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The division of labour between academia and industry for the generation of radical inventions

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Abstract

The paper investigates the relationship between radical technological development and public research. This study draws on the theory of recombinant innovation, and builds on two newly developed indicators of radicalness (Verhoeven et al., 2016) to analyse UK patents filed at the European Patent Office. It assesses whether the proximity of the invention to public research is related to a higher probability of the invention being radical. The results show that, depending on the type of novelty embodied by the radical invention (novelty in recombinant rather than novelty in technological origin), different forms of public research relate to the radicalness of invention in different ways. We found also that these relationships are heterogeneous across technological sectors. Policy implications are derived.

Keywords: Radical invention, novelty, patent, recombination, public research

JEL: O30, O31, O34

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1. Introduction

Technology tends to evolve along predictable trajectories, characterized sometimes by discontinuities brought about by paradigm shifts (Dosi, 1982). These discontinuities represent the main mechanism enabling long-run economic growth (Ollson, 2000) and are at the heart of the generation of new industries (Arthur, 2007). Radical invention is integral to rendering irrelevant what is already established (Schumpeter, 1934), leading to the destruction rather than enhancement of existing competences and practices (Abernathy and Clark, 1985; Henderson and Clark, 1990).

Radical invention is a rare event and only a few develop successfully into viable innovation and often involve a long period of time between the generation of the invention and its diffusion (Rosenberg, 1974; Adams, 1990). Also, the technological uncertainty deriving from novel combinations of previously disjointed activities and elements (Schumpeter, 1934), which constitute a departure from existing/familiar practice (Ettlie et al., 1984; Dewar and Dutton, 1986), can decrease the likelihood of invention success (Fleming, 2001).

Given the pivotal role of radical invention in promoting technological and social change (Nelson and Winter, 1982; Ollson, 2000; Arthur, 2007), two questions arise. How do we identify radical inventions? What are the sources of radical inventions? The first question has been addressed at length in the literature, but standard practice for or guidance about how to identify radicalness is lacking. There are several methodologies that have been proposed to capture radicalness empirically, each of which has pros and cons (e.g. Schoenmakers and Duysters, 2010; Dahlin and Behrens, 2005; Strumsky and Lobo, 2015). From a theoretical perspective, there is a consensus that (radical) inventions should be conceived as the output of some form of knowledge recombination process (Schumpeter, 1934; Nelson and Winter, 1982; Fleming, 2001; 2007; Arthur, 2007; Carnabuci and Operti, 2013). These recombination processes can be at firm level (Ahuja and Lampert, 2001; Carnabuci and Operti, 2013) or at technological field level (Shane, 2001), or may emerge as inventions that are new to the world (Fleming, 2001; Verhoeven et al., 2016).

Identifying the source of radical invention entails a deep understanding of various aspects (Trajtenberg et al., 1997; Popp, 2016). It requires an appreciation of the "innovative division of labour" (Arora and Gambardella, 1994) between public and private Research and Development (R&D) to understand the extent to which they are related to the generation of technological discontinuities. There are numerous examples of radical inventions generated by public research (Rosenberg and Nelson, 1994; Rosenberg, 2004), but the relationship between public research and technology is complex. The benefit industry derives from public R&D – that is, research conducted in universities and public research institutions – is often tacit in nature and based on direct interactions between scientists and technologists (David, 1997; Salter and Martin, 2001). This positive effect of public research on technological change is well established (for a review see Salter and Martin, 2001), and has been often tested empirically by patent data analyses (e.g. Sapsalis et al., 2006; Sorenson and Fleming, 2004; Fleming and Sorenson, 2004), although with some caveats (e.g. Meyer, 2000, Callaert et al., 2006).

However, despite significant investigation of the relationship between technological development and public R&D (e.g. Salter and Martin, 2001; David et al., 2000; Sorenson and Fleming, 2004), the link between public research and radical invention has not been carefully examined. Understanding this relationship would shed light on the factors associated to the generation of long-run increasing returns to R&D (Olsson, 2000) and new technological paradigms (Dosi, 1982; Arthur, 2007). Moreover it would offer important policy implications concerning the mechanisms by which public research contributes to the generation of radical inventions.

Building on the theoretical foundations of invention conceptualized as a recombinant process (Schumpeter, 1934; Fleming, 2001; Arthur, 2007; Carnabuci and Operti, 2013), this paper conducts a patent analysis on the population of patents filed at the European Patent Office (EPO) with at least one UK applicant. Specifically, we investigate the relationship between two output measures of public R&D, i.e. publications and university-owned patents, and two new and efficient indicators of radicalness, operationalized recently by Verhoeven et al. (2016): novelty in recombination and novelty in technological origin. Our results show that public research outputs are related to the probability of an invention being radical in different ways, depending on the type of novelty embedded in the radical invention, and the type of public research outcome. Moreover we also find that academic patents have higher probability to be radical compared to industry patents only in the Chemistry sector, while scientific literature is related to higher level of radicalness both in the Chemistry and in the Mechanical Engineering sectors.

The paper is organized as follow. Sections 2 and 3 provide a review of the literature on radical invention, and discuss the link between public research and the generation of inventions. Section 4 describes the dataset and reports some descriptive statistics and Section 5 describes the empirical analysis. Section 6 concludes by discussing the contributions made by the paper.

2. Defining and identifying radical inventions

Radical inventions are identified according to two main and complementary perspectives. The first adopts an ex ante or backward view and is concerned with the nature of the invention, defined as a new technology that "depart[s] in some deep sense from what went before" (Arthur, 2007, p. 274). In this view, radicalness is identified by its capacity to generate shifts in the technological trajectory and is conceptualized as a process stemming from the recombination of components and the exploitation of new knowledge domains (Schumpeter, 1934). In this approach, radical inventions often are investigated at firm level and identified as technologies that emerge from the exploitation of knowledge residing outside the firm's boundaries (Rosenkopf and Nerkar, 2001; Ahuja and Lampert, 2001; Della Malva et al., 2015). Whether conceptualized at level of the firm (Henderson and Cockburn, 1994; Rosenkopf and Nerkar, 2001) or the technology (Fleming, 2001; Shane, 2001; Verhoeven et al., 2016), radical inventions are regarded theoretically as the output of some recombination processes (Fleming, 2001; 2007; Carnabuci and Operti, 2013).

The second perspective adopts a forward or ex post approach and identifies radicalness as the extent to which the invention impacts on future technological developments (Schoenmakers and Duysters, 2010). This conceptualization revolves around the idea that radical inventions differ from incremental inventions in their capability to promote the development of subsequent inventions (Ahuja and Lampert, 2001). However, this view tends to overlook the fact that, in some cases, it can take decades – even centuries – for an invention to produce important welfare gains (Rosenberg, 1974). Moreover, the innovation process, by definition, is highly uncertain (Rosenberg, 1996; 2004) and only a few inventions become successful innovations in the market.

These two perspectives, of knowledge recombination and of the impact on future innovation, are two sides of the same coin. This has been confirmed by both empirical findings, which show a positive relationship between the degree of knowledge recombination and the impact of an invention (Dahlin and Behrens, 2005; Verhoeven et al., 2016), and by theoretical works, which characterize radical inventions as novel, unique and as having an impact on subsequent inventions (Kaplan and Vakili, 2015; Dahlin and Behrens, 2005). However, the coherence of these approaches is not reflected in the literature: the majority of studies employ either ex ante or ex post approaches to the identification of radical inventions.

Following the theoretical argument that radicalness results from a recombinant process, we adopt an ex ante perspective to categorize and identify radical inventions. This choice is supported analytically: Verhoeven et al. (2016, p. 708) note that, adopting a forward assessment of radicalness overlooks an important part of the phenomenon under analysis, namely unsuccessful short-term inventions. This is relevant to the context of empirical analysis, which frequently relies on patent data and citation counts in limited time frames. For these reasons, we adopt an ex ante perspective and identify and analyse radical inventions by investigating the recombination processes involved in their generation.

2.1. An ex ante theoretical perspective: radical invention as a recombination process

According to this perspective, an invention is the output of a process of recombination of components, that is, of pieces of knowledge (Schumpeter, 1934). A radical invention occurs when a new combination of components creates a departure from the current situation (Arthur, 2007). Although not all radical inventions give rise to paradigm shifts

(Fleming, 2001), to be characterized as radical, an invention needs to show some form of novelty, that is, to emerge from a different recombination process from that characterizing the majority of inventions.

Most measures of radicalness in the literature tend to capture novelty in terms of the distance between new and old combinations of components. For instance, at firm level radicalness or novelty occur when a new invention is based on a combination of knowledge already available in the firm with knowledge from outside the firm's boundaries (Rosenkopf and Nerkar, 2001, Henderson and Cockburn, 1994; Carnabuci and Operti, 2013). In addition, studies at the level of the invention, generally captured by patents, tend to conceptualize radicalness as "the degree to which an invention […] differs from previous inventions in the field" (Shane, 2001, p. 207; Rosenkopf and Nerkar, 2001; Squicciarini et al., 2013).

A recent approach suggests that, to be defined as radical requires the invention to encompass some form of novel combination never observed before (Fleming, 2001; 2007; Verhoeven et al., 2016). For instance, Fleming (2001) conceptualizes the degree of radicalness as a function of the rareness of the combination of the same components observed prior to the focal invention. Recent conceptualizations of radicalness tend to adopt this perspective and view it as the generation of not previously observed component combinations (Fleming, 2007; Verhoeven et al., 2016). Thus, to identify radical inventions requires an in depth exploration of the recombination processes.

Inventive activity can emerge from two distinct, but non-exclusive forms of recombination. Fleming (2001, p. 118), following Henderson and Clark (1990), defines an invention "as either a new combination of components or a new relationship between previously combined components." Similarly, Carnabuci and Operti (2013) characterize recombination processes, identified as the foundations of firm innovativeness, in terms of forms of recombinant creation and recombinant reuse. According to these authors (Carnabuci and Operti, 2013, p. 1592) the former emerges when firms "create combinations using technologies that they have never combined before", while recombinant reuse takes place when firms "refine and improve known technological combinations to discover new contexts in which such combinations can be applied."

In similar vein, Arthur (2007) proposed a theory of radical invention based on the recombination processes aimed at solving a specific issue. He defines a radical invention "as one that achieves a purpose by using a new or different base principle than used before" (Arthur, 2007, p. 278). A base principle is the method used to achieve an effect, the core of invention. Also, a new principle can emerge from two different processes: the first is related to the generation of a new combination of components that gives rise to a new method of doing things; the second is related to novel application of a (frequently recently discovered) phenomenon to some combinations of components. Clearly, the two processes may be interlinked, since application of a new phenomenon to already known combinations may require the development of new combinations, depending on the degree of independence of the components from the whole technology.

Verhoeven et al. (2016) propose two indicators of radically novel technologies, building on the theory in Arthur (2007) and based on patent data. They are Novelty in Recombination and Novelty in Technological Origins. Proxying components by International Patent Classification (IPC) codes, the first characterise the invention as radical if the patent involves two IPC codes that previously have not been linked. In other words, radicalness derives from the generation of a new (re)combination of components. The second form of radicalness refers to novelty in terms of the knowledge domains on which the invention draws. Novelty in Technological Origin is identified if the patent reveals the presence of a new combination between "its own IPC code and an IPC code from its referenced patents" (Verhoeven et al., 2016, p. 711). Novelty of technology origins proxies for the introduction of a new phenomenon to an existing or new combination of components.

Arthur's (2007) theory of radical inventions recognizes the presence of heterogeneity in how these processes emerge. He highlights the variety of routes that can lead to the generation of a radical new technology and claims that: "Sometimes it requires deep theoretical understanding of the phenomenon used; at other times the challenges are more practical and experimental. The possible variations are many" (Arthur, 2007, p. 278). We contribute by investigating the relationship between public R&D and radical invention identified according to Arthur's (2007) definition, and operationalized by Verhoeven et al. (2016).

3. The relationship between public research and radical inventions

There is a large literature on the presence of a positive link between the conduct of public research and the development of industry technological development (Jaffe, 1989; Mansfield, 1991; David et al., 1992; Salter and Martin, 2001). There is an equally large literature highlighting the complexity of the relationship between public research and technology and how they mostly co-evolve and self-reinforce each other (Rosenberg and Nelson, 1994; David, 1997; Rosenberg, 1976). The development of inventions and the diffusion of new technologies are a function of the stock of available useful knowledge (Mokyr, 2002) and the output of continuous knowledge exchange and coordination between private and public R&D (Metcalfe, 1995; Loasby, 1999). Moreover, an important share of the knowledge exchanged is tacit and generally involves a process of knowledge transfer via direct interaction between public sector scientists and private organizations (Rosenberg and Nelson, 1994; Murmann, 2003). Several studies show that the relationship between public research and technological development follows different patterns according to the sector in which the knowledge transfer occurs (Arundel et al., 1995; Malo and Geuna, 2000). For example, in pharmaceuticals, codified public research outcomes are the main input into industry R&D, whereas in other sectors university-industry knowledge transfer takes place through less direct channels, for example, student secondments to industry (Salter and Martin, 2001).

Contemporary mechanisms for the transfer of public science to industry have become increasingly complex (Gibbons et al., 1994) resulting in policies providing incentives for more direct and codified technology transfer from academia to industry (Henderson et al., 1998; Mowery et al., 2001; Mowery and Sampat, 2006; Geuna, 2001). The rise in academic patenting and numbers of new venture created by academic staff are another sign of increased academic involvement in direct transfer of technology from university to industry. Moreover, there are some recent studies showing that basic R&D activity has decreased significantly in private firms although applied and development research have remained stable over time (Arora et al., 2015). This implies that academia is performing a share of the basic research which, formerly, was conducted by industry (Trajtenberg et al., 1997; Mansfield, 1998).

In some sectors, such as biomedicine and chemistry, patents developed by public research institutions are an important share of the sector’s overall patenting activity

(Mowery et al., 2001). Consequently, most empirical studies investigating the relationship between public research and technology rely on analyses of these sectors where the link is more direct and the boundaries between science and technology are less clear (e.g. Henderson and Cockburn, 1994; Narin et al., 1997; Sapsalis et al., 2006).

Several works analyse the difference between university and industry patents (e.g. Trajtenberg et al., 1997; Sapsalis et al., 2006). Trajtenberg et al. (1997) conducted pioneering work in this area. They depart from the theoretical assumption that the characteristics of university patents are significantly different from those of industry patents, arguing that university patents are more basic, more general and less appropriable. Others have explored the differences in patents characteristics according to the public or private nature of the applicant (e.g. Czarnitzki et al., 2012; Sapsalis et al., 2006). Sapsalis et al. (2006) show that university and corporate biotech patents show similar values in terms of forward citations. However, in applied science fields, such as some engineering fields, the share of academic patents in overall sector patents is much smaller. Thus, the most prominent contribution of public research to industrial innovation in these sectors possibly resides outside of university patenting activity and is based on the open model of diffusion of scientific research results. Publications, conferences and staff mobility are among the main instruments for the diffusion of research results into industry (David, 1997).

A large proportion of the empirical work on the relationship between basic science and industrial innovation, rely on patent data to trace these indirect linkages and, specifically, patent citations data. Patent citations and the especially the academic literature cited in patents, represent the main codified link between public R&D and invention (Narin et al., 1997; Tijssen, 2001; Fleming and Sorenson, 2004; Sapsalis et al., 2006), although the results of these studies should be interpreted with some caution (Meyer, 2000; Callert et al., 2014). In particular, it has been argued that citing non-patent literature does not represent a direct link between the output of an open academic science and the invention, but mostly represents the 'vicinity' of (Callert et al., 2006) or 'relatedness' between (Meyer, 2000) open science and industry inventive processes (Callert et al., 2014).

Most empirical analyses use one out of two measures of science relatedness to patented inventions: public ownership of the patent and patent references to scientific literature. However, these capture only the codified academic knowledge related to the inventive activity. While it would be inappropriate to refer to these two measures as indicating respectively applied versus basic research, it would be reasonable to see them as referring to proprietary versus open public research. These two measures are the outcome of different processes of diffusion of public research output. Publicly owned patents represent the direct contribution of public research to inventive activity (Sapsalis et al., 2006), while non-patent references mostly indicate an indirect relation between public research and inventive activity (Tijssen, 2001; Callert et al., 2006).

4. Empirical framework

This section explores our research question empirically, to characterise the relationship between (codified) public R&D and radical invention. We identify two measures of public R&D: the public property of the invention, and the references to the scientific literature included in the patent. We describe the data and its sources and then examine the patent applicants. We investigate the differences between public and privately owned patents in terms of radicalness. Following these descriptive analyses, we investigate the antecedents to radical inventions in terms of their public research relatedness. Finally, we replicate the analyses, distinguishing between technological sectors.

4.1. Data

To explore our research questions we rely on patent data. Patent data provide a wealth of information on invention bibliometric such as technical prior art on which the patent builds, citations to non-patent literature, geographical dimension of the inventions and the type of applicant/inventor that applied for/developed the patent. These features have been exploited in scientific studies that investigate the characteristics of the invention process. However, the use of patents to measure invention activity has been criticized by some authors who stress that the technical and economic values of patents differ (Griliches, 1998; Hall et al., 2005). Others highlight that sectors and technologies are characterized by different propensity to patent (Arundel and Kabla, 1998), which reduces comparability of the results. Although patents are not a perfect proxy for innovation, they are a useful indicator and the main source of information for studies of invention (Schoenmakers and Duysters, 2010).

The empirical analysis is based on the UK. The UK represents a relevant 'proving ground' for investigating the link between public R&D and the nature and characteristics of radical invention (Sterzi, 2013). First, the UK university sector is ranked second only to the US (e.g. Academic Ranking of World Universities, ARWU). University-industry technology transfer in the UK is ranked similarly highly: in the UK these activities were formally recognized and supported before most of Continental Europe and other western countries (Wright et al., 2007; Marzocchi et al., 2017).

Since the objective of the paper is to investigate the nature and characteristics of radical invention, we selected all patents with at least one applicant based in the UK. Patent data are derived from the Worldwide Patent Statistical Database (PATSTAT). Focusing only on patents filed at the European Patent Office (EPO), we identified 126,012 patents, with a priority year between 1978 and 2011, with at least one British applicant. In order to determine the nature of these patents we sought to distinguish between public and private applicants. We identified private organizations using suffice Ltd or Limited. To identify public research institutions we first flagged all patent applicants that were universities listed by the Higher Education Statistics Agency (HESA) and, then, checked the remaining patents manually. This allowed us to assign 113,910 patents, corresponding to 90% of the patent population, to either private companies or public research institutions. The applicants on the remaining 12,102 patents were either individuals or charities. We excluded these patents from our sample. Moreover, since the same EPO invention can be protected in several national patent offices, the so-called patent family, we follow Verhoeven et al. (2016) and aggregate multiple counts of the same invention using the maximum level of each indicator within each patent family:[1] this allow to avoid counting the same invention more than once.[2] This procedures affects overall 6.5% of patents in our dataset. The final dataset comprises 103,697 patent families (our unit of analysis), 6,746 of which include at least one public research institute as an applicant, corresponding to 6.5% of the sample. We collected various

[1] Some patents have missing information, which makes this approach unfeasible. In these cases, following other approaches (i.e. Hall & Helmers, 2013) we identify technological field and geographical code in the patent document with the earliest priority date and assign them to the whole patent family. Since some patents within the same family may have the same earliest priority date, we calculated the share of patent documents for each single code and assigned to the whole family the code with the highest share.

[2] The results of the empirical analysis hold when we calculate the minimum value for each indicator within these patent families, showing that this methodological choice does not affect the results.

information on IPC technological class and backward citations from PASTAT and OECD data.

4.2 Method

The relationship we want to investigate can be formulated as follows:

$$Radicalness_{ijvt} = \alpha + \beta \boldsymbol{PublicR\&D}_{ijvt} + \delta \boldsymbol{X}_{ijvt} + \gamma_j + \tau_t + \varphi_v + \varepsilon_{ijvt}$$

where $Radicalness_{ijvt}$ is proxied by the two main indicators of novelty and their combination as in Verhoeven et al. (2016), referring to patent *i* belonging to technological field *j*, region *v*, at year *t*. $\boldsymbol{PublicR\&D}_{ijvt}$ is a vector of the variables that capture various forms of public research output, and $\boldsymbol{X}_{ijvt}$ includes a set of patent-level variables assumed to be related to patent radicalness. Finally, we control for technological field (γ_j), region (φ_v) and time (τ_t), while ε_{ijvt} represents the disturbance term.

As mentioned above, we employ two dependent variables for the two forms of radicalness; they take the value of 1 if they embody the respective form of novelty, and 0 otherwise. Given the dichotomous nature of our dependent variables, we employ a logit regression model to investigate the probability that the patent is related to a radical rather than an incremental invention, as a function of the patent being linked to public research and based on a series of control variables. Logistic regressions use odds ratios, which, in our case, are given by the probability of the patent being radical divided by the probability of the patent being non-radical as a linear function of the explanatory variables. The logit model log-transforms the odds ratios. Thus, the estimations investigate the relationship between a one-unit change in the predictor of interest, keeping the other predictors constant, and the change in the log of odds ratio of the outcome, invention radicalness.

4.3 Variables

4.3.1 Dependent variables

Drawing on Verhoeven et al. (2016), we identify radicalness based on two main indicators: novelty in recombination (*Nr*) and novelty in technological origins (*Nto*). Novelty in recombination captures whether the invention is a new-to-the-world combination of knowledge components. These knowledge components are identified by the IPC system, which associates technological classes to patents, within a hierarchical structure where the specificity of class, i.e. of the component, increases with the number of digits in the IPC code. Radical inventions combine different pieces of knowledge in previously unexplored ways (Nooteboom 2000; Nemet 2009; Fleming, 2001) and, therefore, are identified in terms of the extent to which they combine different technological classes (Fleming 2001; Hargadon 2002). The novelty in recombination indicator operationalized by Verhoeven et al. (2016) uses the combinations of 8-digit IPC code pairs in the patent and considers the patent to be radical if it combines two IPC codes for the first time. *Nr* takes the value 1 if the focal patent includes at least one IPC code combination that is novel in relation to the PATSTAT population of patents in the years before the application-year of the focal patent, and 0 otherwise. IPC codes are obtained from PATSTAT; for each patent in the PATSTAT population we calculated combinations of codes and compared their priority year to the patents in our sample.

Novelty in technological origins (*Nto*) captures novelty in the knowledge sources from which the focal patent's components and principles are drawn. Thus, it is based on backward citations and IPC codes and produces combined pairs of IPC codes between the focal patent and the patents it references. Within the population of PATSTAT patents, the variable *Nto* takes the value 1 if the focal patent combines at least one own 8-digit IPC code and an 8-digit IPC code from its referenced patents that have not been combined previously in a patent, and 0 otherwise (Verhoeven et al., 2016: 711).

These two indicators are our preferred two measures of radicalness. The choice to proxy radicalness with these indicators follows Verhoeven et al. (2016, p. 708), which states that:

> we compare our measures to measures of related constructs commonly used in the literature, more particularly the 'originality' measure introduced by Trajtenberg et al. (1997) and the 'radicalness' measure employed by Shane (2001). Our technology measures correlate with these existing measures of related constructs, but perform better on characteristics typical for technological novelty.

The descriptive statistics of these variables and the independent variables are described in the following section and presented in the respective Tables 2 and 3.

Table 1 reports the frequencies of patents identified as radical in the UK population of EPO patents. We observe that 5% of patent families are recognized as radical in terms of recombination novelty, while 9% of families are radical in terms of technological origin novelty. Note that, scoring 1 for *Nr* does not exclude the possibility of scoring 1 also for *Nto*.

Table 1. Frequencies of radical patent families

	Measures of radicalness	
	Novelty in recombination (Nr)	*Novelty in technological origins (Nto)*
Observed frequency	5,691	9,744
Percentage	5.49	9.4

These percentages are slightly lower compared to the results in Verhoeven et al. (2016), which show that 7% of patent families are related to recombination novelty and 20% of patent families are related to technological origin novelty. These discrepancies are due to the ‘comparative’ reference populations on which the two indicators are calculated. While Verhoeven et al. (2016) compare combinations of their sample to the population of patents filed at the three major patent offices (United States Patent and Trade Mark Office -USPTO, EPO and the World Intellectual Property Organization - WIPO), we compare our UK sample to the entire PATSTAT population, which includes all patents filed at all national and international patent offices since 1819. In other words, our calculation is more stringent than that in Verhoeven et al. (2016) resulting in fewer patent families showing radicalness.

4.3.2 Independent variables

The main independent variables seek to capture public research relatedness to the invention. We constructed these variables from the available patent information. The first is dummy *Public* which takes the value 1 if the patent includes at least one public research institute as an applicant, and 0 otherwise. The public versus private applicants were identified following the procedure described in Section 4.1 (Data).

The second independent variable for non-patent literature (*Npl*) refers to the references to non-patent literature in the patents. Several papers proxy relatedness between public research[3] and an invention by analysing the cited non-patent literature (Narin et al., 1997; Sorenson and Fleming, 2004; Fukuzawa and Ida, 2015). The dummy *Npl* takes the value 1 if the patent cites any non-patent literature, and 0 otherwise.

In line with other empirical studies of patent data, to control for other important explanatory factors, we include in the regression three other variables derived from PATSTAT. *Bwd_pats* is the counts of patent references in the focal patent and is related to the novelty of the patent (Harhoff et al., 2003). Among the information included in the patent references, cited patents represent the most important direct link between past and present inventions (Callert et al., 2006). *N_ipc* counts the number of 8 digit IPC codes in the patent and controls for patent breadth (Lerner, 1994; Shane, 2001). *N_inv* counts the number of inventors on the patent and is considered also to be related to the radicalness of the invention (Hall and Helmers, 2013). Finally, we control for technological field: the IPC provided in PATSTAT uses 35 technological fields to represent five major technological sectors. We assign patents to technological field following the procedure adopted by Squicciarini et al. (2013). We control also for regional (NUTS II) and priority-year time dummies. Table 2 defines the variables employed in the empirical analysis; Table 3 presents the descriptive statistics and Table 4 presents the correlation matrix.

[3] Most of the studies identify non-patent literature as a proxy for basic research or science

Table 2. Variable description

Variable name	Description
Nr	Dummy variable taking the value of 1 if the patent is radical in terms of novelty in recombination, and 0 otherwise
Nto	Dummy variable taking the value of 1 if the patent is radical in terms of novelty in technological origin, and 0 otherwise
Public	Dummy variable taking the value of 1 if the patent displays at least one public research institute as applicant, and 0 otherwise (only private companies)
Npl	Dummy variable taking the value of 1 if at least one non-patent literature document is reported in the references of the patent, 0 otherwise
Bwd_pat	Number of patents referenced by the focal patent
N_ipc	Number of 8-digit IPC codes of the patent
N_inv	Number of inventors of the patent

Table 3. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Nr	103,697	0.055	0.228	0	1
Nto	103,697	0.094	0.292	0	1
Public	103,697	0.065	0.247	0	1
Npl	103,697	0.36	0.481	0	1
Bwd_pat	103,697	4.824	4.769	0	214
N_ipc	103,697	4.165	4.663	1	247
N_inv	103,697	2.154	1.531	0	49

Table 4. Correlation matrix

	Nr	*Nto*	*Public*	*Npl*	*Bwd_pat*	*N_ipc*
Nto	0.3818					
Public	0.0103	-0.0051				
Npl	0.0058	0.0033	0.1463			
Bwd_pat	0.0138	0.1472	-0.0515	0.036		
N_ipc	0.2213	0.1496	0.0229	0.1506	0.0396	
N_inv	0.0054	-0.002	0.0807	0.1663	0.1041	0.2218

5. Analysis

5.1 Frequency distribution

We observe that the fraction of publicly owned patents is quite small, corresponding to 6.5% (6,746 patents) of the whole sample, while the fraction of patents reporting scientific references corresponds to 36.3% (37,698 patents) in the UK population of patents. Note that, given the low percentage of both radical and public patents, public radical patents are only few hundreds: roughly the 0.5% of UK patents.

To explore the relationship between radicalness and public R&D sources we report in Table 5 the results of four contingency tables. Columns 2 and 3 report results of contingency table between radicalness and public patent ownership, and columns 4 and 5 report the results of the contingency table relating radicalness and non-patent literature references. It can be seen that the proportion of public patents that are radical in terms of novelty in recombination is significantly higher than the proportion of company owned patents. In contrast, when radicalness is expressed in terms of novelty in technological origins the proportion is in favour of company owned patents, although the difference in proportion is not significant at the 5% level of confidence. Putting in relation radicalness and non-patent literature, the last two columns in Table 5 show that patents citing non-patent literature tend to be more radical, although the null hypothesis that the proportions are independent cannot be rejected at the 5% confidence interval level.

Table 5. Results of contingency tables between radicalness and public research sources

	Nr=1 & Public=1	*Nto=1 & Public=1*	*Nr=1 & Npl=1*	*Nto=1 & Npl=1*
Observed frequency	430	596	2,135	3,591
Ratio between observed and expected frequency	1.16	0.94	1.03	1.01
Chi2(1)	10.92**	2.67	3.51	1.16

$^{*}p < 0.05$, $^{**}p < 0.01$

5.2 Logit regressions

In this section, we control in our analysis for other patent characteristics, technological fields, regional and time dummies. Table 6 reports the results of the logit regressions for both of our dependent variables and for the full sample of UK patents. We observe a positive relationship between public research and radicalness, whether in terms of novelty in recombination or novelty in technological origins. This positive relationship applies to both of our public research variables, *Public* and *Npl*.

A finer grained picture of this relationship is obtained by examining the coefficients of *Public* and *Npl*. This requires us to obtain the odds ratio. In relation to patent ownership, the odds of being radical in recombination for public patents are 36% higher than the odds for private patents. If we translate this into probabilities, we can say that, keeping all other variables at their means, a private patent has 3.7% probability of being radical compared to a 4.9% probability for a public patent; thus, a public patent has a 1.2% higher probability of being radical in recombination than a private patent. Conversely, the probability of being radical in technological origins is almost 1% higher if the patent is public, increasing from 6.7% to 7.6%. Comparing the *Public* coefficients across specifications, we can reject at the 1% significance level, the null hypothesis that the difference between the two coefficient is 0 (chi2(1)=8.55). In other words, a public patent is more likely to be radical in recombination than in technological origins.

Regarding the relationship between radicalness and references to non-patent literature, we find a positive relation, but the magnitudes of the coefficients are reversed. That is, the probability of a patent being radical in recombination is 0.7% higher if the patent cites non-patent literature. Conversely, in the case of radicalness in technological origins, the probability increases by 1.8% for patents citing scientific literature, from 6.2% to 8%. Again, a test of the differences in the coefficients rejects the null hypothesis of equality at the 5% significance level (chi2(1)=6.37, p-value= 0.0116). In other words, citing non-patent literature increase the probability that the patent is radical in technological origin more than it increases the probability that the patent is radical in novelty in recombination.

Furthermore, we compared the coefficients of *Public* and *Npl* within the same specification. Specifically, we tested whether the size of these coefficients differed in respect to the same output. At the 5% significance level, the test does not rejects the null hypothesis that *Public* and *Npl* are not statistically different if the outcome variable is *Nr* (chi2(1)= 3.05, p-value=0.08). Conversely the null hypothesis is rejected at the 1% significance level if radicalness is based on novelty in technological origin, and the magnitude of the coefficient of *Npl* is significantly higher than the one of *Public* (chi2(1)= 6.70).

Table 6. Logit regression, full sample

	Nr	*Nto*
Public	0.305**	0.126**
	[0.057]	[0.048]
Npl	0.184**	0.274**
	[0.034]	[0.027]
Bwd_pat	0.009**	0.089**
	[0.003]	[0.004]
N_ipc	0.163**	0.109**
	[0.005]	[0.004]
N_inv	-0.055**	-0.030**
	[0.012]	[0.009]
chi2	2875.76	4768.69
N	103,697	103,697

Robust standard errors in parentheses. Time, technological field and geographical dummies were included in the estimates, but are not reported here.
* p<0.05, ** p<0.01

These results highlight, first, that public research and radical invention are positively related and, second, that different measure of radicalness are related differently to our measures of public science. More specifically, we found that public patents increase the probability that the patent is radical in novelty in recombination, while non-patent references increase the probability that the patent is novel in technological origin.

In relation to the other variables used in the estimation, we observe that citing a higher number of patents and being based on a higher number of IPC codes are related to a higher probability of being radical, which is in line with the findings from other studies (Sapsalis et al., 2006; Fleming and Sorenson, 2004; Schoenmakers and Duysters, 2010). In contrast, a higher number of inventors in the patent is related negatively to the probability of being radical.

5.3 Sectoral analysis

It is relevant to show how the investigated relation changes depending on the technological sector. PATSTAT identifies 5 macro-sectors – Electrical Engineering, Instruments, Chemistry, Mechanical Engineering and Other – to which belong the 35 technological fields. Table 7 presents the radicalness frequencies in these sectors.[4] It shows that Chemistry and Mechanical Engineering generate more (in number and percentage) radical inventions than Electrical Engineering and Instruments.

Table 7. Frequencies of radical inventions in different technological sectors

Sector	Obs	Radicalness	Frequencies	Percentage
Electrical Engineering	19,355	*Nr*	589	3.03
		Nto	866	4.47
Instruments	16,654	*Nr*	715	4.29
		Nto	1,176	7.06
Chemistry	34,266	*Nr*	2,302	6.72
		Nto	3,617	10.55
Mechanical Engineering	25,384	*Nr*	1,745	6.87
		Nto	3,278	12.91

Table 8 replicates our econometric specifications presented above, for the four sectors separately. As expected, the relationship between public research and radicalness is heterogeneous across sectors. We observe that the two sectors with the lower share of patents and radical inventions – Electrical Engineering and Instruments – mostly do not show a significant relationship between public research and radical invention. This is

[4] We excluded the sector "Other" which includes 3 non-related technological field (Furniture and games, Other consumer goods and Civil engineering).

shown by our variables capturing public research output: public ownership of the patent and references to non-patent literature.

For Chemistry and Mechanical Engineering the picture changes. For Chemistry, the results are qualitatively similar to those for the full sample, but with larger coefficients and odds ratios. For instance, the probability of being radical in *Nr* is 1.7% higher if the patent is publicly owned, moving from a probability of being radical of 4.4% if the patent is private to a probability of 6.1% if the patent is public, keeping all other variables at their means. If the patent cites scientific works, this probability increase by only 0.9%. When the output measure is *Nto*, the *Public* ownership of the patent increases its probability to be radical of 1% although this coefficient is not statistically different from 0. Conversely this probability increase of 2.3% if the patent cites scientific works, moving from 6.5% to 8.9%.

Publicly owned patents have a higher probability of being radical in recombination rather than in technological origins (chi2(1) = 5.14 with p-value=0.02). Conversely radicalness related to novelty in technological origin is linked more to the inclusion of non-patent citations than to public ownership (chi2(1) = 4.50 with p-value = 0.03). Similar to the results for the full sample, the coefficient of *Public* is not statistically higher than the coefficient of *Npl* if radicalness is due to novel recombination (chi2(1) = 1.53), while there is statistical difference between the two coefficients if the dependent variable is *Nto*: *Npl* is significantly higher than *Public* (chi2(1) = 4.82).

For Mechanical Engineering we note a significant relationship between radicalness and public research only when radicalness is captured by novelty in technological origin. In this case, the generation of radical patents is associated positively to both public patenting activity and scientific publications. The probability of being radical increases by 2.5% and 2.1% respectively for a publicly owned patent and patents that cites non-patent literature; the two coefficients are not statistically different.

Table 8. Logit regression, different technological sectors

	Electrical Engineering		Instruments		Chemistry		Mechanical Engineering	
	Nr	*Nto*	*Nr*	*Nto*	*Nr*	*Nto*	*Nr*	*Nto*
Public	0.059	0.152	0.101	-0.216	0.341**	0.138	0.206	0.252*
	[0.209]	[0.171]	[0.134]	[0.117]	[0.081]	[0.071]	[0.146]	[0.108]
Npl	-0.255**	0.001	-0.001	0.106	0.217**	0.327**	0.103	0.225**
	[0.098]	[0.080]	[0.094]	[0.073]	[0.051]	[0.041]	[0.074]	[0.053]
Bwd_pat	0.017	0.147**	0.004	0.141**	0.006	0.061**	-0.004	0.157**
	[0.015]	[0.011]	[0.010]	[0.015]	[0.004]	[0.004]	[0.008]	[0.006]
N_ipc	0.366**	0.205**	0.468**	0.321**	0.097**	0.069**	0.358**	0.213**
	[0.020]	[0.015]	[0.017]	[0.013]	[0.004]	[0.003]	[0.012]	[0.008]
N_inv	-0.029	-0.030	-0.043	-0.036	-0.052**	-0.022	-0.026	-0.008
	[0.038]	[0.030]	[0.034]	[0.024]	[0.015]	[0.012]	[0.025]	[0.018]
chi2	565.7	703.4	947.5	1075.6	1278.9	1815.7	1287.5	1884.8
N	19,355	19,355	16,654	16,654	34,266	34,266	25,384	25,384

Robust standard errors in parenthesis. Time, technological field and geographical dummies have been included in the estimates but not reported
* p<0.05, ** p<0.01

Overall, we can confirm that the relation between (codified) public science and radical patented inventions changes consistently across sectors and radicalness measures. Two sectors reveal the absence of a relationship between radicalness and public research, while Chemistry shows a strong and positive relationship mostly in respect to *Nr* and Mechanical Engineering shows a strong relationship only if radicalness is captured by novelty in technological origin.

6. Conclusions

We employed patent analysis to explore the relationship between public research (captured by patent information) and radical inventions, using the population of UK patents filed at the EPO with a priority year between 1978 and 2011. We used two measures of radicalness: novelty in recombination of components and novelty in technological origin of the invention in relation to two measures of public research derived from patent information: public ownership and references to the scientific literature. Our analysis shows that there is an overall positive relationship between public research and radical invention, but that this relationship varies consistently across radicalness typologies and public research output, and across technological sectors. The proprietary output of public research – measured in terms of public ownership of patents – is related to a higher probability of producing a radical invention in terms of recombination of components. Conversely, open science – captured by non-patent references – is more likely to be related to the generation of radical inventions based on application of a new phenomenon to existing components (novelty in technological origin).

We provide evidence also that this relatedness emerged at the full population level, changes depending on the technological sector. Among the four PATSTAT technological sectors, two – Chemistry and Mechanical Engineering – seem to related to the available measures of public research, while Instruments and Electrical Engineering mostly show an absence of this relationship. The former two sectors have higher numbers and percentages of radical inventions, although the relationship between the two measures of radicalness and the two measures of public research change between the two, highlighting the complexity of the relationship between public research and radicalness.

This work has some limitations. As already mentioned, the absence of a relationship in our empirical framework does not imply a low level of influence of public research on industrial technological change. It might be that this interaction is not captured by patent related information, and we are capturing only the proximity of the codified public research to radical invention generation. This conjecture is supported by the literature (Rosenberg and Nelson, 1994; Meyer-Krahmer and Schmoch, 1998; Meyer, 2000) and by the fact that these sectors show lower levels of patenting activity. Further research could focus on identifying patterns of knowledge exchange between public and private research in order to better frame the antecedents to radical invention, and across sectors.

This work constitutes a first step towards disentangling the factors associated to the generation of radical invention, that is, to fundamental knowledge advances that, eventually, might lead to a paradigm shift. Although further research is needed to enrich our findings, we can offer some conclusions. First, public research is linked to the probability of an invention being radical in different ways, depending on the type of novelty on which the radical invention is built and the type of public research outcome. Second, the relationship between radical invention and public science is heterogeneous across sectors and is more prevalent in those sectors that patent more and produce a higher share of radical inventions. Some policy indications can be derived from these findings, although this paper does not directly test any relationship between public policy toward university-industry technology transfer and the generation of radical inventions. In particular our results indicate that pushing universities to patent their inventions – as all European economies did since the Nineties – will lead to an increase in radical inventions only in the chemistry sector. Conversely the contribution of open science scientific output is related to an increase in radical inventions both in the chemistry and in the mechanical engineering sectors. Finally we also noted that the share of public patents is quite low: the lion's share of the radical inventive activity embodied in patents is confined to the private sector.

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