0.425]				[0.559]
Generality					10.7871***		7.2033***	7.7490***
					[1.000]		[1.177]	[1.261]
Originality					-0.4447	-0.0723		-1.0977***
					[0.349]	[0.382]		[0.423]
Count assignees	0.0181	0.0929	0.0172	0.0353	0.0165	0.0320	0.0846	0.0997
	[0.141]	[0.136]	[0.138]	[0.132]	[0.150]	[0.137]	[0.137]	[0.136]
Count inventors	-0.0103	-0.0482	-0.0077	-0.0092	-0.0140	-0.0112	-0.0576	-0.0468
	[0.045]	[0.057]	[0.046]	[0.045]	[0.045]	[0.046]	[0.059]	[0.058]
Count PRS	0.0009	0.0054	0.0010	-0.0052	-0.0011	-0.0013	0.0039	0.0063
	[0.003]	[0.004]	[0.003]	[0.004]	[0.003]	[0.004]	[0.005]	[0.004]
Count NPRS	0.0046***	0.0019*	0.0045***	0.0041***	0.0042***	0.0045***	0.0013	0.0014
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Count claims	0.0099***	0.0083***	0.0101***	0.0099***	0.0090***	0.0099***	0.0088***	0.0092***
	[0.002]	[0.003]	[0.002]	[0.002]	[0.002]	[0.002]	[0.003]	[0.003]
Count tech. classes	-2.4708**	-3.3732**	-2.5014**	-2.3964**	-2.6907***	-2.4373**	-3.3615***	-3.5808***
	[1.000]	[1.341]	[1.027]	[1.006]	[1.020]	[1.010]	[1.254]	[1.386]
Count tech. subclasses	0.0454**	0.0170	0.0059	0.0437**	0.0409**	0.0324	0.0018	-0.0032
	[0.020]	[0.025]	[0.025]	[0.020]	[0.020]	[0.021]	[0.024]	[0.024]
Patent age	-0.1142***	-0.1110***	-0.0864***	-0.1167***	-0.1025***	-0.1125***	-0.0958***	-0.0841***
	[0.016]	[0.020]	[0.015]	[0.016]	[0.016]	[0.016]	[0.021]	[0.023]
Technology dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Log Pseudolikelihood	-796.08	-525.67	-774.40	-771.60	-732.18	-783.82	-495.08	-489.51
Pseudo R^2	0.1255	0.4225	0.1493	0.1512	0.1957	0.1377	0.4562	0.4615
Exp. Pr. >=0.5 as cut off								
Recall Pr(+ | BT)	0.00%	22.95%	2.46%	0.00%	0.00%	0.00%	25.41%	24.59%
Specificity Pr(- | NBT)	100.00%	99.98%	100.00%	100.00%	100.00%	100.00%	99.99%	99.98%
PrecisionPr(BT | +	.	70.00%	50.00%	.	.	.	73.81%	69.77%

)								
Neg. pred. value Pr(NBT | -)	99.84%	99.88%	99.85%	99.84%	99.84%	99.84%	99.88%	99.88%
False + for NBT Pr(+ | NBT)	0.00%	0.02%	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%
False - for BT Pr(- | BT)	100.00%	77.05%	97.54%	100.00%	100.00%	100.00%	74.59%	75.41%
False + for BT Pr(NBT | +)	.	30.00%	50.00%	.	.	.	26.19%	30.23%
False - for NBT Pr(BT | -)	0.16%	0.12%	0.15%	0.16%	0.16%	0.16%	0.12%	0.12%
Correctly classified	99.84%	99.86%	99.84%	99.84%	99.84%	99.84%	99.87%	99.86%

Robust standard errors in brackets
*** p<0.01, ** p<0.05, * p<0.1

Table 4. Identifying Important Contributions: Matched Sample USPTO Biotechnology Patents

VARIABLES Model	(1) BT Logit	(2) BT Logit	(3) BT Logit	(4) BT Logit	(5) BT Logit	(6) BT Logit	(7) BT Logit	(8) BT Logit
outlier FC 1SD		1.5898***					0.9133	0.9783*
		[0.500]					[0.606]	[0.591]
outlier FC 2SD		1.6466***					1.9823***	1.9991***
		[0.591]					[0.691]	[0.731]
outlier FC 5SD		2.6926***					1.8784**	2.1092***
		[1.000]					[0.846]	[0.813]
outlier FC 10SD								
First Subclass Combi Dummy			0.7056**			0.8372**		0.6515
			[0.336]			[0.332]		[0.465]
First Subclass Combi Count Re-use			0.0004*				0.0004*	0.0003*
			[0.000]				[0.000]	[0.000]
D&B dissimilarity				0.4999		0.3600		0.0668
				[0.392]		[0.390]		[0.548]
D&B uniqueness				-0.5751		-0.9180**		-0.6018
				[0.393]		[0.407]		[0.555]
D&B adoption				1.1302**			0.4001	0.5749
				[0.456]			[0.454]	[0.566]
D&B composite				-0.3595				-0.6684
				[0.820]				[0.915]
Generality					12.4757***		9.0847***	8.8964***
					[1.913]		[2.152]	[2.181]
Originality					-0.5293	-0.4069		-1.6120*
					[0.573]	[0.537]		[0.891]
Count assignees	0.4870	0.4101	0.5020	0.5789	0.2076	0.5494	0.2253	0.3385
	[0.396]	[0.365]	[0.397]	[0.371]	[0.433]	[0.411]	[0.423]	[0.390]
Count inventors	-0.0373	-0.1682	-0.0620	-0.0380	-0.0448	-0.0422	-0.1881	-0.1568
	[0.077]	[0.107]	[0.081]	[0.078]	[0.094]	[0.077]	[0.120]	[0.113]
Count PRS	-0.0166	0.0149	-0.0161	-0.0247*	-0.0033	-0.0193*	0.0112	0.0116
	[0.011]	[0.014]	[0.011]	[0.013]	[0.011]	[0.012]	[0.016]	[0.016]
Count NPRS	0.0150***	0.0080*	0.0158***	0.0141***	0.0130***	0.0165***	0.0076	0.0080
	[0.005]	[0.004]	[0.005]	[0.005]	[0.004]	[0.005]	[0.005]	[0.005]
Count claims	0.0490***	0.0388***	0.0495***	0.0481***	0.0518***	0.0516***	0.0399***	0.0459***
	[0.010]	[0.012]	[0.010]	[0.010]	[0.011]	[0.010]	[0.014]	[0.014]
Count tech. classes	0.4422	0.0834	0.4705	-0.0792	0.4491	0.6230	-0.1230	0.3086
	[0.766]	[1.025]	[0.790]	[1.000]	[0.797]	[0.766]	[1.073]	[1.196]
Count tech. subclasses	-0.0678	-0.1199**	-0.1253**	-0.0777	-0.0988*	-0.1256**	-0.1569**	-0.2045***
	[0.048]	[0.053]	[0.055]	[0.051]	[0.056]	[0.052]	[0.063]	[0.063]
Patent age	-0.0579**	-0.0278	-0.0189	-0.0565**	-0.0497	-0.0342	0.0027	0.0350
	[0.027]	[0.037]	[0.029]	[0.027]	[0.035]	[0.029]	[0.039]	[0.044]
Technology dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Log Pseudolikelihood	-187.10	-124.55	-182.46	-181.67	-150.02	-181.88	-109.12	-105.75
Pseudo R2	0.1237	0.4167	0.1455	0.1492	0.2974	0.1482	0.4890	0.5047
Exp. Pr. >=0.5 as cut off								
Recall Pr(+ | BT)	17.98%	62.92%	22.47%	22.47%	35.96%	21.35%	67.42%	68.54%
Specificity Pr(- | NBT)	96.21%	95.90%	96.21%	96.85%	94.32%	96.21%	94.95%	96.21%
Precision Pr(BT | +)	57.14%	81.16%	62.50%	66.67%	64.00%	61.29%	78.95%	83.56%
Neg. pred. value Pr(NBT | -)	80.69%	90.21%	81.55%	81.65%	83.99%	81.33%	91.21%	91.59%
False + for NBT Pr(+ | NBT)	3.79%	4.10%	3.79%	3.15%	5.68%	3.79%	5.05%	3.79%
False - for BT Pr(- | BT)	82.02%	37.08%	77.53%	77.53%	64.04%	78.65%	32.58%	31.46%
False + for BT Pr(NBT | +)	42.86%	18.84%	37.50%	33.33%	36.00%	38.71%	21.05%	16.44%
False - for NBT Pr(BT | -)	19.31%	9.79%	18.45%	18.35%	16.01%	18.67%	8.79%	8.41%
Correctly classified	79.06%	88.67%	80.05%	80.54%	81.53%	79.80%	88.92%	90.15%

Robust standard errors in brackets, outlier FC 10SD is dropped because it predicts important contributions perfectly in the matched sample,

*** p<0.01, ** p<0.05, * p<0.1

Appendix 1. References used to map the (recent) history of Biotechnology

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Appendix 2. List of major innovations in Biotechnology (1976-2001)

U.S. PATENT #	TITLE	INVENTOR(S)	APPLICANT(S)	FILING DATE	PUBLICATION (YES/NO)
1. 4237224	Process for producing biologically functional molecular chimeras	COHEN STANLEY N.; BOYER HERBERT W.	UNIV LELAND STANFORD JUNIOR	January 4, 1979	NO
2. 4363877	Recombinant DNA transfer vectors	GOODMAN HOWARD M.; SHINE JOHN; SEEBURG PETER H.	UNIV CALIFORNIA	April 19, 1978	YES
3. 4322499	Adrenocorticotropin-lipotropin precursor gene	BAXTER JOHN D.; ROBERTS JAMES L.; SEEBURG PETER H.; GOODMAN HOWARD M.; SHINE JOHN	UNIV CALIFORNIA	December 22, 1978	NO
4. 4304863	Process for the production of hybrid bacteria	COLLINS JOHN; HOHN BARBARA	BIOTECHNOLOG FORSCHUNG GMBH	March 30, 1979	YES
5. 4366246	Method for microbial polypeptide expression	RIGGS ARTHUR D.	GENENTECH INC	November 5, 1979	YES
6. 4356270 4704362	Recombinant DNA cloning vehicle	ITAKURA KEIICHI	GENENTECH INC	November 5, 1979	YES
7. 4262090	Interferon production	COLBY JR CLARENCE; DENNEY JR DAN W.	CETUS CORP	June 4, 1979	NO
8. 4283489	Purification of nucleotide sequences suitable for expression in bacteria	GOODMAN HOWARD M.; SHINE JOHN; HORST PETER	UNIV CALIFORNIA	November 23, 1979	NO
9. 4530901	Recombinant DNA molecules and their use in producing human interferon-like polypeptides	WEISSMANN CHARLES	BIOGEN NV	February 4, 1980	YES
10. 4259444	Microorganisms having multiple compatible degradative energy-generating plasmids and preparation thereof	CHAKRABARTY ANANDA M.	GENERAL ELECTRIC	June 7, 1972	NO
11. 4394443	Method for cloning genes	WEISSMAN SHERMAN M; PEREIRA DENNIS; SOOD ASHWANI	YALE UNIVERSITY	December 18, 1980	YES
12. 4358535	Specific DNA probes in diagnostic microbiology	FALKOW STANLEY; MOSELEY STEPHEN L.	UNIVERSITY OF WASHINGTON	December 8, 1980	YES
13. 4338397	Mature protein synthesis	GILBERT WALTER; TALMADGE KAREN	HARVARD COLLEGE	April 11, 1980	NO

14. 4399216	Processes for inserting DNA into eucaryotic cells and for producing proteinaceous materials	AXEL RICHARD; WIGLER MICHAEL H.; SILVERSTEIN SAUL J.	COLUMBIA UNIVERSITY	February 25, 1980	YES
15. 5582824 5096705 4925793 4762791 4727138	Recombinant DES-CYS-TYR-CYS human immune interferon	GOEDDEL DAVID V.; GRAY PATRICK W.	GENENTECH INC	November 12, 1993	YES
16. 4474893	Recombinant monoclonal antibodies	READING CHRISTOPHER L.	UNIVERSITY OF TEXAS	July 1, 1981	YES
17. 4458066	Process for preparing polynucleotides	CARUTHERS MARVIN H.; MATTEUCCI MARK D.	UNIVERSITY PATENTS INC	March 24, 1981	YES
18. 4467036	Bacillus thuringiensis crystal protein in Escherichia coli +B	SCHNEPF H ERNEST; WHITELEY HELEN R.	UNIVERSITY OF WASHINGTON	March 30, 1982	YES
19. 5118800	Oligonucleotides possessing a primary amino group in the terminal nucleotide	SMITH LLOYD M.; FUNG STEVEN; KAISER JR ROBERT J.	CALIFORNIA INSTITUTE OF TECHNOLOGY	February 27, 1991	YES
20. 4690915	Adoptive immunotherapy as a treatment modality in humans	ROSENBERG STEVEN A.	US DEPARTMENT OF HEALTH AND HUMAN SERVICES	August 8, 1985	YES
21. 4711955	Modified nucleotides and methods of preparing and using same	WARD DAVID C.; LANGER PENNINA R.; WALDROP III ALEXANDER A.	YALE UNIVERSITY	May 23, 1983	YES
22. 4816567	Recombinant immunoglobin preparations	CABILLY SHMUEL; HEYNEKER HERBERT L.; HOLMES WILLIAM E.; RIGGS ARTHUR D.; WETZEL RONALD B.	GENENTECH INC	April 8, 1983	YES
23. 4518584	Human recombinant interleukin-2 muteins	MARK DAVID F.; LIN LEO S.; LU SHI-DA Y	CETUS CORP	December 20, 1983	NO
24. 4683194	Method for detection of polymorphic restriction sites and nucleic acid sequences	SAIKI RANDALL K.; ERLICH HENRY A.	CETUS CORP	March 28, 1985	YES
25. 4714680	Human stem cells	CIVIN CURT I.	JOHNS HOPKINS UNIVERSITY	February 6, 1984	NO
26. 4945050	Method for transporting substances into living cells and tissues and apparatus therefor	SANFORD JOHN C.; WOLF EDWARD D.; ALLEN NELSON K.	CORNELL RESEARCH FOUNDATION INC	November 13, 1984	NO
27. 4473452	Electrophoresis using alternating transverse electric fields	CANTOR CHARLES R.; SCHWARTZ DAVID C.	COLUMBIA UNIVERSITY	November 18, 1982	YES

28. 4675285	Method for identification and isolation of DNA encoding a desired protein	CLARK STEVEN C.; KAUFMAN RANDAL J.; WONG GORDON G.	GENETICS INSTITUTE INC	September 19, 1984	YES
29. 4883750	Detection of specific sequences in nucleic acids	WHITELEY NORMAN M.; HUNKAPILLER MICHAEL W.; GLAZER ALEXANDER N.	APPLIED BIOSYSTEMS INC	December 13, 1984	YES
30. 5175082	METHOD OF CHARACTERIZING GENOMIC DNA	JEFFREYS ALEC J.	IMPERIAL CHEMICAL INDUSTRIES PLC	March 19, 1987	YES
31. 4677063	Human tumor necrosis factor	MARK DAVID F.; WANG ALICE M.; LADNER MARTHA B.; CREASEY ABLA A.; LIN LEO S.; VAN ARSDELL JANELLE	CETUS CORP	July 30, 1985	YES
32. 4683202	Process for amplifying nucleic acid sequences	MULLIS KARY B.	CETUS CORP	October 25, 1985	YES
33. 4683195	Process for amplifying, detecting, and/or-cloning nucleic acid sequences	MULLIS KARY B.; ERLICH HENRY A.; ARNHEIM NORMAN; HORN GLENN T.; SAIKI RANDALL K.; SCHARF STEPHEN J.	CETUS CORP	February 7, 1986	NO
34. 4940835	Glyphosate-resistant plants	SHAH DILIP M.; ROGERS STEPHEN G.; HORSCH ROBERT B.; FRALEY ROBERT T.	MONSANTO COMPANY	July 7, 1986	YES
35. 4811218	Real time scanning electrophoresis apparatus for DNA sequencing	HUNKAPILLER MICHAEL W.; CONNELL CHARLES R.; MORDAN WILLIAM J.; LYTLE JOHN D.; BRIDGHAM JOHN A.	APPLIED BIOSYSTEMS INC	June 2, 1986	NO
36. 4855225	Method of detecting electrophoretically separated oligonucleotides	FUNG STEVEN; WOO SAM L.; HAUGLAND RICHARD P.; MENCHEN STEVEN M.; CONNELL CHARLES R.	APPLIED BIOSYSTEMS INC	February 7, 1986	NO
37. 4889818	Purified thermostable enzyme	GELFAND DAVID H.; STOFFEL SUSANNE; LAWYER FRANCES C.; SAIKI RANDALL K.	CETUS CORP	June 17, 1987	NO
38. 4801540	PG gene and its use in plants	HIATT WILLIAM R.; SHEEHY RAYMOND E.; SHEWMAKER. CHRISTINE K.; KRIDL JEAN C.; KNAUF VIC	CALGENE INC	January 2, 1987	YES

39. 4889806	Large DNA cloning system based on yeast artificial chromosomes	OLSON MAYNARD V.; BURKE DAVID T.	WASHINGTON UNIVERSITY	April 15, 1987	YES
40. 4965188	Process for amplifying, detecting, and/or cloning nucleic acid sequences using a thermostable enzyme	MULLIS KARY B.; ERLICH HENRY A.; GELFAND DAVID H.; HORN GLENN; SAIKI RANDALL K.	CETUS CORP	June 17, 1987	NO
41. 4994368	Amplification method for polynucleotide assays	GOODMAN THOMAS C.; BECKER MARTIN; ULLMAN EDWIN F.; ROSE SAMUEL	SYNTEX INC	July 23, 1987	NO
42. 5064754	Genomic sequencing method	MILLS RANDELL L.	MILLS RANDELL L.	November 13, 1987	NO
43. 5476997 5612018	Extended human hematopoiesis in a heterologous host	KANESHIMA HIDETO; NAMIKAWA REIKO; MCCUNE JOSEPH M.	SYSTEMIX INC	May 17, 1994	YES
44. 4760025	Modified enzymes and methods for making same	ESTELL DAVID A.; WELLS JAMES A.	GENENCOR INC	May 29, 1984	NO
45. 5200313	Nucleic acid hybridization assay employing detectable anti-hybrid antibodies	CARRICO ROBERT J	MILES INC	April 25, 1988	NO
46. 5075216	METHODS FOR DNA SEQUENCING WITH THERMUS AQUATICUS DNA POLYMERASE	INNIS MICHAEL A.; MYAMBO KENNETH B.; GELFAND DAVID H.; BROW MARY ANN D.	CETUS CORP	September 23, 1988	YES
47. 4736866	Transgenic non-human mammals	LEDER PHILIP; STEWART TIMOTHY A.	HARVARD COLLEGE	June 22, 1984	YES
48. 4946778	Single polypeptide chain binding molecules	LADNER ROBERT C.; BIRD ROBERT E.; HARDMAN KARL	GENEX CORP	January 19, 1989	NO
49. 5162430	COLLAGEN-POLYMER CONJUGATES	RHEE WOONZA; WALLACE DONALD G.; MICHAELS ALAN S.; BURNS JR RAMON A.; FRIES LOUIS; DELUSTRO FRANK; BENTZ HANNE	COLLAGEN CORP	November 14, 1989	NO
50. 5143854	LARGE SCALE PHOTOLITHOGRAPHIC SOLID PHASE SYNTHESIS OF POLYPEPTIDES AND RECEPTOR BINDING SCREENING THEREOF	PIRRUNG MICHAEL C.; READ J. LEIGHTON; FODOR STEPHEN P. A.; STRYER LUBERT	AFFYMAX TECHNOLOGIES N.V	March 7, 1990	YES
51. 5188642	Glyphosate-resistant plants	SHAH DILIP M.; ROGERS STEPHEN G.; HORSCH ROBERT B.; FRALEY ROBERT T.	MONSANTO COMPANY	February 12, 1990	NO

52. 5198346	Generation and selection of novel DNA-binding proteins and polypeptides	LADNER ROBERT C.; GUTERMAN SONIA K.; KENT RACHEL B.; LEY ARTHUR C.	PROTEIN ENGINEERING CORP	July 26, 1990	YES
53. 5226914	Method for treating connective tissue disorders	CAPLAN ARNOLD I.; HAYNESWORTH STEPHEN E.	CAPLAN ARNOLD I.; HAYNESWORTH STEPHEN E.	November 16, 1990	YES
54. 6027729	NANBV Diagnostics and vaccines	HOUGHTON MICHAEL; CHOO QUI-LIM; KUO GEORGE	CHIRON CORP	May 15, 1995	YES
55. 5231020	Genetic engineering of novel plant phenotypes	JORGENSEN RICHARD A.; NAPOLI CAROLYN A.	DNA PLANT TECHNOLOGY CORPORATION	March 29, 1990	YES
56. 5622829	Genetic markers for breast, ovarian, and prostatic cancer	KING MARY-CLAIRE; FRIEDMAN LORI; OSTERMEYER. BETH; ROWELL SARAH; LYNCH ERIC; SZABO CSILLA; LEE MING	UNIVERSITY OF CALIFORNIA	April 19, 1995	YES
57. 5217889	METHODS AND APPLICATIONS FOR EFFICIENT GENETIC SUPPRESSOR ELEMENTS	RONINSON IGOR B.; HOLZMAYER TATYANA; CHOI KYUNGHEE	RONINSON IGOR B.; HOLZMAYER TATYANA; CHOI KYUNGHEE	October 19, 1990	YES
58. 5283173	System to detect protein-protein interactions	FIELDS STANLEY; SONG OK-KYU	STATE UNIVERSITY OF NEW YORK	January 24, 1990	YES
59. 5180669	LIQUEFACTION OF GRANULAR-STARCH SLURRIES USING ALPHA-AMYLASE IN THE PRESENCE OF CARBONATE ION	ANTRIM RICHARD L.	GENENCOR INTERNATIONAL INC	March 27, 1991	YES
60. 5424186	Very large scale immobilized polymer synthesis	FODOR STEPHEN P A.; STRYER LUBERT; PIRRUNG MICHAEL C.; READ J. LEIGHTON	AFFYMAX TECHNOLOGIES N.V	December 6, 1991	YES
61. 5223409	Directed evolution of novel binding proteins	LADNER ROBERT C.; GUTERMAN SONIA K.; ROBERTS BRUCE L.; MARKLAND WILLIAM; LEY ARTHUR C.; KENT RACHEL B.	PROTEIN ENGINEERING CORP	March 1, 1991	YES
62. 5202231	Method of sequencing of genomes by hybridization of oligonucleotide probes	DRMANAC RADOJE T.; CRKVENJAKOV RADOMIR B.	DRMANAC RADOJE T.; CRKVENJAKOV RADOMIR B.	June 18, 1991	YES
63. 5225539	Recombinant altered antibodies and methods of making altered antibodies	WINTER GREGORY P.	MEDICAL RESEARCH COUNCIL	October 25, 1991	YES

64. 5223408	Method for making variant secreted proteins with altered properties	GOEDDEL DAVID V.; RICE GLENN C.; LEUNG DAVID W. H.	GENENTECH INC	July 11, 1991	YES
65. 5304487	Fluid handling in mesoscale analytical devices	WILDING PETER; KRICKA LARRY J.; ZEMEL JAY N.	UNIVERSITY OF PENNSYLVANIA	May 1, 1992	YES
66. 5445934	Array of oligonucleotides on a solid substrate	FODOR STEPHEN P. A.; PIRRUNG MICHAEL C.; READ J. LEIGHTON; STRYER LUBERT	AFFYMAX TECHNOLOGIES N.V	September 30, 1992	NO
67. 5288644	Instrument and method for the sequencing of genome	BEAVIS RONALD C.; CHAIT BRIAN T.	ROCKEFELLER UNIVERSITY	November 13, 1992	NO
68. 5350836	Growth hormone antagonists	KOPCHICK JOHN J.; CHEN WEN Y.	OHIO UNIVERSITY	May 4, 1992	YES
69. 5605662	Active programmable electronic devices for molecular biological analysis and diagnostics	HELLER MICHAEL J.; TU EUGENE	NANOGEN INC	November 1, 1993	YES
70. 5403484	Viruses expressing chimeric binding proteins	LADNER ROBERT C.; GUTERMAN SONIA K.; ROBERTS BRUCE L.; MARKLAND WILLIAM; LEY ARTHUR C.; KENT RACHEL B.	PROTEIN ENGINEERING CORPORATION	January 26, 1993	YES
71. 5474796	Method and apparatus for conducting an array of chemical reactions on a support surface	BRENNAN THOMAS M.	PROTOGENE LABORATORIES INC	May 27, 1993	NO
72. 5539082	Peptide nucleic acids	NIELSEN PETER E.; BUCHARDT OLE; EGHOLM MICHAEL; BERG ROLF H.	NIELSEN PETER E.; BUCHARDT OLE; EGHOLM MICHAEL; BERG ROLF H.	April 26, 1993	YES
73. 5352605	Chimeric genes for transforming plant cells using viral promoters	FRALEY ROBERT T.; HORSCH ROBERT B.; ROGERS STEPHEN G.	MONSANTO COMPANY	October 28, 1993	YES
74. 5610287	Method for immobilizing nucleic acid molecules	NIKIFOROV THEO; KNAPP MICHAEL R.	MOLECULAR TOOL INC	November 16, 1994	YES
75. 5525464	Method of sequencing by hybridization of oligonucleotide probes	DRMANAC RADOJE T.; CRKVENJAKOV RADOMIR B.	HYSEQ INC	February 28, 1994	YES
76. 5723323	Method of identifying a stochastically-generated peptide, polypeptide, or protein having ligand binding property and compositions thereof	KAUFFMAN STUART ALAN; BALLIVET MARC	KAUFFMAN STUART ALAN; BALLIVET MARC	December 2, 1994	NO

77. 5580859	Delivery of exogenous DNA sequences in a mammal	FELGNER PHILIP L.; WOLFF JON A.; RHODES GARY H.; MALONE ROBERT W.; CARSON DENNIS A.	VICAL INCORPORATED; WISCONSIN ALUMNI RESEARCH FOUNDATION	March 18, 1994	YES
78. 5399346	Gene therapy	ANDERSON W. FRENCH; BLAESE R. MICHAEL; ROSENBERG. STEVEN A.	US DEPARTMENT OF HEALTH AND HUMAN SERVICES	March 30, 1994	YES
79. 5486359	Human mesenchymal stem cells	CAPLAN ARNOLD I.; HAYNESWORTH STEPHEN E.	OSIRIS THERAPEUTICS INC	February 8, 1994	YES
80. 5700637	Apparatus and method for analyzing polynucleotide sequences and method of generating oligonucleotide arrays	SOUTHERN EDWIN	ISIS INNOVATION LIMITED	April 19, 1994	YES
81. 5632957	Molecular biological diagnostic systems including electrodes	HELLER MICHAEL J.; TU EUGENE; BUTLER WILLIAM F.	NANOGEN INC	September 9, 1994	NO
82. 5494810	Thermostable ligase-mediated DNA amplifications system for the detection of genetic disease	BARANY FRANCIS; ZEBALA JOHN; NICKERSON DEBORAH; KAISER JR ROBERT J.; HOOD LEROY	CORNELL RESEARCH FOUNDATION INC	November 22, 1994	YES
83. 5736330	Method and compositions for flow cytometric determination of DNA sequences	FULTON R. JERROLD	LUMINEX CORP	October 11, 1995	YES
84. 5677177	FLP-mediated gene modification in mammalian cells, and compositions and cells useful therefor	WAHL GEOFFREY M.; O'GORMAN STEPHEN V.	THE SALK INSTITUTE FOR BIOLOGICAL STUDIES	June 7, 1995	YES
85. 5589466	Induction of a protective immune response in a mammal by injecting a DNA sequence	FELGNER PHILIP L.; WOLFF JON A.; RHODES GARY H.; MALONE ROBERT W.; CARSON DENNIS A.	VICAL INCORPORATED; WISCONSIN ALUMNI RESEARCH FOUNDATION	January 26, 1995	NO
86. 5744305	Arrays of materials attached to a substrate	FODOR STEPHEN P. A.; STRYER LUBERT; READ J. LEIGHTON; PIRRUNG MICHAEL C.	AFFYMETRIX INC	June 6, 1995	NO
87. 5807522	Methods for fabricating microarrays of biological samples	BROWN PATRICK O.; SHALON TIDHAR DARI	THE LELAND STANFORD JUNIOR UNIVERSITY	June 7, 1995	YES
88. 5585089	Humanized immunoglobulins	QUEEN CARY L.; SELICK HAROLD E.	PROTEIN DESIGN LABS INC	June 7, 1995	YES
89. 6210919	Genetic sequences and proteins related to alzheimer's disease	ST GEORGE-HYSLOP PETER H.; ROMMENS JOHANNA M.; FRASER PAUL E.	HSC RESEARCH AND DEVELOPMENT LIMITED; UNIVERSITY OF TORONTO	June 28, 1995	YES

90. 5750376 5851832	In vitro growth and proliferation of genetically modified multipotent neural stem cells and their progeny	WEISS SAMUEL; REYNOLDS BRENT; HAMMANG JOSEPH P.; BAETGE E. EDWARD	NEUROSPHERES HOLDINGS LTD	June 7, 1995	YES
91. 5830721	DNA mutagenesis by random fragmentation and reassembly	STEMMER WILLEM P. C.; CRAMERI ANDREAS	AFFYMAX TECHNOLOGIES N.V	March 4, 1996	YES
92. 5811238	Methods for generating polynucleotides having desired characteristics by iterative selection and recombination	STEMMER WILLEM P C.; CRAMERI ANDREAS	AFFYMAX TECHNOLOGIES N.V	November 30, 1995	YES
93. 5792613	Method for obtaining RNA aptamers based on shape selection	SCHMIDT FRANCIS J.; CHO BONGRAE; NICHOLAS JR HUGH B.	UNIVERSITY OF MISSOURI	June 12, 1996	YES
94. 5837458	Methods and compositions for cellular and metabolic engineering	MINSHULL JEREMY; STEMMER WILLEM P. C.	MAXYGEN INC	May 20, 1996	NO
95. 5776748	Method of formation of microstamped patterns on plates for adhesion of cells and other biological materials, devices and uses therefor	SINGHVI RAHUL; KUMAR AMIT; WHITESIDES GEORGE M.; INGBER DONALD E.; LOPEZ GABRIEL P.; WANG DANIEL I. C.; STEPHANOPOULOS GREGORY N.	HARVARD COLLEGE; MASSACHUSETTS INSTITUTE OF TECHNOLOGY; CHILDREN'S MEDICAL CENTER CORPORATION	June 6, 1996	YES
96. 5800992	Method of detecting nucleic acids	FODOR STEPHEN P. A.; SOLAS DENNIS W.; DOWER WILLIAM J.	FODOR STEPHEN P. A.; SOLAS DENNIS W.; DOWER WILLIAM J.	June 25, 1996	NO
97. 6150584	Human antibodies derived from immunized xenomice	KUCHERLAPATI RAJU; JAKOBOVITS AYA; BRENNER DANIEL G.; CAPON DANIEL J.; KLAPHOLZ SUE	ABGENIX INC	October 2, 1996	NO
98. 5843780 6200806	Primate embryonic stem cells	THOMSON JAMES A.	WISCONSIN ALUMNI RESEARCH FOUNDATION	January 18, 1996	YES
99. 5922591	Integrated nucleic acid diagnostic device	ANDERSON ROLFE C.; LIPSHUTZ ROBERT J.; RAVA RICHARD P.; FODOR STEPHEN P. A.	AFFYMETRIX INC	June 27, 1996	NO
100. 6207446	Selection of proteins using RNA-protein fusions	SZOSTAK JACK W.; ROBERTS RICHARD W.; LIU RIHE	THE GENERAL HOSPITAL CORPORATION	October 29, 1999	YES
101. 5695967 5869294 6348353	Method for stably cloning large repeating units of DNA	VAN BOKKELEN GIL B.; HARRINGTON JOHN J.; WILLARD HUNTINGTON F.	CASE WESTERN RESERVE UNIVERSITY	June 7, 1995	YES

102. 5874241	Clock gene and gene product	TAKAHASHI JOSEPH S.; TUREK FRED W.; PINTO LAWRENCE H.	NORTHWESTERN UNIVERSITY	March 13, 1997	YES
103. 6090622 6245566	HUMAN EMBRYONIC PLURIPOTENT GERM CELLS	GEARHART JOHN D.; SHAMBLOTT MICHAEL JOSEPH	THE JOHNS HOPKINS SCHOOL OF MEDICINE	March 31, 1997	YES
104. 6294330	Protein fragment complementation assays for the detection of biological or drug interactions	MICHNICK STEPHEN WILLIAM WATSO; REMY INGRID	ODYSSEY PHARMACEUTICALS INC	July 30, 1998	YES
105. 6641526 6331659	Development of normal offspring from oocytes injected with freeze-dried spermatozoa	WAKAYAMA TERUHIKO; YANAGIMACHI RYUZO	UNIVERSITY OF HAWAII	October 23, 1998	YES
106. 6180406	Methods for generating polynucleotides having desired characteristics by iterative selection and recombination	STEMMER WILLEM P. C.	MAXYGEN INC	June 17, 1998	NO
107. 5801154	Antisense oligonucleotide modulation of multidrug resistance-associated protein	BARACCHINI EDGARDO; BENNETT C. FRANK; DEAN NICHOLAS M.	ISIS PHARMACEUTICALS INC	April 8, 1997	YES
108. 6258538	DNA diagnostics based on mass spectrometry	KOESTER HUBERT; LITTLE DANIEL P.; BRAUN ANDREAS	SEQUENOM INC	April 6, 1999	YES
109. 6403367	Integrated portable biological detection system	CHENG JING; WU LEI; HELLER MICHAEL J.; SHELDON ED; DIVER JONATHAN; O'CONNELL JAMES P.; SMOLKO DAN; JALALI SHILA; WILLOUGHBY DAVID	NANOGEN INC	December 22, 1999	NO
110. 6277573	DNA diagnostics based on mass spectrometry	KOESTER HUBERT	SEQUENOM INC	April 6, 1999	NO
111. 6303305	Method for quantification of an analyte	WITTWER CARL T.; GUTEKUNST MARTIN; LOHMANN SABINE	ROCHE DIAGNOSTICS, GMBH; UNIVERSITY OF UTAH RESEARCH FOUNDATION	March 30, 1999	YES
112. 6949520	Methods related to immunostimulatory nucleic acid-induced interferon	HARTMANN GUNTHER; BRATZLER ROBERT L.; KRIEG ARTHUR M.	COLEY PHARMACEUTICAL GMBH	September 27, 2000	YES
113. 6365408	Methods of evolving a polynucleotides by mutagenesis and recombination	STEMMER WILLEM P. C.	MAXYGEN INC	January 4, 2000	NO

114. 6893850	Cell patterning technique	OSTUNI EMANUELE; KANE RAVI; WHITESIDES GEORGE M.; JACKMAN REBECCA J.; DUFFY DAVID C.	OSTUNI EMANUELE; KANE RAVI; WHITESIDES GEORGE M.; JACKMAN REBECCA J.; DUFFY DAVID C.; PRESIDENT AND FELLOWS OF HARVARD COLLEGE	March 15, 2001	YES
115. 6936750	Increasing salt tolerance in plants by overexpression of vacuolar cation-proton antiporters	BLUMWALD EDUARDO; APSE MARIS	BLUMWALD EDUARDO; APSE MARIS	May 24, 2002	YES
116. 6818437	Instrument for monitoring polymerase chain reaction of DNA	GAMBINI MICHAEL R.; ATWOOD JOHN G.; YOUNG EUGENE F.; LAKATOS EDWARD J.; CERRONE ANTHONY L.	APPLERA CORP	November 29, 2001	NO
117. 6268169	Recombinantly produced spider silk	FAHNESTOCK STEPHEN R.	DU PONT	December 11, 1995	YES

Appendix 3. Illustrative examples of important inventions in the field of biotechnology and the calculated indicators: Polymerase Chain Reaction (PCR) and Recombinant DNA

GENERAL DESCRIPTION	*Information*			
Event	Kary Mullis and colleagues at Cetus Corporation in Berkeley, California, invented a technique for multiplying DNA sequences in vitro: the polymerase chain reaction (PCR). PCR has been called the most revolutionary new technique in molecular biology in the 1980s. Cetus patented the process, and in the summer of 1991 sold the patent to Hoffman-La Roche, Inc. for $300 million. It took close to 4 years for specialists to appreciate the technology's potential, and longer still for a larger scientific community to begin practically exploiting its potential.			
Patent#	US 4683202			
Title	Process for amplifying nucleic acid sequences			
Inventor; Assignee	Kary B. Mullis; Cetus Corporation			
Filed	October 25, 1985			
INDICATORS (average values)	***Patent***	***Important contrib. (122)***	***Control group (83997)***	***Remarks***
Forward Citation Count	1,555	146.082	6.932	This invention received a high number of forward citations (1,555) well above the average (146) even of the subset of important contributions.
Forward Citation Count 5y	76	36.230	2.813	This invention received a high number of forward citations within 5 years of its application (76), above the average (≈36).
Forward Citation Lag	12.11	7.575	5.874	Besides serving more extensively as prior art for future generations of inventions, it also tends to remain cited for a longer time with a forward citation lag of 12.11 years, extraordinarily high compared with the average 7.57 years of the set of the major technological inventions and the average 5.87 for the control group.
Generality	.76	.735	.510	A beyond the average generality score (.76) means an impact on multiple different fields. One need only reflect on the fact that PCR has found widespread applications in many areas of genetic analysis: medical applications (genetic testing, oncogenes, tissue typing), infectious disease applications (PCR tests for HIV), tuberculosis, disease organism), forensic applications (genetic fingerprinting, parental testing); plus a variety of research applications such as generation of hybridization probes for blotting, DNA sequencing, DNA cloning, sequence-tagged sites, phylogenic analysis of DNA from ancient sources, gene expression, and genetic mapping by studying chromosomal crossovers after meiosis.
Count Claims	21	23.336	15.421	This patent contains 21 claims, approaching the average of the set of major technological inventions (≈23).
Count main technology classes	2	2.475	2.195	It covers 2 main technology classes: 435 'CHEMISTRY: MOLECULAR BIOLOGY AND MICROBIOLOGY', and 536 'ORGANIC COMPOUNDS -- PART OF THE CLASS 532-570 SERIES'
Count technology subclasses	5	8.016	6.248	It covers 5 technology subclasses: 91.2; 317.1; 320.1; 23.1; 24.33
First Subclass Combi Dummy	1	.656	.452	It is a patent with novel pair wise combinations of technology subclasses: 435/91.2 & 435/317.1; 435/91.2 & 435/320.1; 536/23.1 & 435/91.2; 536/24.33 & 435/317.1; 536/24.33 & 435/91.2, contributing to the trend that sees important contributions more likely to have a novel pair wise combination of technology subclasses (≈66%).
First Subclass Combi Count Re-Use	4,021	1,525.70	45.677	4,021 subsequent patents used the same component configuration more than doubling the average of its set of important contributions (≈1,526).
Count Backward Citations	0	9.861	5.879	This invention has no backward citations.
No Backward Citations	1	.172	.193	This patent is one of the few (17.2%) which has not citations to technical prior art.
Backward Citation Lag	-	6.063	7.506	As this patent does not have any backward citation, this indicator cannot be calculated. There is no prior art being

				cited.
Originality	0	.513	.516	As this patent does not have any backward citation, this indicator being based on main technological classes of all cited patents cannot be calculated. There is no prior art.
Count Non-Patent References	5	43.836	22.439	5 non-patent references are cited, well below the average (≈44).
Dahlin and Behrens dissimilarity (before grant)	1	.549	.465	This patent show a completely dissimilar citation pattern from prior inventions (the overlap score is 0, the lowest value possible, as there are no backward citations).
Dahlin and Behrens uniqueness (year grant)	1	.590	.668	This patent show a completely dissimilar citation pattern from its current inventions (the overlap score is 0, the lowest value possible, as there are no backward citations).This patent can be considered unique from patent granted in the same year and in the same technology field. As dissimilarity and uniqueness criteria have been fulfilled, this patent could be claimed ex ante radical innovation.
Dahlin and Behrens adoption (after grant)	0	.361	.076	As there is no citation structure, it cannot be adopted. For this reason this indicator gives 0.
Dahlin and Behrens composite	0	.139	.022	Further considerations on the composite criteria cannot be provided as only 2 criteria out of 3 have been fulfilled.

GENERAL DESCRIPTION	***Information***
Event	The Cohen-Boyer technology for recombinant DNA is a path-breaking one by any standard, 'arguably the defining technology of modern molecular biology' (National Research Council, 1997, p.40). There are in fact three Boyer and Cohen patents: 4740470, 4468464, 4237224. All patents are continuations or continuations-in-part of patents originally filed in 1974, 1976, 1978. However, patent 4237224 is the dominant one of the three aforementioned, and has been widely adopted in the field of biotechnology.
Patent#	US 4237224
Title	Process for producing biologically functional molecular chimeras
Inventor; Assignee	Stanley Cohen N. and Herbert Boyer W.; The Leland Stanford Junior University
Filed	January 4, 1979

INDICATORS (average values)	***Patent***	***Important contrib. (122)***	***Control group (83997)***	***Remarks***
Forward Citation Count	256	146.082	6.932	This invention received a high number of forward citations (256), above the average of the important contribution group (≈146). It follows that current patent has a big impact.
Forward Citation Count 5y	94	36.230	2.813	This invention received a high number of forward citations within 5 years of its application (94), almost three times the average of the set of major contributions (≈36). It provides further evidence that current patent has a big impact.
Forward Citation Lag	10.09	7.575	5.874	Besides serving more extensively as prior art for future generations of inventions, it also tends to remain cited for a longer time with a forward citation lag of 10.09 years, compared with the average 7.57 years of the set of the major technological inventions and the average 5.87 for the control group.
Generality	.70	.735	.510	This invention impacts on multiple different fields as shown by the high generality score (.70). One need only reflect on the fact that recombinant DNA has found widespread applications in biotechnology, medicine and research. Many additional practical applications of recombinant DNA are found in industry, food production, human and veterinary medicine, in agriculture, and in bioengineering: Recombinant chymosin, Recombinant human insulin, Recombinant human growth hormone (HGH, somatotropin), Recombinant blood clotting factor VIII, Recombinant hepatitis B vaccine, Diagnosis of infection with HIV, Golden rice, Herbicide-resistant crops, Insect-resistant crops, among many others.
Count Claims	14	23.336	15.421	This patent contains 14 claims, below the average of the set

				of major technological inventions (≈23).
Count main technology classes	3	2.475	2.195	It covers 3 main technology classes (above the averages): 435 'CHEMISTRY: MOLECULAR BIOLOGY AND MICROBIOLOGY'; 530 'CHEMISTRY: NATURAL RESINS OR DERIVATIVES; PEPTIDES OR PROTEINS; LIGNINS OR REACTION PRODUCTS THEREOF'; and 536 'ORGANIC COMPOUNDS -- PART OF THE CLASS 532-570 SERIES'
Count technology subclasses	24	8.016	6.248	It covers 24 technology subclasses (three times the averages of its group): 69.1 (Recombinant DNA technique included in method of making a protein or polypeptide); 183 (ENZYME (E.G., LIGASES (6.), ETC.); PROENZYMES, COMPOSITIONS THEREOF; PROCESS FOR PREPARING, ACTIVATING, INHIBITING, SEPARATING, OR PURIFYING ENZYMES); 207 (Acting on beta-galatose-glycoside bond (e.g., beta-galactosidase, etc.); 212 (Acting on peptide bond (e.g., thromboplastin, leucine amino-peptidase, etc. (3.4)); 231 (Acting on amide linkage in cyclic amides (e.g., penicillinase, etc. (3.5.2)); 252.33 (Escherichia (e.g., E. coli, etc.)); 320.1 (VECTOR, PER SE (E.G., PLASMID, HYBRID PLASMID, COSMID, VIRAL VECTOR, BACTERIOPHAGE VECTOR, ETC.)); 69.2 (Enzyme inhibitors or activators); 69.3 (Antigens); 69.4 (Hormones or fragments thereof); 69.5 (Lymphokines or monokines); 69.51 (Interferons); 69.52 (Interleukins); 69.6 (Blood proteins); 820 (SUBCELLULAR PARTS OF MICROORGANISMS); 849 (Escherichia coli); 91.1 (Polynucleotide (e.g., nucleic acid, oligonucleotide, etc.)); 91.4 (Modification or preparation of a recombinant DNA vector); 91.41 (By insertion or addition of one or more nucleotides); 311 (Somatostatin (SRIF); related peptides); 397 (Glycoprotein hormones); 399 (Hormones, e.g., prolactin, thymosin, growth factors, etc.); 808 (MATERIALS OR PRODUCTS RELATED TO GENETIC ENGINEERING OR HYBRID OR FUSED CELL TECHNOLOGY, E.G., HYBRIDOMA, MONOCLONAL PRODUCTS, ETC.); 23.1 (DNA or RNA fragments or modified forms thereof (e.g., genes, etc.).
First Subclass Combi Dummy	1	.656	.452	It is a patent with 263 novel pair wise combinations of technology subclasses, contributing to the trend that sees important contributions more likely to have a novel pair wise combination of technology subclasses (≈66%).
First Subclass Combi Count Re-Use	35,549	1,525.70	45.677	35,549 subsequent patents used the same component configuration outclassing the average of its set of important contributions (≈1,526).
Count Backward Citations	1	9.861	5.879	This invention has 1 backward citation: US 3813316 which is considerably less compared to the control group as well as the set of other major inventions
No Backward Citations	0	.172	.193	This patent does not belong to the 17.2% of patents with no backward citations.
Backward Citation Lag	6	6.063	7.506	This invention relies on more recent technical prior art with a backward citation lag of 6 years, in line with the average of its group (6.063).
Originality	0	.513	.516	This patent does not rely on prior art stemming from a broad range of technology fields as only one patent document is being cited.
Count Non-Patent References	23	43.836	22.439	23 non-patent references are cited, well below the average (≈44).
Dahlin and Behrens dissimilarity (before grant)	1	.549	.465	This patent's citation structure is dissimilar to the citation structures of past patents.
Dahlin and Behrens uniqueness (year grant)	1	.590	.668	This patent's citation structure is dissimilar to concurrent patents' citation Structures, contributing to the 59% of its group. As dissimilarity and uniqueness criteria have been fulfilled,

				this patent could be claimed as an ex ante radical innovation.
Dahlin and Behrens adoption (after grant)	0	.361	.076	This patent's citation structure does not become replicated in the future.
Dahlin and Behrens composite	0	.139	.022	Further considerations on the composite criteria cannot be provided as only 2 criteria out of 3 have been fulfilled.

CHAPTER 2

Antecedents of Radical Innovations: the Discovery of DNA structure and the invention of DSL[7]

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No scientific discovery is named after its original discoverer.
Stephen Stigler's Law of Eponymy (1980)

Abstract

Outlining and characterizing the antecedents of Radical Innovation is the only way to unveil the complex traits of the path to those innovations that dramatically and irreversibly alter the status quo of the economic and industrial context and structure in which they come to life. The two brief accounts presented in this paper attempt to sketch the paths characterizing both the discovery of DNA structure and the invention of DSL. By digging into the chain of historical events, we aim at understanding the role of time in nurturing ex ante radicalness, the technological combinatorial evolution unchained by different degrees of knowledge recombination, the importance of forgotten and unpublished discoveries, the influence of experimental systems in determining the course of scientific and technological developments, the role of market and technological attributes in redefining the boundaries of industries, the more than often neglected role of the personality of inventors. Accordingly, a number of

[7] Working Paper at Istituto di Management (Scuola Superiore Sant'Anna). Online http://www.idm.sssup.it/wp/201303.pdf

propositions are advanced and implications concerning ex ante indicators building, policy and ingredients of innovative processes discussed.
Keywords: antecedents of radical innovation, innovation process, knowledge recombination, socio-technical dynamics, DNA, DSL.

JEL codes: 031, 033

Introduction

Identifying and characterizing the antecedents of Radical Innovation is the only way to unveil the complex traits of the path to those innovations that, for their inherent challenges, dramatically and irreversibly alter the status quo of the economic and industrial context and structure in which they come to life and take shape. Behind the scene of two major events of the XXth century, the discovery of DNA structure and the invention of Digital Subscriber Line (DSL), lay important socio-technical dynamics involving intra- and inter-collective actions of individuals. Actions that push those informed individuals to identify a scientific and/or technological opportunity and select and recombine pieces of knowledge coming from quasi-independent scientific and technological streams, each of which at its stage of evolution. These dynamics force the overall innovative process to span over extended time frames. The ex ante assessment of (ex post) radical innovations, with all its implications in terms of indicators building, policy, and ingredients of innovative processes, is to date the dark side on which we try to shed some light with the retrospective analysis of two aforementioned case studies.

Defining Radical Innovation prima facie seems to be a difficult task. More than two decades of research around this topic[8], have not resulted in an equivocal definition (Garcia and

[8] See e.g. Henderson and Clark (1990), Anderson and Tushman (1990), Rosenberg (1994), Veryzer (2005), Leifer, O'Connor, and Rice (2001), Nooteboom (2000), O'Reilly and Tushman (2004), Hill and Rothaermel (2003), Majchrzak, Cooper, and Neece (2004), de Brentani (2001), Mascitelli (2000), Wheelrwright and Clark

Calantone, 2002). The term radical takes somehow the form of a 'plastic word' (Pörksen, 1988) because of its malleability and the uncanny way it is being used to fit every circumstance. All in all, scholars have used the notion of radical innovation in at least two distinct ways (Murmann and Frenken, 2006) to signal that something big and exceptional happens. Radical innovations have been defined either in terms of their antecedents (e.g. the scope of new knowledge required) or in terms of their consequences (e.g. the increased performance they make possible). We will select two radical innovations from the point of view of their undisputed and dramatic consequences, trying to understand their antecedents.

To disentangle the antecedents of whatever innovation the importance of identifying a market, technological, or scientific opportunity, of advancing it to a community or individual in search of approval, all the way to starting the development phase setting up experimental systems, has to be highlighted. We might roughly coalesce these steps into two phases: the inception phase (identifying and advancing) and the enactment phase (development). In both cases the investigator is concerned with some newly observed relation of new or old properties, abstract or concrete (Mach, 1896). The achievement of the inventor consists in his sharpened attention, which detects the uncommon features of an occurrence and their determining conditions from their most evanescent marks, submitting them to exact and full observation, and advancing them to a member or a group of a certain community. A more extensive chain of images is then necessary, the excitation by mutual contact of widely different trains of ideas, a more powerful, more manifold, and richer connections of former pieces of knowledge to set up experimental systems and begin the development phase. Under this head belong the discovery of the structure of the DNA due to Watson and Crick in 1953 and the invention of DSL technologies by its pioneers Cioffi and Lechleider late in the 1980s. By belonging to different realms (Taton, 1957), the retrospective investigation of those two Radical Innovations will

(1992), Christensen and Overdorf (2000), Phene, Fladmoe-Lindquist, and Marsh (2006), Lettl, Herstatt, and Gemuenden (2006), among many others.

allow us to shed some light on the process of discovery, of invention, besides the meanings of originality and novelty. The latter being strictly related to the concepts of phenomenon and principle. Arthur (2009) states that phenomena are natural effects and as such, they have no inherent use attached to them; a principle, by contrast, is the idea of use of a phenomenon for some purpose. Accordingly, an invention or discovery can be considered original when it exploits a new natural phenomenon, being it described by a physical or biological law. On the contrary, it can be considered novel once a new recombination of components functions properly. The discovery of DNA structure and the invention of DSL are respectively histories of some phenomena transformed in principles constituting the backbone of respectively original and novel things. Investigating the antecedents also means characterizing the complex path to the discovery or invention.

Scholars advanced many models to face such a complexity. For instance, it has long been claimed that technological change should be conceived as a patterned process of knowledge creation. In this regard, notions such as technological paradigms (Dosi, 1982; Granberg and Stankiewicz, 1981; Johnston, 1972), trajectories (Nelson and Winter, 1977) or frames (Bijker, 1987; Kaplan and Tripsas, 2008) have been advanced, building further on Kuhnian ideas about scientific progress. These concepts suffer from a strong interpretation of Kuhn's notion of incommensurability, and, consequently, from what could be called artifact centrism. Due to this heritage, they are unable to grasp innovation processes that cut across the boundaries of established patterns of technological change.

Fleck's framework seems to be much more suitable, as it entertains a weak notion of incommensurability. While Kuhn has resembled some of Fleck's central ideas, he was reluctant to accept Fleck's more radical claim that science is an essentially social process (Peine, 2011). It is the Fleckian prototype, with a combination of intra- and inter-collective communication of thought, that bears the potential to overcome the explanatory limitations of

artifact centrism. Fleck defines “thought collective” (Denkkollektiv) as a community of persons mutually exchanging ideas or maintaining intellectual interaction. Instead, the “thought style” (Denkstil) is the readiness for directed perception, with corresponding mental and objective assimilation of what has been so perceived. Conceiving of technological communities and their involvement with a technology as a thought collective is a powerful perspective to capture the intricate entanglement of the inputs of technologists, policy makers, users, and other players in innovation. Also, the functioning of technological artifacts would correspond to that of ‘proto-ideas’ in the Fleckian sense. They contain the basis for further articulation to which different circles of a collective can relate. Jointly, these proto-ideas are further articulated through intra-collective communication until they may obtain a degree of stability that makes them similar to Kuhn’s exemplars. Artifacts in a Fleckian imagery constitute ‘‘boundary objects’’ (Star, 1993) that facilitate heterogeneous problem solving and crystallize the knowledge inputs from diverse specialisms. The general structure of a thought collective consists of both a small esoteric circle (i.e. specialized experts) and a larger exoteric circle (i.e. educated amateurs), each consisting of members belonging to the thought collective and forming around any work of the mind. A thought collective consists of many such intersecting circles. Any individual may belong to several exoteric circles but probably only to a few, if any, esoteric circles. Hence, each scientist belonging to both the exoteric and the esoteric circles (Fleck, 1935) are free to move among the scientific communities, exchanging ideas and influencing one another.

Mulkay (1972) further argues that: firstly, intellectual migration occurs in most if not all scientific disciplines; secondly, that movement tends to occur from areas of declining interest into those with greater opportunities for recognition; thirdly, that migration can promote radical innovation without engendering serious opposition.

The growth of science through the migration of researchers into new areas will find an exemplary case in the birth of Molecular Biology. The DSL case study offers the perspective of a cross-pollination between a member of an exoteric circle and specialized experts of an esoteric circle. Fleck's rich description of the social structure of thought collectives in modern science favors heterogeneity, pluricentricity, negotiated degrees of stability, sustained openness and related terms populating the conceptual and technological landscape. Going through the landscape means undertaking the Innovation Journey (Van de Ven, Polley, Garud, Venkataraman, 2008) a metaphor aptly describing innovation as open-ended because of vicissitudes during the journey, of branching patterns with different dynamics (Rip, Schot, and Misa, 1995), of hills and valleys (Sahal, 1985). A concept put to the extreme by Geels (2002) with the representation of the dynamic multi-level technological transitions, where novelty needs to be nurtured in technological niches and mediated by socio-technical regimes before impacting and shaping the landscape. Obviously, these proto-ideas are already embedded in regimes and in existing landscapes.

When it comes to the epistemological standpoint (Rheinberger, 1996), it is in the fabric of properly "tuned" experimental systems that scientific and technological events materialize. Experimental systems are machines for reducing complexity. In both DNA and DSL case studies we will shed some light on the role of the different experimental systems in modeling the opportunity landscape ahead of the two thought collectives. Both the research domains of DNA and DSL still redefine their boundaries repeatedly. However, some relevant differences emerge: the coherence of molecular biology is not tied into an axiomatic structure or an algorithm; it is embedded in a complex set of experimental systems, each with its genuine epistemic practices, that have evolved over time and that have constrained earlier interpretations as well as allowed new ambiguities to arise. In the case of DSL, within the telecommunication domain, the experimental system is tied into an algorithm embedded in a

clear and well defined experimental system (i.e. set of procedures); The collective action of experimental systems may lead to a constellation of conjunctures, hybrids, and bifurcations, decisive in both case studies. Conjunctures derive from unprecedented events and may lead to major rearrangements and recombination of given representational spaces in an experimental system. Events that produce linkages between independent systems, thus leading to hybrid formations are also important. Interfaces are settled when the quasi-indipendent scientific and technological developments intermingle and result in integrated setups. The histories of molecular biology and telecommunications is replete with hybridization events. Bifurcations of a particular experimental system lead to offspring arrangements that tend to form ensembles, or clusters, that yield an experimental space for enlarged scientific communities. Generally speaking, bifurcations of an experimental system occur when it has reached a level of complexity that allows researchers to pursue slightly divergent, but sufficiently different epistemic tracks to enable them to arrive at significantly different results. Conjunctures, hybridizations, and bifurcations basically describe types of shifts, linkages, and descents through which the dynamics of reorientation, fusion, and proliferation of particular experimental systems is made possible.

The paper is organized as follows: a rich description of the two case studies, with a brief historical account, stylized observations of process ingredients, and key concepts with illustrative empirical evidence will be described, followed by an interpretation and the development of some tentative propositions. Implications for the process of invention and discovery and more specifically for the development of ex ante indicators will be discussed.

The path to the discovery of the DNA structure: history, concepts and illustrative examples

The path to the double helix should not be reduced to a continuous development effort guided by a long-term research program that had its origin in Friedrich Miescher's characterization of

nuclein in the late 1860s (Olby, 1974). Rather, a complex chain of discoveries concerned the period preceding the discovery of the DNA structure in 1953, where a number of quasi-independent scientific programs and technological developments started intertwining one another.

The path[9] to the discovery of the double helix consisted of answering some fundamental questions: Q1-Is there a physical basis for heredity? Q2-What molecule is the basis of heredity? What is the genetic material? Q3-What is the structure of this molecule? Q4-What is this genetic material doing?

It took about 85 years – counting from the first discovery of nuclein in 1869 by Miescher - to get exhaustive answers on all questions. Notwithstanding, the answer to Q1 came a little bit earlier, in 1865, from the Czech monk G. Mendel who carried out a series of experiments with peas. His observations turned out to be closely connected to the finding of nuclein. Mendel was able to show that certain traits in the peas, such as their shape or color, were inherited in different packages. These packages are what we now call genes. He published "Experiments in Plant-Hybridization," which proposed that invisible internal units of information account for observable traits, and that these factors, the principles of heredity, passed from one generation to the next. So, he determined that there was a physical basis for inheritance. However, the significance of his work was not immediately recognized. Regrettably, his work was forgotten. Mendel's resurrection involved independent rediscoveries of his work by botanists Correns, von Tschermak, and De Vries in 1900 (annus mirabilis).

The conclusive answer to Q2 was given in 1952 with Hershey and Chase's experiment: they wanted to determine what the genetic material was of a bacteriophage. They knew that a bacterial virus is composed only of protein and DNA. Protein makes up the exterior of the virus and the DNA is in the inside. When a bacterium is infected by bacteriophage, the internal

[9] An expanded and detailed timeline, is available upon request from the authors. It mainly relies on Olby (1974), Maddox (2003), Lydon (2003), Pollock (1970), and Klug (2004).

machinery falls under the control of the virus which uses the bacterium to produce more viruses. They wanted to understand which substance directed this take over - the DNA or the protein? The final proof that the DNA was the genetic material and not the protein, was provided by examining the children of the DNA bacteriophages. The radioactive DNA had passed down to them from their parents, but not the radioactive protein. It then became very difficult to maintain that nucleic acid was not the key substance in the maintenance of genetic continuity; even though evidence on the pivotal role of DNA have been advanced 8 years before when Avery, MacLeod, and McCarty showed that DNA, and not protein, had the ability to transform cells. But at that time the dominant paradigm favored proteins as vehicle of the genetic material and biological specificity. The research stream thanks to which these results came to life date back to the discovery of Miescher (1869). But no one grasped the real significance of his findings: nuclein did not mean much because Mendel's work and its connection to DNA was not yet understood. We should also consider the fact that Miescher's scientific career was constellated by a huge amount of unpublished discoveries: he published just nine scientific papers and only a handful of lecture manuscripts were printed. A substantial part of Miescher's decisive results and ideas have been passed down only through letters he wrote to friends and colleagues. Then, the scientific community could not be aware of his real contribution. In 1928, building on the contribution of Arkwright concerning the rough and smooth forms in 1921, Griffith's work laid the foundation for the experiments that led to the discovery of the molecular basis of heredity and the birth of molecular genetics.

Now that the scientific community started to become convinced that DNA is the genetic material, questions on the exact structure and processes remained unanswered (Q3). The important first building blocks have been advanced by Levene in the 1920's with the formulation of the tetra-nucleotide hypothesis which first proposed that DNA was made up of equal amounts of adenine, guanine, cytosine, and thymine. Up to 1940 no one challenged the

hypothesis of the tetra-nucleotide, as it seemed to represent an incontrovertible evidence. This hypothesis meant that it did not seem that nucleic acids would be able to play a role as carriers of biological specificity. In 1950, Chargaff was one of the few researchers who decided to take Avery's results seriously: he determined that in all DNA the amounts of adenine and thymine were equal, as were the amounts of cytosine and guanine (Chargaff's rule). These famous ratios served to disprove the tetra-nucleotide hypothesis. The race for discovering the structure of DNA started. In less than 3 years (1950-1953) that race led to deciphering the structure of DNA by Watson and Crick. They were less influenced by conceptual and methodological apparatus used to study the DNA, put together their respective expertise, and selected data they deemed essential, and then proceeded with a series of attempts to construct structural models, managing them on the basis of the problems that gradually arose in defining the organization of nucleotide chains. Mindful that they already had some basic information: Todd (1951) had clarified the nature of the links between nucleotides; Chargaff (1950) had discovered the quantitative relationships between the purine and pyramidine bases; Wilkins and Gosling had established that the fibers consist of crystalline DNA bases stacked (1951); Furberg had shown the perpendicularity of the base with respect to sugar (1951); Gulland had shown the existence of hydrogen bonds between the bases (1947); and Franklin and Gosling had obtained the crystallographic evidence that the skeleton phosphate-sugar is external while the bases are internal and that the molecule is double or triple helix with dual axis of symmetry (1951-53). In addition, Watson and Crick saw the data collected by Franklin from which to derive decisive physical-structural information; read the report sent by Franklin at the Medical Research Council provided by Perutz; had, by Donohue, a decisive suggestion about the correct tautomeric form of the bases to be taken into consideration in the construction of the model and the definition of the hydrogen bonds: bases, in fact, could exist in 2 forms, "chetonic" form and "enolic" form; Watson was using the outdated enolic form. Using

cardboard cutouts representing the individual chemical components of the four bases and other nucleotide subunits, Watson and Crick shifted molecules around on their desktops, as though putting together a puzzle. They were misled for a while by an erroneous understanding of how the different elements in thymine and guanine were configured. Only upon the suggestion of American scientist J. Donohue did Watson decide to make new cardboard cutouts of the two bases, to see if perhaps a different atomic configuration would make a difference. It did. Not only did the complementary bases now fit together perfectly (i.e., A with T and C with G), with each pair held together by hydrogen bonds, but the structure also reflected Chargaff's rule. In 1953, Watson and Crick published their structure of DNA and definitely showed how it might explain the chemical mechanism by which cells passed on their characters accurately to their daughter cells. This was one of the most fundamental and important discoveries in biology of all time (Pollock, 1970). This was because it shows not only how living systems replicate themselves (and not something different) but has led directly to an understanding of how their functional characters re expressed. Watson and Crick, along with Maurice Wilkins, will be awarded the Nobel Prize in 1962. Note that other attempts were made in building structural models of the DNA: at first sight, their discovery seemed similar to that of the triple helix proposed by Pauling and Corey in 1952, which was wrong. Indeed, it wasn't until late 1952 that Pauling would make a serious attempt at the structure of DNA. Unfortunately, when he did decide to put in some time with DNA, he still had insufficient data to correctly deduce its structure. He only used a few blurry x-ray patterns done by Astbury in the 1930s and a photograph published by Astbury in 1947. He wanted to be the first to publish a roughly correct structure of DNA. Instead, it was immediately clear that Watson and Crick's event was qualitatively different: first, in solving the structure of DNA, Watson and Crick introduced for the first time in the field of structure determinations, a genetic topic; second, it gave enormous perspectives as it paved the way to the knowledge of the functioning of genetic material. This

brilliant blend of structural and genetic considerations, started the Molecular Biology era. However, their discovery was not immediately accepted which is well illustrated from the writings of Goldschmidt. In 1955 he described the Watson-Crick model as ingenious and experimentally well founded, but he assured his readers that the geneticist: "… will not be content to accept a fine explanation of self-duplication as proof that the substance in question, DNA, is the genetic material. Such a proof requires agreement with the entire body of biochemical, genetical, and cytological facts…, and the exclusion of alternative interpretations."

So, once understood that DNA was the genetic material, once deciphered its structure, the natural question was about its functioning (Q4). For answering this question, we need to go back to 1902 when Garrod suggested that genetic diseases were due to "inborn errors of metabolism" meaning a genetic mistake was disrupting the metabolic process which require enzymes; genetic factors determine the working of enzymes. This idea was picked up by Beadle and Tatum in 1941who showed that Garrod was correct and developed the one gene-one enzyme hypothesis. Later, in 1949, Pauling and Itano first demonstrated was that genes could qualitatively alter the structure of proteins, and that mutations could therefore result in structurally different proteins.

One of the landmarks of the following 50 years that we can recall in this paper is the discovery of recombinant DNA in 1973. Stemming from three quasi-independent scientific programs and/or technological developments – the discovery of plasmids started with Sutton and Boveri in 1903 and concluded with Bazarle and Helinski in 1969; the discovery of restriction enzymes started with Temin, Baltimore, Smith, Nathan, and Kelly, Smith, Wilcox, ending up with what can be considered the first recombinant DNA molecule created by Berg; the discovery of the structure of DNA in 1953. The era of biotechnology as an 'industry' officially begins when Cohen and Chan of Stanford University, and Boyer of U.C. San Francisco

successfully recombine ends of bacterial DNA after splicing a foreign gene in between. Three years later, in 1976, Genentech, the first genetic engineering company, was producing genetically modified microorganisms that could produce human insulin and growth hormones using recombinant DNA technology.

The path to the invention of the DSL: history, concepts and illustrative examples

The path to the DSL[10] is one of accumulation of various inventions (Greene, 2011), disseminated along a complex chain of events spanning over about one hundred years (1850-1950), where three quasi-independent scientific programs and technological developments started intertwining one another: understanding the basic laws of electricity and the discovery of gutta-percha began the evolution of copper-line transmission systems on open wire, copper cable, and coaxial cable. Carrier-frequency systems were used to increase the number of channels per physical circuit. Digitalization substantially improved the quality and reduced the cost of transmission and switching. The basic theory of sound developed by Helmholtz supported the evolution from telegraphy to telephony. National telephone networks were built in most countries. Direct dialing in international telephone networks became possible worldwide when submarine telephone cables and satellite systems were installed. The early automation of industrial processes enabled the replacement of manual switchboards by automatic switching devices. In switching, quite unnoticed by the general public, a tremendous evolution happened in a 100-year period, from electro-mechanical switching by means of crossbar and electronic switching to digital switching with integrated services digital network (ISDN) functions (Huurdeman, 2003).

There are today more than 1.3 billion copper phone-line connections upon which the modern world of telecommunications inexorably relies, a growing 1/3 of them now using DSL. Since

[10] This case study mainly relies on Starr, Cioffi, and Silverman (1999), Cioffi (2011), Goralski (1998), Greene (2011), Lechledier (1991), and Andrews (2011).

Bell's 1881 invention of the twisted pair (patent US 244426), an essential copper dependency emerged. Twisted pair cables have found a lot of applications in the telecommunications industry before getting popular in the computer networking industry.

This history also intersects with the first serious efforts to circumvent the analog voice band. Nyquist's seminal 1928 work motivated conversion from analog to digitized voice transmission (Cioffi, 2011). Bell Laboratories' Robert Aaron recognized such digital-switch-connect simplification with the 1962 introduction of "T1" transmission technology (Isaksson, 2006), a transmission system architecture fundamentally different from what had been used in telecommunications network in the past. This project started in 1956. Before it, the simplest families of frequency-division multiplex (FDM) carrier systems were that of N-Carrier (for distances as great as 250 miles) and L-Carrier (spanning cross-continental distances). The first versions of N- and L-Carriers were based on well-proven electron tube technology. But the work to transistorize the FDM architectures began. The advantage of the transistor was not so much lower cost in these applications but lower power consumption, reliability, and size of the electronic equipment. But the savings were not enough to make FDM systems economic for the shorter distances between local switching offices. The need for more system capacity was definitely there. The state of the art of telephone networks laid on a combination of time-division multiplexing (TDM) developed by E. Baudot in the 1870s, and pulse code modulation (PCM) invented by A.H. Reeves in 1937, with the aim of exploiting the still higher speed capabilities of ordinary cable pairs and save in the costs of multiplexing terminal equipment.

It then came the time in which research people in the Bell Labs transmission research organization settled an experimental system (Rehinberger, 1996): it was the specific application, not the TDM/PCM principles involved, that was particularly novel. Their goal was not to duplicate the research experiment but to construct a further experiment suitable for testing in a real world environment. The most notable commercial application for the transistor

was being used for transistor radio. The device speeds required to implement the common circuit functions challenged the state of the transistor art in 1956. Some problems emerged with the original line format in matching the characteristics of cable pairs and high frequencies. As soon as B. Aron found some compelling reasons to change to the new bipolar format, important advantages appeared in no time. By 1981 T-carrier with several successive generations of terminal and repeater designs was providing over 100,000,000 voice circuit miles in the Bell System far exceeding initial expectations (O'Neill, 1985). The licensing of this technology cased a whole new industry to be formed: these standards are now the basis for today's seamless network both for wire-line, wireless and the Internet (McDonald, 2010). While simple to implement, this technology was used a low-cost early transmission line code called "alternate mark inversion" (AMI). AMI achieved less than a few percent of the famous (Claude) Shannon[11] capacity but was simple to implement and sufficient for the intended use.

However, T-Carrier had a major impact (Andrews, 2011), basically enabling a digital telecommunications network. This technology might perhaps be considered the first DSL (Cioffi, 2011).

The consequent digital core network and proliferation of digital switches left analog transmission only in the last few miles of copper closest to the customer. Circa 1980, R. Wyndrum, B. Bossick, J. Lechleider and many others at Bell Telephone Laboratories in Whippany, New Jersey were trying to complete a plan for an all-digital network. They investigated simple transmission technologies slightly more advanced than T-Carrier which yielded to the ISDN (Integrated Services Digital Network). The data rates contemplated did not yet anticipate a need for higher-speed services and instead focused on ubiquitous digital extension of the voice network. Their biggest challenge was simultaneous bi-directional digital transmission on a single twisted pair. Digital transmission required either that time-division

[11] In 1948, Shannon showed that by proper encoding of the information, errors induced by a noise channel can be reduced to any desired level without sacrificing the rate of information transfer.

multiplexing, frequency division multiplexing, or digital echo cancellation be used to separate the two directions of transmission. Suddenly a dispute arose as to which multiplexing method was best. Continuous data-driven echo cancellation had only months earlier been demonstrated at that 100 times greater precision for voice band modems by a young 23-year-old engineer, John Cioffi. The Whippany investigators (coincidentally, sans Lechleider) invited the very young designer to a meeting that would compare echo cancellation versus ping-pong for ISDN (they preferred ping-pong). After explaining the echo cancellation to a hostile audience and how it could be done, the same young engineer then had the audacity to suggest that 160 kb/s was too slow, and they really ought to consider a much higher speed, 1.5 Mb/s, much closer to Shannon capacity for a four-mile twisted-pair telephone connection. The laughter was thunderous, and the kid was embarrassed beyond belief (particularly when even his own boss told him to “shut up and sit down”). Cioffi, in the very beginning of his career, challenged the esoteric circle at Bell Telephone Laboratory when, thanks to his analytical capabilities and logical reasoning, advanced the possibility of approaching the Shannon capacity giving customers much higher speed. That was modern DSL’s birth. Lechleider, absent from that first echo / ping-pong-debate meeting, independently championed echo cancellation. Under the guidance of T. Starr ISDN became reality.

ISDN might more realistically be considered the first DSL because it really did connect the subscriber digitally while T-Carrier basically did not. As such, ISDN formed a foundation for future DSLs. However, ISDN was a commercial failure almost everywhere in the world - basically, ISDN was too slow to offer anything much more than analog phone service. Following ISDN standardization success, Lechleider (then at Bellcore) proposed what he called High-Speed Digital Subscriber Line (HDSL), which became a standard in USA by 1991. Unlike ISDN, HDSL’s higher speeds increase the twisted pair’s radiation. But crosstalk noise thus limited HDSL’s signal-to-noise ratio and consequently HDSL’s data rates but at

least 1.6 Mb/s could reliably traverse two miles. Something more was needed for digital connectivity to the residential customer. Lechleider proposed asymmetric transmission rates in non-overlapping upstream/downstream frequency bands. Thus was born a basic concept of ADSL (where A = asymmetric).

The success and diffusion of ADSL was strongly conditioned by the merging of three quasi-independent scientific and/or technological developments (Cioffi, 2011): the recognition around 1987 that DSL would require an "adaptive multi-carrier" solution (the "DMT with bit-swapping"), the invention of vectoring in 2000 (recognizing that crosstalk noise between lines could be removed), and the creation of the concept of Dynamic Spectrum Management roughly around 2000. Discrete MultiTone (DMT) and Orthogonal-Frequency Division Multiplexing (OFDM) are two very common forms of Vector Coding that add a restriction to reduce complexity of implementation. Cioffi founded Amati Communications Corporation in June 1991 to design and manufacture a multicarrier ADSL modem, proposing Discrete MultiTone (DMT) which, among the many alternatives competing for a standard, proved itself faster, more efficient and more flexible. In 1993, ANSI chose DMT for its asymmetric DSL (ADSL) standard following a test rapidly to be known as the “Bellcore ADSL Olympics.” Amati basically proposed a form of multicarrier that heavily favors digital low-cost implementation, with bit-swapping (a method to adapt continuously to the unique changes in noise on each, and across all the billion DSL connections). Broadcom, the second competitor, proposed QAM. AT&T Information Systems/Paradyne, the third competitor, proposed CAP. Tom Starr insisted on due process and laboratory testing of all three before a decision could be made. All the laboratory reports arrived at the March 1993 and the measured Olympic results showed that the Amati system had large advantages over single carrier systems. A special credit is due to European-based equipment manufacturer Alcatel, who observed and respected the American standard, and helped drive it internationally. Alcatel did invest in standardized

DMT ADSL, and remained the number one supplier of DSLAM equipment worldwide for the next 14 years. Also the invention of OFDM for digital broadcasting in 1987 by Alard and Lassalle, whose research stream dates back to 1966 when Chang, at Bell Labs, published a paper on OFDM and obtained a patent (US 3488445), represents an important step in the DSL history.

The latest evolution of DSL is the emergence of VDSL and its successors. VDSL delivers the extremely high-speed connectivity necessary to support triple play services that combine video, data and voice. With three key papers by Isaksson et al in 1999, and Ginis and Cioffi in 2000 and 2002, an important problem was solved: crosstalk noise between lines was removed. Conceived in 2000, DSM focuses on the management of the DSL's effect on neighboring DSLs. ASSIA Inc., founded by Cioffi in 2003, was formed in partnership with the USA's largest DSL service provider AT&T. The US standards effort eventually defined three levels of DSM: 1) The first level addresses time-varying noise on a DSL connection; 2) DSM Level 2 extends DSM Level 1 by reducing overall crosstalk and further increasing data rates; 3) DSM Level 3 introduced the concept of vectored DSLs.

Interpretation and Propositions

These two stories show inherent differences, but also important similarities. Notwithstanding they spring up in two different fields, two phases clearly emerge: inception (seeing an opportunity and advancing it), and enactment (developing it and by doing so, proving the relevancy and feasibility). Each phase, being characterized by different facts and different roles played by actors.

The discovery of DNA structure and the invention of DSL put in evidence the tremendous importance of the role played by knowledge recombination in impacting and modifying the scientific and technological landscape of both early Biotechnology and Telecommunication fields. Although the context of a discovery and the context of an invention are somehow

different, the dynamics with which peculiar paths come to life are quite similar. Indeed, they can be easily considered offsprings of a number of quasi-independent research streams which people like Watson and Crick, and Cioffi and Lechleider, were able to coalesce in one new stream, paving the way to authentic (ex post) revolutions. It then follows the Proposition 1: *both inception and enactment imply revisiting and recombining older truths/observations which in a number of cases (more often than not) have been available for a considerable time.*

The ideas of thought style (Denkstil) and thought collective (Denkkollektiv) provided by Fleck (1935), together with the insights provided by Mulkay (1972), show that we can never sever our links with the past, complete with all its errors; it survives in accepted concepts, in the presentation of problems, in the syllabus of formal education, in everyday life, as well as in language and institutions. All in all, these past findings/insights serve as the soil for future developments, both in terms of inception of novel ideas and the consecutive enactment. The concepts of DNA and DSL must be investigated like any other case in the history of ideas, as being a result of the development and confluence of several lines of collective thoughts. These two solidly established scientific and technological facts are undeniably linked, in their development and generation, to somewhat hazy proto-ideas or pre-ideas, even though such links cannot be easily substantiated. Proto-ideas must be regarded as developmental rudiments of modern theories and as originating from a socio-cogitative foundation (Fleck, 1935). As such, they are neither right nor wrong: the idea of DNA as genetic material and DSL as a potential vehicle of voice and data with much more speed were proto-ideas. The discovery by Avery, MacLeod, and McCarty (in 1944) is considered premature by Stent (1972, 2002). A discovery is premature if its implications cannot be connected by a series of simple logical steps to contemporary canonical (or generally accepted) knowledge. The conceptual difficulty of assigning the genetic role to DNA had by no means escaped Avery and his colleagues. On the contrary the general impact of the Hershey-Chase experiment was immediate and

dramatic. DNA was suddenly in and protein was out. Some technical advances were essential to solve the puzzle: the X-ray crystallography (1912), the X-ray tube, the technical laboratory at universities well equipped for 3D model building, the advances in microscopy. Ok to delete? Certain fundamental discoveries which have transformed some sectors of science have required exceptional intellectual courage on the part of their authors. This is the common trait which ties Watson and Crick with Cioffi and Lechleider. Cioffi believed in his ideas and founded two DSL startups, opening a new market; worthy of mention is the open-minded approach of Lechleider in agreeing with Cioffi about his ideas. The innovator who reverses a theory and tries to replace it by another, as in the case of the shifting from the Protein version of the central dogma to the DNA version of it, cannot hope to produce the most unimpeachable arguments and the most convincing demonstrations overnight. It follows the Proposition 2: *in inception and enactment proto-ideas are advanced by informed persons at the boundaries of – or partially included in - thought collectives. These embryonic ideas might clash with the canonical knowledge, as contrasting with the 'truths' of the different thought collectives involved. The latter might not take immediate advantage of such revolutionary perspectives. Only the prolonged persistence and perseverance of such originators may contribute to discard the set of norms which rule the current paradigm. This is why proto-ideas and current paradigms coexist.*

The two case studies are also populated by a number of experimental systems, ranging from the less systematic and focused ones in the case of DNA to the well-defined and stylized one in the case of DSL. However, while in the first case the experimental systems were widespread over a number of different disciplines, schools, laboratories, each of them with its own protocols, in the second case it turns out to be exactly the contrary: the Olympics for awarding the standard for commercializing the invention undergo precise protocols of actions and procedures of results assessment. To be more clear, Watson and Crick persisted in

building models even after the fiasco model (in 1951) and against Pauling's ideas (DNA as triple helix). Instead, Franklin was too hypercritical with herself, but perfectly in line with the UK research tradition at that time. She already had some pieces of evidence, but she did not succeed in reading the solution through them. Avery was not so confident with its early results. This was also the case with Miescher. Accidental facts also constellates the current experimental systems. In some cases, they have led research works into particularly fruitful directions play an important role in the discovery process. As his pet cell for investigation, Miescher chose white blood cells, because they occurred as individual cells and were easy to obtain. Performing some analyses, he noticed a precipitate that differed from previously characterized proteinaceous compounds in several ways, different from proteins, which he named 'nuclein'.It follows the Proposition 3: *both inception and enactment show complex paths cluttered with more or less formalized experimental systems, whose expected or unexpected results might influence the emergence and acceptance of some key results or even of entire discipline, and cause the reorienting of entire research programs and projects*.

In the case of DNA, intellectual migrations were massive and determined a number of biologists, chemists and physicists (some attracted by Bohr, some inspired by Schrödinger) exploring the combined role of traditional physical laws and orthodox structural chemistry. Finding no contradictions, Watson and Crick found their own way to solve of the puzzle. The relationship between Cioffi and Lechleider, the first one belonging to the exoteric circle of Holmdel Bell Telephone Laboratories (BTL), being him a young 23-year-old engineer working in the voice band modem area, the second one belonging to the esoteric circle of Bell Telephone Laboratories, might be considered a migration within the confines of the discipline. It does not expand beyond the borders of the ICT thought collectives. Cioffi, acting as young researcher, had everything to gain from nonconformity (Mulkay, 1972). It follows the Proposition 4: *both inception and enactment benefit from flows within and between thought*

collectives, influencing thought styles, by means of more or less continuous flows of intellectual migrations. Such cross-pollination activities of exoteric members belonging to different collectives, which keep on feeding during the enacting phase, is what allows new ideas to intercept different esoteric circles, moving from one thought collective to another. Radicalness might come from new entrants formerly belonging to transient or stable thought collectives.

Implications

One of the most important implication of our paper is to underscore the idea that knowledge recombination, stimulated by inter- and intra-collective socio-technical dynamics, is at the origin of the concept of ex ante radicalness. Along the path of the two (ex post) radical innovations analyzed in this paper, many different researchers discovered important bits of evidence – pieces of the puzzle – and the breakthrough arose when one group or individual saw how the puzzle pieces could logically fit together. New findings and technological advances have made so many new puzzle pieces available that the odds of someone putting them together seem quite high. Making this final leap often involves a brilliant insight – but it is important to recognize all the clues which make that insight possible.

Phenomena and principles are at the core of the originality and novelty as attributes of radicalness; from them it descends e.g. the possibility to patent the discovery or the invention in question; visualizing the quasi-independent scientific and technological developments from which inventors draw their pieces of the puzzle, disentangling their different origins even within the boundaries of the field, might be key to unveil which event has the potential of being the backbone of a radical innovation, rather than a branch or a leave of an incremental improvement.

Another implication concerns understanding market and technological attributes, notwithstanding the complex set of norms and practices which are lighted up political and

economic actors. Changing exogenous factors, and mutable and self-adapting industry definitions, interact to redefine the dynamics between different thought collectives.

Furthermore, the detailed investigation of the events preceding the discovery of the DNA structure and the invention of DSL highlight something interesting concerning the ex ante assessment of radical innovations. People's perception of radicalness must be examined: variations in individuals' genetic makeup, background, experience, exposure to the diversity of stimulus coming from different thought collectives and thought styles, and amount of information they possess concerning a particular opportunity. Some individuals, as we have shown in our case studies, coming from different backgrounds, recognize and develop different business or scientific opportunities even assessing the same discovery or invention.

Ex ante indicators, such as e.g. those defined by Dahlin and Behrens (2005), roughly compare innovations to the current and prior inventions and don't focus on any inherent attributes embedded in – and emerging from – the long path to invention and discovery.

Ex ante assessments show that (ex-post) radical innovations are nothing more than the last incremental advancement of a long and complex chain of events; it is the objectification of a radical event occurred years before, sometimes neglected, sometimes unpublished, with the help of more converging results made possible by more sophisticated technological and scientific tools.

The last implication worthy of being mentioned concerns the time frames that radicalness needs to be recognized as such. It seems that inventions and discoveries that can easily be considered radical for their dramatic impact, barely are radical in terms of their most direct antecedents. Rather, they are just the last ring of a long chain characterized by incremental and radical turning points, the latter occurring many years before. Hence, there is always a time lag to consider; but what it makes things more difficult is that some discoveries or inventions are neglected; then, a critical look at their real value is needed.

Conclusions

What has been recounted in this paper is neither the History of the discovery of the DNA structure nor the History of the invention of DSL. History cannot be told as it really was, as the historian Paul Veyne has pointed out in Comment on écrit l'Histoire. Essai d'épistémologie (1971) because there is an infinite recession of causal connections between the infinitude of events that have made the world as it is today. Thus, historical facts, just as scientific facts, are human creations - abstractions made and propagated by thought-collectives for the purpose of bringing some order to the immensely complex phenomena of our experience. The two brief accounts presented in this paper attempt to sketch the paths characterizing both the discovery of DNA structure and the invention of DSL, to single out the socio-technical dynamics acting behind the scene of two (ex post) radical innovations which dramatically depart from current practices in their fields respectively.

Through in depth longitudinal historical analysis and empirical illustrations we also aimed at understanding the role of time in nurturing ex ante radicalness, the technological combinatorial evolution unchained by different degrees of knowledge recombination, the importance of forgotten and unpublished discoveries, the influence of experimental systems in determining the course of scientific and technological developments, the role of market and technological attributes in redefining the boundaries of industries, the more than often neglected role of the personality of inventors. Accordingly, some propositions have been advanced.

More broadly, we can conclude that to assess ex ante radicalness a holistic view should be adopted, meaning that a number of characteristics have to be taken in consideration, the greatest part of which are common to the context of discovery and the context of invention. Underlying this holistic approach are disciplines such as sociology, history of science, and philosophy of science, helping scholars in escaping the temptation of approaching the study of

radical innovation from a reductionist standing, enlightening them in building up reliable ex ante indicators with the caution of not basing them on patent data only.

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CHAPTER 3

Inviting Strangers to get the gist of Radical Innovation: The Diversity Dilemma[12]

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Abstract

This paper is about the way companies from a variety of industries (called strangers) come to create and develop innovation together, with the aim of accomplishing the holy-grail: a certain degree of radicalness in order to make money out of it, adapt the environment and increase the chances of surviving. On the basis of the configurations stemming from the assessment concerning the knowlegde about the likelihoods of accomplish a certain innovation, the knowledge about the nature of the outcomes, and the time frames, a theoretical model has been advanced. Two dimensions have been contrasted: the non-spatial proximity characteristics (knowledge base) of the partners involved into the collaboration setting, and the collaboration strategy in terms of the number of partners involved. The nature of the innovation accomplished was meant ot be incremental or radical in terms of its antecedents (nature of knowledge required) and consequences (impact). A typology of innovation resulted from the model: incremental2 innovation (risky context), incremental-s1 x radical-s2 innovation (uncertain context), radical-s1 x incremental-s2 innovation (fuzzy context), radical2 innovation (ignorance context). The framework contributes to understanding the primary and controversial role of diversity in order to make managers aware of the profound implications that such a strategic setting will bring when collaborations are to be planned.

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Keywords: diversity, discoursive search, collaborative development, radical innovation, non-spatial proximity, theoretical framework.

Introduction

This paper is about the way companies from a variety of industries (called strangers) come to create and develop innovation together, with the aim of accomplishing the holy-grail: a certain degree of radicalness in order to make money out of it, adapt the environment and increase the chances of surviving. The intuition behind this research comes from a book written by Richard Sennett, one of the most prominent living American sociologists. In his last scientific effort, Together: The Rituals, Pleasures, and Politics of Cooperation (2012), in the chapter in which he argues about competition and cooperation in nature and culture he writes: "Natural cooperation begins with the fact that we can't survive alone. But cooperation cannot be stable either, as the natural environment is never fixed." A similar situation might be envisaged in Economics and Management.

As a matter of fact companies, regardless of their size and sectors, should heed the fact that as complexity rises, they are called in a mighty effort of undertaking virtuous Invention/ Innovation capabilities. Indeed, the competitive arena poses serious challenges to every company in the system, forcing them to shift towards more collaborative competitive strategies; and in so doing, they are more likely to adapt, profit and survive (Helmich 1974).

Mindful that collaborative creation and development – in the case of breakthroughs / radical / discontinuous innovations – implies multiple-heterogeneous parties along the trajectory, conditional to both the time frames requirements and the different categories of 'incertitude' implied by the twofold distinction between knowledge about likelihoods and knowledge about outcomes (Striling 1998, 2007). There are some key terms I will come back in the next sections as they will be the basis on which the theoretical model is grounded.

So the long-term aim is studying which paths multiple-heterogeneous actors can undertake in order to create and develop radical innovations, and which are the thresholds – in terms of likelihoods-outcomes-time – that enable such an accomplishment; mindful that the threshold makes us able to see when further pushing the innovative effort becomes detrimental for gaining a radical outcome.

What do we mean by collaboration? Talking about collaboration is referring to joint work (e.g. R&D cooperatives) - not simply shared positions (e.g. industry association, lobbying group) - able to leverage the differences, in terms of knowledge, skills, and resources, so as to develop innovative, synergistic solutions to complex problems companies cannot solve on their own (Hardy, Lawrence, and Grant 2005; Deck 2004; Doz and Hamel 1998; Verganti 2009). Leading companies like Alessi and Artemide collaborate respectively with more than 50 and 200 companies, each of which has a specific opinion about the innovation in question. They create what Verganti (2009) calls the Design Discourse which, put at the extreme, would help companies to create new languages and new meanings without being user-centered. A more refined view of the discourse is provided by Hardy, Lawrence, and Grant (2005): collaboration represents a complex set of ongoing communicative processes among individuals who act as members of the still separate organizational hierarchies. There is also a collective identity, a concept grounded in a variety of traditional sociological concepts, ranging from Durkheim's ‘collective conscious’ to Marx's ‘class consciousness.’ It addresses the 'we-ness' of a group. Such a discourse can be enacted in different ways depending on the number of partners involved. The literature focuses mainly on two kinds of collaboration settings: one-to-one (dyads) and one-to-many (networks).

However, the term discourse, to be of interest for our research, should emphasize not only the quantity of partners involved but also their quality, their inherent diversity. This diversity can be better characterized in what the literature calls the non-spatial proximity characteristics of

partners (Knoben and Oerlemans 2006; Aguiléra, Lethiais, and Rallet 2012). When the proximity concept is used, what is often actually meant is geographical proximity. However, other forms of proximity, such as institutional proximity (Kirat and Lung 1999), organizational proximity (Meisters and Werker 2004), cultural proximity (Gill and Butler 2003), social proximity (Bradshaw 2001) and technological proximity (Greunz 2003) are used as well. All these kind of proximities can coahlesce in the more generic concept of knowledge base. In this paper, three levels of non-spatial proximity will be used: high, meaning that partners who are going to be involved into the collaboration setting share very similar knowledge bases with the company which is deciding to start the collaboration; low, on the contrary, meaning that partners who are going to be involved into the collaboration setting share very different knowledge bases with the company which is deciding to start the collaboration; mid, meaning all the plethora of potential partners not so different, but at the same time entailing a considerable different knowledge base. The spatial-proximity characteristics (dealing with the geographical dimension) will not be included into the model in that especially nowadays the Internet and more generally the ICT technologies can kick down the geographical barriers. In this sense, Ramaswamy and Gouillart (2010) argues that enterprises are building platforms that engage not only the firm and its customers, but also the entire network of suppliers, partners, and employees in a continuous development of new experiences with individuals. Because of this, and of the fact that the arena in which companies compete and collaborate transcend the phisical borders of the nations, we decided to not take into account the geographical dimension which would have consituted the spatial-proximity characteristic of the partners involved into the collaboration setting.

These will be our two main dimensions.

The need to create a theoretical model with testable propositions comes from the fact that the bulk of the managerial literature copes with this topic by relying mainly on case studies. So,

there is an important bias from the methodological point of view. To say, inductive reasoning prevails and this inherits important drawbacks impacting generalizability (Lee and Baskerville 2003).

All in all, the two research questions we try to answer with this paper are the following: which innovation paths can different companies undertake in order to grasp radical innovation in a collaborative way, once recognized the opportunity/threat to cope with? Which are the advantages and disadvantages of involving multiple-heterogeneous partners in collaborative strategies in order for the firm to innovate along - and outside - existing technological trajectories?

In the next sections, it will follow a more detailed description of what is meant as Radical Innovation, the inevitability of collaborating, and the importance of sizing up the process in order to get effective collaborations. Then, some notes on the methodology and the theoretical framework from which a set of propositions will be derived.

Defining Radical Innovation

There is a vast and sprawling literature on radical innovations, covering (among others) historical, sociological, managerial perspectives, as well as a large body of economic research. The fil rouge connecting all these perspectives lead us to a un understanding of Radical Innovations as innovations which introduce new concepts that: depart significantly from past practices and have the potential to generate new markets (Carayannis, Gonzales, and Wetter 2003); embody a new technology that results in a new market infrastructure (Song and Montoya-Weiss 1998); and through a mix of competitive and cooperative interactions, trigger follow-up innovations and growth in other firms. Then, they can result in discontinuities on both a macro and micro level (Garcia and Calantone 2002): a macro-level where the concern is measuring how the characteristics of product innovation is new to the world, the market, or an industry (Atuahene-Gima 1995; Schmidt and Calantone 1998), and a micro-level where

product innovativeness is identified as new to the firm or the customer (More 1982). Another point of view is provided by O'Connor (2006) who argues that Radical Innovation can be thought of as the ability for an organization to commercialize products and technologies that have: a) high impact on the market in terms of offering wholly new benefits, and b) high impact on the firm in terms of their ability to spawn whole new lines of business. One way to operationalize these impact levels is as projects with the potential to offer either a) new to the world performance features; b) significant (e.g. 5-10x) improvement in known features, or c) significant (e.g. 30-50%) reduction in cost (Leifer et al. 2000; McDermott and O'Connor, 2002). All in all, radical innovations are critical building blocks of nations' creative destruction capacity and their long-term economic growth.

But how can we univoquely and effectively capture the gist of radicalness? Although a number of definitions have been advanced both in the management literature (Henderson and Clark 1990; Chandy and Tellis 2000; Tushman and Anderson 1986; Utterback 1994; Fleming 2001; Ahuja and Lampert 2001) and evolutionary economics literature (Dosi 1982; Freeman 1992), all these scholars have used the notion of radical innovation in at least two distinct ways. The only common feature of these two uses is that in both cases something big and exceptional happens. According to Murmann and Frenken (2006), radical innovations have been defined either in terms of their antecedents (sense 1, i.e. the scope of new knowledge required) or in terms of their consequences (sense 2, i.e. the increased performance they make possible). Given these two different dimensions of radicalness, an innovation could be:

1. incremental on both sides (incremental2), purely exploiting along well-established technological trajectories;
2. radical on both sides (radical2), having the potential to reshape entire industries opening up new technological paradigms;

3. incremental in terms of the new knowledge required but radical in terms of the additional performance achieved;
4. radical in terms of the new knowledge required but incremental in terms of the additional performance achieved.

In this sense we have a blurry meaning to cope with. Most scholars do not distinguish between these two meanings, which makes it difficult to interpret in what sense they see an innovation as being radical (Murmann and Frenken 2006).

However, a number of questions remain for research in this unchartered space. One of them is whether – and how – collaborative creation and development practices can help companies in generating and grasping the high returns of Radical Innovations.

The Rise and Importance of Collaborative Creation and Development

Innovation is a crucial factor for a company's survival and success, and collaborative development partnerships are an increasingly utilized way of improving innovation effectiveness. These partnerships are working relationships between two or more partners with the goal of creating and delivering a new product, technology or service (Chesbrough and Schwartz 2007). While the traditional business model centers on a company which develops a new product in-house (from own R&D) and then produces, markets and sells it using its own internal resources, the open innovation practices include co-creation and development partnerships. In this way different partners' resources and capabilities can be optimally combined, thus creating significant reductions in R&D expense and time-to-market. According to Quinn (2000), by using co-development ''leading companies have lowered innovation costs and risks by 60% to 90%, while similarly decreasing cycle time and leveraging their internal investments by tens to hundreds of times." Then, working across corporate boundaries to co-create and develop products and customer solutions is becoming a critical aspect of product development in a wide range of industries (Deck 2004). Consider also that not only is product

development becoming more important to organizations, but it is also becoming complex (Clark and Fujimoto 1991; Brusoni 2005). Also, given a short product life cycle and because of limited internal competencies, a company may increase its options by iteratively co-developing products with supply chain partners. This approach would help with the sharing of bodies of tacit and specialized knowledge throughout the chain (Ernst 2005; Sabel and Zeitlin 2004). Increased disaggregation of value chains and the growing need to develop innovative, complete solutions across multiple products combine to drive companies toward this collaborative approach to development (Deck and Strom 2002).

Moreover, advances in technology, have finally made effective co-creation and development – and the integration it demands – truly feasible (Deck 2004). Indeed, technology gives innovators and marketers more and more options in designing and delivering products and services, yet they struggle to connect people value, and this further frustrates people (Ramaswamy and Gouillart 2010). Major discontinuities in the competitive landscape – ubiquitous connectivity, globalization, industry deregulation, and technology convergence – are blurring industry boundaries and product definitions. At the same time, competition is intensifying and profit margins are shrinking. Managers can no longer focus solely on costs, product and process quality, speed, and efficiency. For profitable growth, managers must also strive for new sources of innovation and creativity.

But what does co-creating and developing really mean? There is no one-size-fits-all definition, or approach. The most interesting ones are briefly introduced. In the terms of Wyatt et al. (1997), this new way of working has been termed co-development and can be defined as ‘the ability of an original equipment manufacturer to develop competitive, customer-focused products in partnership with its first tier suppliers.’ Dyer (1996) proposes that this is the second stage of supplier involvement and requires radically changing the nature of the relationship to ensure that there is an unimpeded two-way flow of ideas between the

organizations. Other scholars like Levinson (2008) argue that co-development encompasses the notions of both co-deployment and co-evolution. Both terms are appropriate, though they have somewhat different meanings. Evolution refers to the change in the state of a technology, here through research and development coupled with market or governmental selection. Deployment refers to the spatial extent over which a particular technology is extant. The idea of co-evolution has received currency in a number of fields. In biology, it refers to the change in the genetic makeup of one species as another species also changes. Co-deployment is a related concept, but refers to the location of the technology (or species) in space. As one technology is deployed, related technologies respond to the change in their environment that the first technology created. While no new technologies are necessarily created, technologies that were successful in one area can now follow related complementary technologies to new territory. Co-development alliances, much more focused on new-generation new product development, tends to define them as nonequity-based collaborative relationships by two or more firms to create value by integrating and transforming disparate pools of know-how related to new product or service development (Link and Bauer 1989). Hence, in co-development alliances, each party contributes a significant portion of the end solution (Emden, Calantone, and Droge 2006). However, the most comprehensive definition of co-development is provided by Deck (2004): in a collaborative development partnership, two or more independent enterprises work together to design and release a new product development, service, or technology for mutual benefit. Such partnerships share the following characteristics:

- The parties will interact closely over a period of time.
- All parties are willing to invest – time, energy, and money – in each other for their mutual goals.
- All parties will benefit from the success of the partnership.

Obviously, not all relationships are strategic or require such an investment. However, although many managers now talk about their desire to turn their suppliers into development partners, the fact of the matter is that actually doing it – after decades of exploiting suppliers by pitting one against the other – is exceedingly difficult (Stuart 1997). What is worse, although more and more firms have devoted into co-development alliances in the past decade, a significant number of alliances failed (Dacin, Hitt, and Levitas 1997; Arino 2003). Unintended knowledge spillovers (Teece 2002), learning races between the partners (Hamel 1991; Larsson et al. 1998), diverging opinions on intended benefits (Larson 1992; Lorange and Roos 1992), incompatibility between partners (Buyukozkan, Feyzioglu, and Nebol 2008), and lack of flexibility and adaptability (Doz 1996; Ring and Van de Ven 1994) are frequently cited reasons for alliance failure. Partner selection becomes a strategic problem for firms (Cowan, Jonard, and Zimmermann 2007). It may affect an alliance performance and even decide the alliance's fate. It is therefore an important decision problem in the formation of co-development alliances, but few scholars pay much attention to it (Feng, Fan, and Ma 2010). As for partner selection of co-development alliances, the good collaboration situation between partners contains the noncompeting goal, compatible cultures and so on (Emden, Calantone, and Droge 2006), all of which avail to the future communication, knowledge sharing and reciprocal exchange of information between the selected partners (Feng, Fan, and Ma 2010). Meanwhile, good collaboration situation between desired partners allows for cross-disciplinary integration, which may be essential for creating new products (Chesbrough 2003). It may lead to shared research and development (R&D), reduce costs and risks (Perks 2000), create opportunities for the utilization of technologies that have not yet been found application, or increase the speed to a new market (Bronder and Pritzl 1992; Deck and Strom 2002).

The real problem is that too many companies jump into co-development efforts without thinking strategically about who to partner with, how to leverage key capabilities, and what outcome to aim for. A co-development practices survey conducted by the Product Development & Management Association (PDMA) and The Management Roundtable (MRT) in 2002, further reflects this emerging co-development trend: more than half of the respondents said that at least 20% of their projects involved a co-development partner. More importantly, almost half said that this percentage would likely double over the next two years. Across all industry segments in the study, the top reason given for co-development partnerships among smaller companies (less than $500 million in revenues) was “faster time to market”; for large companies, the number one motivator was “innovation.” Almost 70% of the respondents said they were unsatisfied with their co-development efforts. The top two reasons given were “poor foundation for collaboration” and “inadequate executive leadership,” two key ingredients for building strong relationships (Deck 2004).

Co-creation involves both a profound democratization and decentralization of value creation, moving from concentration inside the firm to interactions with its customers, customer communities, suppliers, partners, and employees, and interactions among individuals. Once an organization accepts this premise, it starts on a journey that will require it to develop new capabilities (Ramaswamy and Gouillart 2010) and organizational routines (Nelson and Winter 1982).

Setting the Scene for Collaborative Innovation

Doz and Hamel (1998) in their book “Alliance Advantage” aptly describe the process to go through in order to build up an effective collaboration strategy. It comprises a series of steps:

1) Recognizing the need and benefits for collaboration: “executives do not awake one morning with an unexplained urge to collaborate. It is not in their nature. In the absence of some compelling reasons, they steer their own courses and avoid entangling alliances. Something

has to drive them to collaborate with other firms: typically an external threat (e.g. economic crisis) or a compelling opportunity (or a combination of them) that can be addressed only with the help of others." But, how many others? Here the book relies on case studies and does not offer any general scheme or guidance. What is really important at the beginning is then recognizing the need to collaborate: Todeva and Knoke (2005) group the motives to engage in collaborative alliances in four different categories: Organizational (learning / competence building), Economic (market-cost and risk related), Strategic (competition shaping / pre-emption / product & technology related), Political (market development). By the way, the opportunity identified has to be worth of exploration: as mentioned by Hobbs and Andersen (2001), "Questioning standards and well-established project models is threatening and creates anxiety and complexity. If exposure to this complexity does not seem to be productive in terms of creating results, one reverts to the old ways." What is also self evident is that organizations in all sectors of society increasingly are becoming involved in a variety of collaborative arrangements – alliances, partnerships, roundtables, networks, and consortia – in order to promote innovation, enter new markets, and deal with intractable social problems. By collaborating, organizations hope to leverage the differences among them – in terms of knowledge, skills, and resources – so as to develop innovative, synergistic solutions to complex problems they cannot solve on their own. But not all collaborations are successful. Consequently, researchers and managers alike are interested in identifying the factors and processes that lead to the accomplishments of effective collaboration. But then the benefits of the joint work have to be identified, as they are a key step toward a multilateral action. This is easier said than done because the benefits of collaboration are not necessarily perceived until the inadequacy of the current situation is recognized and accepted, even in the face of a crisis or competitive threat. What complicates the picture is that most executives are action oriented, with a tendency to move too quickly, restrict the network to a few participants, define the

problem too narrowly, seek an immediate solution, and revert to autonomous – rather than joint – action. Moreover, positioning the project as new research rather than simply sharing existing knowledge is key. Ramaswamy and Gouillart (2010) Managers had to make the fundamental shift to go beyond their conventional goods-services mind-set to an experience mind-set – defining value based on human experiences rather than features and processes, whether downstream or upstream, in the value chain.

2) Mobilizing network participants: each project of such a kind needs a "mobilizer" – either an institution or an individual – to get the ball rolling. The mobilize articulates a vision of how value can be created, works through other resources (pre-existing networks), establishes the right sequence of commitments (existing members facilitating the co-option of future members) and the inclusion of a large number of diverse participants to develop a common ground – one that does not reflect the perspective of a single participant or category of participants. Still a convergence of interests is needed.

3 & 4) Defining common ground and Making formal mutual commitment. To this regard, Hardy, Lawrence, and Grant (2005) clarify these two points. They argue that partners are in the need of establishing a collective identity, within a discursive approach. The latter referred to organizational phenomena is more than a focus on language and its usage in organizations. It highlights the ways in which language constructs organizational reality, rather than simply reflects it. We rely on the following definition of discourse: it is a set of interrelated texts that, along with the related practices of text production, dissemination, and reception, bring an object or idea into being. One form that relationships among texts take is that of "conversation". Authors define conversation as a set of texts that are produced as part of an interaction between two or more people and that are linked together both temporarily and rhetorically. When collaborating partners discursively produce a collective identity, they produce a discursive object that refers to themselves as some form of collective, rather than as

simply a set of disconnected individuals or as a group of organization representatives. Collective identity is important because of the absence of market and hierarchical controls among participants, meaning that they cannot rely on monetary exchange or hierarchical authority to achieve cooperation. Setting up a formal mutual commitment, especially concerning the management of IP assets, means e.g. following a structured approach (Mehlman et al. 2010; Deck 2004). Indeed, formal inter-firm collaboration has become an important means by which businesses in many industries gain access to capabilities needed to compete in changing markets. Empirical research suggests that collaborating firms sometimes realize corporate financial benefits (Berg, Duncan, and Friedman 1982; Hagedoorn and Schakenraad 1990), and survival advantages (Miner, Amburgey, and Steams 1990; Baum and Oliver 1991; Mitchell and Singh 1996). Authors in several research traditions, though, note that collaborating firms risk becoming dependent on their partners (Simon 1969; Barnett 1994). Dependence on an ally may leave a business in a precarious position if a partnership changes. Then, along with its advantages, collaboration also creates potential problems, including risks of losing proprietary information to a partner (Jorde and Teece 1990; Hamel 1991) and adaptation difficulties imposed by high adjustment costs and the absorption of interorganizational routines. Establishing and renewing cooperative agreements is often costly (Coase 1960; Akerloff 1970), while businesses also frequently develop routines that span organizational boundaries as they learn to collaborate (Fombrun 1988). Interdependence arising from the interorganizational routines often makes it difficult for a single partner to act independently (Williamson 1991). Barnett (1994) refers to problems that result from collaboration as liabilities of collective action. As a general empirical outcome, businesses with collaborative agreements will tend to outperform businesses that take independent approaches in complex business situations, if managers are at least intendedly rational in their approach to inter-firm relationships. Nonetheless, severe negative influences may arise if

unanticipated problems occur after the formation of collaborative relationships. The key to avoiding these problems is to establish a repeatable process for partner selection and management, a process with a clear definition of strategy inputs, process steps, inputs and outputs for each process step, decisions, governance and process ownership, organizational approach, and metrics. What is needed is a process alignment strategy (Evans and Jukes 2000): their research has explored the importance of process synchronicity as an important element in achieving co-development success. Their main conclusion is that organizations need to consider the total product development value chain and optimize operations throughout their supply base. Dyer, Kayle, and Singh (2001) researched more than 1,500 alliances in 200 corporations and found that companies with a dedicated function and process for partner management had both more alliances (by about 50%) and more successful alliances (39% success rate improvement).

5) Moving from commitment to process: putting everything into practice. Here we start talking about acting into a network. Self-adjusting processes are at work.

6) Monitoring and potentially re-orienting the evolution of collaboration: collaborative processes involving multiple actors are ever changing in that the key interpreters of the exchange between two companies change and great part of the decisional routine cannot be codified, are tacit in nature (Nelson and Winter 1982).

Despite this detailed account and a still large and growing literature on technological collaboration, there still remains a somewhat hazy picture concerning trends in the numbers of collaborations, their focus and form, and their technological basis and strategic nature. It is then clear that the challenge is building cross-enterprise processes (Deck and Strom 2002) and innovative ways of managing these processes (Jassawalla and Sashittal 1998); also, considerable time and energy must be put forth by all involved in order to create a successful

alliance (Elmuti and Kathawala 2001). At first sight, collaborating is a very challenging and tough experience. If this is true among individuals, it is definitely true among organizations. Some key sections will follow concerning the methodology used, the dimensions identified, the underlying assumptions behind the subsequent theoretical framework, from which a set of propositions are obtained.

Methodology and Dimensions

A propositional-conceptual model is proposed by considering the following two dimensions:

1. *Co-development strategy* (Ramaswamy and Gouillart 2010; Verganti 2009) a certain company decides to adopt (one-to-one or one-to-many). Whether one-to-one or one-to-many will depend e.g. on the opportunities a company face in a certain moment (opportunities identified thanks to the company's inspection capability which is a function of intelligence and intuition; we shall come back to that in the next section); on the "key/complementary" capabilities at play (the company that has the key capability to go ahead developing the opportunity identified, will automatically be entitled in driving the collaborative development process); among many other factors (e.g. locus of control). According to Prahald and Ramaswamy (2004), the patterns of interaction among the key actors are different, and each of them require attention. But, the more these interactions are pushed towards involving many actors, the more complex will be the interaction itself (because of the rising complexity of the network); but the other side of the coin is that the uniqueness of value created increases as well. Then there is an incentive to make those experiences concrete. It is worthy to consider that each company can engage in multiple one-to-one/many projects to say, a company can have a number of projects going ahead in parallel, some of which being one-to-one, some others, one-to-many. This would introduce another level variable which

could be “number of projects into the portfolio.” But this is out of the scope of this paper.

2. *Partner non-spatial proximity* (Aguiléra, Lethiais, and Rallet 2012; Knoben and Oerlemans 2006), function of some variables belonging to the following macro-categories: cognitive, technological, organizational, social, cultural, and institutional. In a mighty effort, but letting alone this preliminary work, all these characteristics might be quantitatively measured with a set of (non-)parametric indicators stemming mainly from Information Theory, Psychology, and Biology: the Shannon’s dual-concept diversity index (Shannon and Weaver 1962), Junge’s triple-concept diversity index (Junge 1994), and Stirling’s integrated multicriteria diversity index (Stirling 1998/2007), among many others. However, this – although valuable - goes beyond the scope of this preliminary attempt to fix the ideas into a theoretical framework. By stickying to the qualitative level then, the lower the non-spatial proximity characteristics’ values, the more distant and diverse the partners involved, et viceversa. A valuable perspective is provided by Faems, Van Looy, and Debackere (2005). Their article examines whether evidence can be found for the idea that interorganizational collaboration supports the effectiveness of innovation strategies. In other words, they investigate whether firms that engage in interorganizational collaborations within the framework of their innovation strategy perform better in terms of innovative performance. And here, the Radical Innovation topic in the background comes up as relevant once again, in that organizations that possesses a diverse network of interorganizational collaboration are better equipped to create and to commercialize new or improved products (and/or services). Adopting a more exploration-oriented perspective, Christensen and Overdorf (2000) convincingly argued that collaborations with suppliers and customers will not be helpful in supporting innovation projects of a

more novel nature. According to these authors, customers and suppliers – which in our model would be considered the closest potential partners in terms of non-spatial proximity characteristics - often have an interest in the status quo and tend to preserve the dominant role of existing technologies and competencies by developing them further. On the other hand, collaborations with universities and research institutes – which in our model would be considered the farthest potential partners in terms of non-spatial proximity characteristics - are considered to be of a more exporative-oriented nature. Collaboration with such partners focuses on the creation of insights relating to new technologies that can be translated eventually into commercial development (Wheelwright and Clark 1992; George, Zahra, and Wood 2002). However an important gap emerges: for the other types of partners no straightforward diagnosis in terms of exploration or exploitation seems plausible. Here the contribution of the literature is ambiguous (Faems, Van Looy, and Debackere 2005). Accordingly this zone will be called Grey-Zone.

Then, three probabilistic paths emerge, being them potential ways by means of which companies can get radical innovations, conditional to the configuration of knowledge about likelihoods, knowledge about outcomes, and time frames that each path requires. What does it lay at the very basis of these three keys to interpreting these paths? Starting from an examination of the degree to which probabilistic techniques actually adress the full character of incertitude in the real world, Stirling (1998, 2007) advances the following characterization:

--- Figure 1 here ---

What is of interest is the application of the categories of Risk, Uncertainty, Fuzziness and Ignorance to our theoretical model.

About risk and uncertainty there is an ongoing debate (see Lane and Maxfield 2005). We maintain F. Knight's distinction (1921): propositions about risk are probabilizable by

reference to a series of fungible propositions with known truth-values; the others, 'truly' uncertain, refer to events that have no such reference set and hence cannot be measured probabilistically.

Probabilities we are talking about are subjective in nature, and retrieve the conceptualization of B. De Finetti (1974, 1975): probability as degree of belief. It is nothing more than the feeling which makes someone more or less confident or skeptical about the truth of an assertion, the success of an enterprise, the occurrence of a specific event whatsoever, and that guides him/her, consciously or not, in all his actions and decisions. Kahneman and Tversky (1973) and Kahneman, Slovic, and Tversky (1982) among others introduced the idea of subjective probability heuristics - rules that people tend to rely on when assessing the likelihood of alternative events. While these heuristics are drawn from psychological studies, they can be supported by economic models with boundedly rational agents (Simon 1955). In other words, agents do not always have the time or the cognitive ability to process all of the data provided by the economic environment with the necessary accuracy. Instead, people might employ these heuristics to arrive at analyses that are less costly to calculate than optimal decisions (Evans and Ramey 1992); and, often, the optimal decisions themselves are impossible to calculate for difficult problems. Thus, boundedly rational agents do not maximize expected utility; they maximize perceived expected utility, a quantity based not on actual probabilities but on their beliefs about those probabilities (Rabin 1998, 2002).

Concretely, uncertainty and risk of not knowing each other, of having different IP strategies, of having considered disciplines as silos with rigid borders so difficult then to cross-pollinate, of not being able to align their business models, can feed these two factors and discourage any discourse.

About the temporal dimension we rely on Iansiti (1995, 1997) and Norman and Verganti (2012). Companies, in order to get their innovation process more and more effective, need to

leave the window of opportunity (Iansiti 1995) open as long as possible, overlapping it with the development window. Moreover, most radical innovations take considerable time to become accepted (Norman and Verganti 2012; O'Connor 2005). Hence, companies being aware of that, should decide if wait or not. As we companies operate in taking a world of fast changes both on the market and technological sides, they more and more embark on these collaboration projects to speed up the time to market of innovative solutions. However, the more you speed up the product development process, the higher the probability to kick out radicalness. Golder, Shacham and Mitra (2009) examined 29 radical innovations from initial concept to commercialization. They found that these innovations were developed over an average of at least 50 years and divide this long development period into distinct stages. They also found that the duration of a stage is longer when different firms lead product development at the beginning and end of the stage. But this, if we consider collaboration as discourse and as a means of creating a collective identity, would be the norm. Because, collaboration as discourse, tends to ditribute responsibilities horizontally rather than hierarchichally.

Assumptions

The first step in order to start whatever kind of collaboration is recognizing opportunities (or threats). The first assumption deals with carrying out this step, by assuming that each company has a more or less developed 'inspection capability' (IC) that allows it to navigate the opportunity/threat landscape. Thanks to this IC, each company is more or less able to identify market and technological opportunities. IC can be thought of as a combination of intelligence (e.g. competitive intelligence) and intuition. According to Bergson (1903-23), Intelligence points to the ways of looking at – and organizing – the existent. One proceeds from a settlement of things to a re-settlement of things. It necessarily drops what happens in between the two instants. Intuition differs from intelligence – which is pure analysis. On the basis of the analytical process we operate 'rigid' distinctions, bringing the object under study back to

already known elements, i.e. elements common to more objects: this is a knowledge of the relative which uses symbols and abstract templates. Analysis is the expression of something 'function of something that it is not'. It is a translation, a symbolic explanation. Intelligence thinks of fluid and changing reality by means of the mediation of the immutable. The intelligence is a faculty which serves to the practical life, which exclusively dominates the dimension of materiality, spatiality, homogeneity and divisibility; by means of which the thought tries to reconstruct the duration as a series of 'immobilities'. Intuition allows us to read through the path, instead of only analyzing the starting and the ending points. It introduces the concept of duration; it introduces the mobility.

The second assumption is that agents, although intelligent and intuitive, are still boundedly rational. Bounded rationality asserts that decision makers are intendedly rational; that is, they are goal-oriented and adaptive, but because of human cognitive and emotional architecture, they sometimes fail, occasionally in important decisions. Limits on rational adaptation are of two types: procedural limits, which limit how we go about making decisions, and substantive limits, which affect particular choices directly (Simon 1991; Jones 1999).

The third assumption is about collaborative creation and development requiring new managerial mindset (Bettis and Hitt 1995), especially when it comes to consider multiple actors involved into the collaboration effort. The watchword here is flexibility in decision making to maintain flexibility in the deployment of critical resources. Managers must develop a mindset that allows cooperation. Firms cannot remain static even if they operate in mature industries. The dynamism requires that firms concurrently unlearn and learn: managers must have a mindset that allows them to unlearn traditional practices, processes, and strategies and to be receptive to new ones. Indeed, Levinthal and March (1981) argue that learning can improve organizational performance, but also limit future improvements. The self-reinforcing nature of learning helps sustain a current focus (e.g. core competence). By doing this,

companies become vulnerable. One of the most important capabilities companies need to develop is the adaptation especially in networks in which agents self-adapts their organizational routines to the ongoing changes of the context. Self-organization denotes a system of synergistically cooperative elements whose patterns of global behavior are distributed (i.e., no single element coordinates the activity) and self-limiting in nature (Foster 2000; Bonabeau, Dorigo, and Theraulaz 1999). Self-organization usually relies on three basic ingredients: a strong dynamical non-linearity, often though not necessarily involving positive and negative feedback; a balance of exploitation and exploration; and multiple interactions.

Theoretical Framework

On the basis of the two dimensions aforementioned to say, non-spatial proximiy characteristics and collaboration strategy in terms of number of partners involved, we identified three main paths:

--- Figure 2 here ---

Incremental^2: if a company decides to establish a dyadic collaboration with a very 'close' partner, i.e. a partner having almost the same knowledge base, then the chances to accomplish a certain degree of radicalness on both sides (s1 and s2) is very low. Then we will have a incremental-s1 x incremental-s2 innovations: in this sense, an incremental2 innovation. This is a strategy in which the only category at play from the Stirling's framework is the one of Risk, as actors have a well engough defined set of outcomes (knowledge about ouctomes) and an at least shaky basis of probabilities (knowledge about likelihoods). This strategy entails very short time frames.

Radical-s_1 x Incremental-s_2: if a company decides to engage in a one-to-many collaboration setting (and this is a considerable effort in itself), but it also wants to take the levels of uncertainty and risk low, and above all wants to do everything as fast as possible (reducing the time to market), then the probability of getting an impactful innovation is low;

notwithstanding the chances (still low however) of creating a lively conversation, which can even provide original knowledge recombinations. However, the time frames are so constrained since the beginning, that this conversation would go straight to the point without deepening any other original perspective (that, by definition, to be understood and explicitly articulated takes time!). Still low probability because the knowledge basis are very similar. So, this is much like a Local Search behavior, where a firm's R&D activity is closely related to its previous R&D activity; to say, building on the concepts introduced by March and Simon (1958) and Nelson and Winter (1982), a behavior that can be assmilated to any firm or entity searching for solutions in the neighborhood of its current expertise or knowledge. This empirical evidence suggests that firms focus their exploration on closely related technological domains. By indulging in LOCAL SEARCH, the firm focuses on similar technology, creates incremental innovations, and becomes more expert in its current domain. This is a situation in which there is at least a shaky basis for probabilities formulation (knowledge about likelihoods), but a poorly defined set of continuum and/or discrete outcomes (knowledge about outcomes). This strategy classifes for a context in which Fuzziness prevails.

Incremental-s_1 x Radical-s_2: if a company decided to establish a dyadic collaboration with one very diverse partner (e.g. a university), even though their knowledge bases are different, the chances of getting an original recombination are low because in a dyad the risk of getting stucked in an average solution, in a trade off is very high. There is no such a conversation, such a cross-pollination of a so wide range of ideas so that these two diverse actors can really create something which revolutionarize a certain sector. This does not mean that they cannot create impactful innovations. This impact, however, will not be able to reshape the industry or create new meanings. Ford et al. (1986) and Anderson et al. (1994) make a critical claim for the development of a dyadic capabilities view - that resources possessed by an organisation may be considered to be inert (passive) and of no competitive value until activated by

interaction with others. This is an important point, and is similar to Teece's (1987) contention that competitive advantage is gained through the development of distinctive capabilities supported by `complementary assetsa through the network. To trivialize, the two companies will just use the few things they need for making a particular project work. The two actors seem to not have strong incentives to put all their key assets on the table. This is a situation in which there is no basis for probabilities formulation (knowledge about likelihoods), but a well enough defined set of continuum and/or discrete outcomes (knowledge about outcomes). This strategy classifes for a context in which Uncertainty prevails.

Radical[2]: if this company, decided to engage not only in a dyadic collaboration but decided to involve many strangers, which by the way can also be connected one another, then the discourse becomes very lively, the conversation fruitful, new original and novel knowledge recombinations are very likely; and as such, they are the innovations they can come up with: revolutionary. In this case we might have what we labeled as DISCOURSIVE SEARCH. The solution they will get is something which does not have a clear authorship. The true author is the collective. This strategy deserves particular attention for the following two reasons. First, for this strategy the concept of Ignorance applies: this is a state under which there exist neither grounds for the assignment of probabilities, nor even a basis for the definition of a comprehensive set of outcomes (the lower right hand quadrant in Figure 1). This peculiar concept arises from many familiar sources, including incomplete knowledge, contradictory information, data variability, conceptual imprecision, divergent frames of reference and the intrinsic indeterminacy of many natural and social processes. Put it its simplest, ignorance is a reflection of the degree to which ‘we don’t know what we don’t know’ (Stirling 1998, 2007), reflecting our uncertainty about out uncertainty (Cyranski 1986). Second, there may be a threshold: we expect that, due to the ignorance concerning likelihoods and outcomes, and extended time frames it takes to set up and nurture these collaborations, the relation between

overall strategy adopted and degree of radicalness accomplished will be an inverted U-shape. Although it is true that diversity can be a key factor in the promotion of beneficial forms of innovation and growth, a means to hedge against exposure to strict uncertainty and ignorance in decision making over alternative technological strategies, a tool for mitigating the adverse effects of institutional 'momentum' and 'lock-in' in long term technological trajectories, and a way of accomodating the disparate array of interests and values typically associated with social choice in modern pluralistic industrial societies (Stirling 1998, 2007); but is also true that too much diversity becomes detrimental for even starting a conversation. Diversity cannot be assumed to be a free good (Cohendet, Llerena and Sorge, 1992): too 'noisy' a diversity can actually risk suppressing vital selection processes. Some authors describe the optimal configuration of these kind of networks as being 'loosely coupled'. But the structure in the collaborative setting goes beyond this paper.

For the other types of partners (those with Mid non-spatial partner characteristics) no straightforward diagnosis in terms of exploration or exploitation seems plausible. Here the contribution of the literature is ambiguous. There is what Faems, Van Looy and Debackere (2005) call a Grey Zone: here the literature concludes that by collaborating with partners which are not so different, but at the same time entail a considerable different knowledge base, the (subjective) probability of getting radical rather than incremental innovations seems to be equal. This is a potential zone in which the majority of local optima would emerge. It can be seen as a kind of 'chasm' to cross (Moore 1991).

Conclusions and Future Research

This research paper aims at figuring out how companies from a variety of industries come together to create and develop innovation, with the aim to accomplish a certain degree of radicalness in order to earn supernormal profits, adapt and increase the chances of surviving. This strategy implies multiple-heterogeneous parties along the trajectory, and the probability

to succeed relies on the configuration stemming from a trade-off among the knowledge about outcomes, the knowledge about likelihoods, and the time frames. By relying on an extensive literature review on the topics of collaborative creation and development (CCD) and radical innovations, a theoretical framework has been advanced by considering two dimensions: non-spatial proximity characteristics of partners (cognitive, technological, organizational, social, cultural, institutional), and collaboration strategy in terms of numbers of partners involved (one-to-one, one-to-many). The major contribution is highlighting the importance of collaborating, giving managers an typology of paths in order to orient their companies in dealing with different partners and opening further their collaboration boundaries, to spur radical innovations. The typologies are: incremental2 innovation (risky context), incremental-s1 x radical-s2 innovation (uncertain context), radical-s1 x incremental-s2 innovation (fuzzy context), radical2 innovation (ignorance context). The framework contributes to understanding the primary and controversial role of diversity in order to make managers aware of the profound implications that such a strategic setting will bring when collaborations are to be planned: the systematic lack of information and knowledge concerning the likelihoods and the outcomes may seriously hamper any attempt of this kind; a thing is dealing with a risky or uncertain situation, quite another thing is facing a situation in which ignorance reigns; jointly, the extended time frames such endevor requires; the grey zone a company has been able to cross in order to escape local optima with the consequence of wasting money and time on fallacious radicalness; the potential inverted U-shape relationship between the overall collaboration strategy and the degree of radicalness accomplished may undermine and discourage any discourse to start, regardless the breadth and depth such collaborative settings entail.

The Future Research closes the circle with the initial argument about Nature and its dynamics in Management and Economics. We might simulate the trade-off likelihoods-outcomes-time,

understanding what are the thresholds beyond which inviting more strangers becomes detrimental to innovation; in this vein, a set of diversity indicators stemming mainly from the Information Theory and Biology can better characterize the dimension of non-spatial proximity. Also, we might explore the concept of biological symbiosis e.g. how genotype-phenotype maps change once a certain kind of symbiosis takes place (commensalism, mutualism, parasitism), in order to understand how the genotypic changes (pleiotropy at component level) impacts phenotypic traits of innovation (phenotypic plasticity at system-subsystem level). Finally, empirically validating the matrix with multiple case studies is more than necessary.

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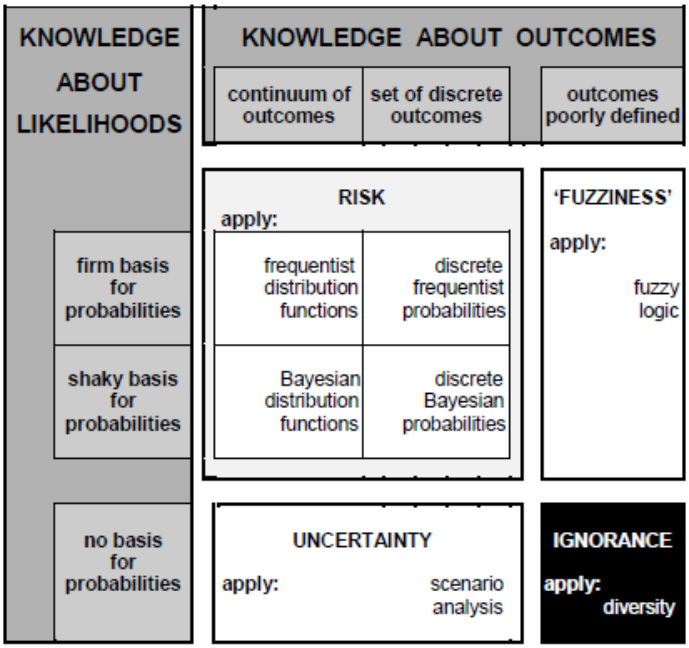

Figure 1. A formal scheme for the definition of 'risk', 'uncertainty' and 'ignorance' (Stirling 1998/2007)

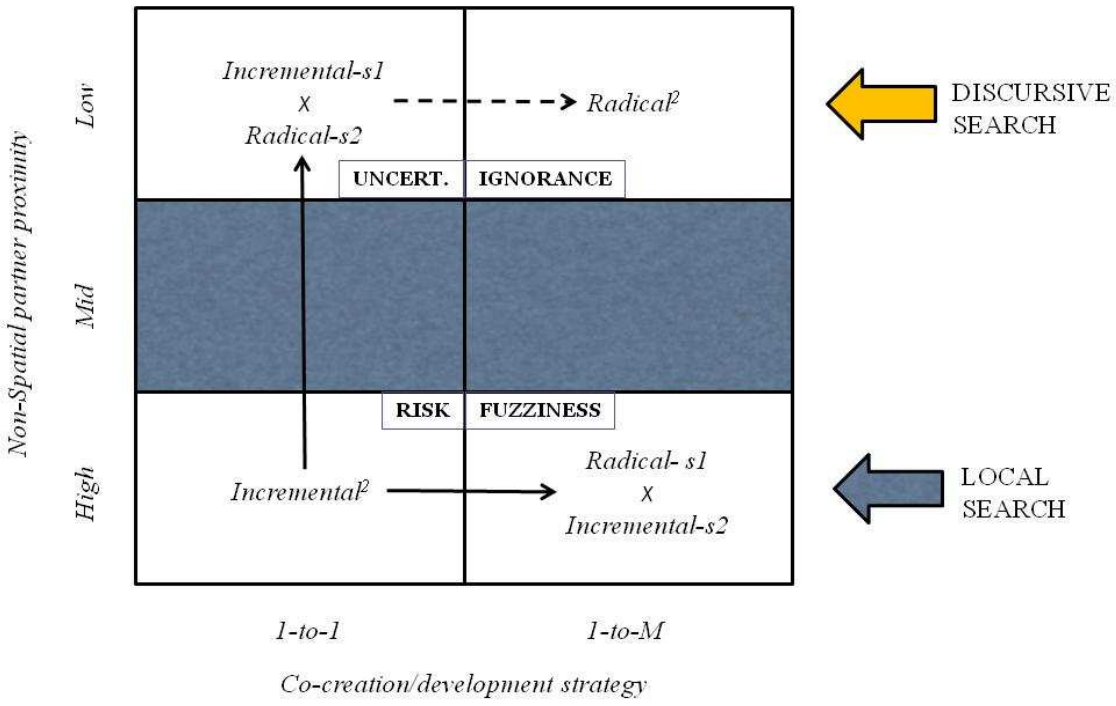

Figure 2. Theoretical framework

GENERAL CONCLUSIONS AND FUTURE RESEARCH

The aim of this dissertation is to increase our understanding of the concept of Radical Innovation.

This dissertation has made significant contribution to scholarship in technology innovation and management, as well as – although scattered – addition to the sociology of innovation. It has systematically constructed, quantified and characterized some of the unique attributes of Radical Innovations.

Through a methodological and thorough review of the ex-ante and ex-post patent-based indicators, this dissertation has provided insight to the measurement of radicalness both in terms of novelty and impact.

In addition, through a comprehensive review of two of the few dramatic (ex-post) radical innovations of the XIX century, namely the discovery of the structure of DNA and the invention of DSL, this research work attempted to be informative in terms of key factors characterizing both novelty and originality; a deep exploration and systematic characterization of antecedentes of radical innovations has been carried out.

Finally, this dissertation has provided a useful theoretical framework to investigate the role of multiple-heterogeneous agents in shaping and characterizing, by means of different collaborative development strategies, their innovation paths, and getting certain degree of radicalness according to the 'incertitude' surrounding them.

As mentioned in each chapter, some major limitations are present: concerning the first chapter, the fact that we relied on US patents only and restricted the time window to the last (of the four) phases of the Biotechnology history; concerning the second chapter, we built up our set of propositions by making reference to a bunch of case studies only which, although important, cannot allow us to abstract and generalize the emerging insights: they just signal that something interesting comes out if someone looks at the longitudinal development of their

inventive paths; and finally, concerning the third chapter, enriching and validating the theoretical framework with a survey or multiple-case studies, objectively defining and measuring the non-spatial proximity characteristics of partners, and exploring the zone standing in between the two extremes (the grey zone).

This dissertation has also outlined a number of areas for future research, stemming from each chapter.

From chapter 1:

- refining current ex-ante patent-based indicators,
- building up new composite ex-ante and ex-post patent-based indicators,
- building up new indicators by relying on text mining algorithms to delve into the content of scientific and technological documents,
- exploring the role of scientific contribution (i.e. NPRs) to patenting,
- exploring the role of claims in patents.

From chapter 2:

- investigating other case studies coming from different domains,
- going through in depth comparative analysis of socio-technical models available in the literature,
- mapping differences and similarities with the elements coming out from the case studies,
- understanding whether a one-size-fits all model is suitable to characterize the innovative paths or not.

From chapter 3:

- validating the theoretical framework with a survey or multiple case studies,
- finding out a way of quantifying the subjective probabilistic innovation paths,
- better characterizing the non-spatial proximity characteristics of partners,

- measuring diversity among partners by relying on diversity indicators stemming from Information Theory, Biology, and Psychology.

As we have seen, Radical Innovation represents an interesting and challenging phenomenon worthy of further investigation at least under the following respects:1) Socio-technical process models , reinforcing the belief that invention and innovation are both collective acts and as such their modeling should escape the reductionst points of view by broadening the range of influencing factors; 2) Managerial indicators and theories, where ex-ante and ex-post scientific and technological indicators can be further refined by going through the history of some other key inventions, and through the content of their related patents; 3) Economic dynamics, by implementing the agent-based modeling especially the History-friendly approach in order to try to mimic the evolution of the Biotech industry, with the purpose of describing its main dynamics and relations and understanding what the factors and fundamental processes are that make the model behave as it does. On the other hand, the purpose would be prescriptive in nature. From this point of view, History-friendly simulations are interestingly implemented both to understand what circumstances cause a given outcome and to study counterfactual analyses.