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The scientific influence of nations on global scientific and technological development

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ABSTRACT

Determining how scientific achievements influence the subsequent process of knowledge creation is a fundamental step in order to build a unified ecosystem for studying the dynamics of innovation and competitiveness. Relying separately on data about scientific production on one side, through bibliometric indicators, and about technological advancements on the other side, through patents statistics, gives only a limited insight on the key interplay between science and technology which, as a matter of fact, move forward together within the innovation space. In this paper, using citation data of both research papers and patents, we quantify the direct influence of the scientific outputs of nations on further advancements in science and on the introduction of new technologies. Our analysis highlights the presence of geo-cultural clusters of nations with similar innovation system features, and unveils the heterogeneous coupled dynamics of scientific and technological advancements. This study represents a step forward in the buildup of an inclusive framework for knowledge creation and innovation.

1. Introduction

Developing a comprehensive conceptual framework capturing the emergent properties of the knowledge creation process requires, as building blocks, quantitative indicators providing insights into the structure and dynamics of innovation systems. In this respect, numerous metrics for the impact of scientific research based on publication outputs exist in the literature—see Waltman (2016) for a recent overview of the field. Similar (yet less refined) indicators for technological development based on patent data have been introduced as well (Kürtössy, 2004; Nagaoka, Motohashi, & Goto, 2010). However, the majority of these metrics focus on either scientific or technological activities separately. Nevertheless, any effort for a thorough understanding of the innovation system cannot leave out of consideration the interactions between scientific and technological developments. Indeed, all of the recent models of knowledge production—from the "Mode 2" model (Gibbons et al., 1994) and the National Innovation System view (Lundvall, 1988) to the Triple Helix models (Etzkowitz & Leydesdorff, 2000)—involve non-academic forces shaping the scientific process, and identify different actors and stakeholders of scientific production (Firms, State) mostly involved with the spillovers of scientific work on innovation and economic performances. In this paper we focus on specific aspects of the knowledge transfer process, namely those within science and from science to technology, at the country-level. To this end, we propose two bibliometric indicators based on citations that journal research papers receive from other papers as well as from patents.

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Most of the standard bibliometric impact indicators for science are indeed based on the analysis of the citations received by scientific publications from other journal papers (Waltman, 2016). The underlying assumption that citations actually reflect scientific importance, and as such are appropriate to measure scientific impact, is controversial. Many scientometricians agree on the fact that "citing behavior is not motivated solely by the wish to acknowledge intellectual and cognitive influences of colleague scientists, since the individual studies reveal also other, in part non-scientific, factors that play a part in the decision to cite" (Bornmann & Daniel, 2008)—such as improper citation practices like boosting self or friend's citations, or satisfying referees (Werner, 2015). Citing also appears to be understood as a non-trivial psychological process (Nicolaisen, 2007). Thus, overall there is a large consensus on the fact that citations cannot provide an "ideal" monitor on scientific performance at a statistically low aggregation level (*e.g.*, individual researchers), but that they can yield a strong indicator of scientific performance when considered at the level of large group of researchers and over a long period of time (van Raan, 2005). In any event, by relying only on citations within research papers, scientific impact metrics can only assess how much a given scientific achievement is relevant for the community of researchers, neglecting its potential influence on other research and development (R&D) areas.

In this respect, references to research papers listed in patents as *prior art* can be used to assess the importance of scientific research on technology outputs (Callaert, Van Looy, Verbeek, Debackere, & Thijs, 2006). The mainstream approach (Narin, 2000; Narin, Hamilton, & Olivastro, 1997) is to compute the *science intensity* parameter, namely the average number of references to scientific literature per patent. While originally intended to characterize the scientific base of a company's patent portfolio, this indicator has been subsequently used for discovering the value of scientific research and forecasting future disruptive technologies. However, whether patent citations to papers reflect a flow of knowledge from science to technology is an even more debated issue than for paper citations. In fact, references in the scientific literature are added by the authors, supposedly to acknowledge existing work on which the article builds (with the exceptions outlined above). References in patents on the other hand have a precise legal function (Callaert et al., 2006): "they are brought by the applicant/inventor to the attention of examiners, who ultimately decide which references are relevant to evaluate novelty and inventiveness, to qualify the claims made in the patent, and at last to decide on granting".[1] Inventors opinions on the meaning of patent references to papers, collected in a recent survey (Callaert, Pellens, & Van Looy, 2014), suggest that while about one-third of patents that were inspired by scientific knowledge do not contain any scientific references, half of actual scientific references are evaluated at least as important (*i.e.*, having directly contributed to the inventive process), and only 10% as not important (see Table 6 therein). Despite other issues affecting patent citation data, such as the difference between patent offices practices (Nelson, 2009), these and others observations suggest that patent citations to papers can be considered an indicator of the relevance of scientific findings for assessing and contextualizing technology development—especially at large aggregation scales of analysis (Harhoff, Scherer, & Vopel, 2003; Jaffe, Trajtenberg, & Fogarty, 2000; Roach & Cohen, 2013; Tussen et al., 2000; Van Looy et al., 2003; Verbeek et al., 2002).[2]

Notably, various studies (Callaert et al., 2014; Meyer, 2000a, 2000b; Narin et al., 1997) conclude that interactions between science and technology are much more complex (and reciprocal) than a linear model of knowledge flow would suggest. Indeed, scientific and technological activities mutually benefit from such interactions: patent-cited papers perform better in terms of standard bibliometric indicators (Meyer, Debackere, & Glänzel, 2010), and patents that cite journal research articles receive more citations—possibly because their influence diffuses faster in time and space (Sorenson & Fleming, 2004). Recently, Ahmadpoor and Jones (2017) corroborated these observations using the network of references listed in papers and patents, which also allows to quantify the descriptors around basic and applied scientific research. Besides giving insights on specific knowledge creation patterns, citation-based indicators can also offer a broader and more systematic view on science-technology relations, potentially addressing policy relevant issues on how to efficiently shape national innovation systems. Indeed, when performed at the level of nations, *science intensity* has been often compared to technological productivity (*i.e.*, number of patents per capita), finding a positive relation in specific technological fields (biotechnology, pharmaceuticals, organic fine chemistry and semiconductors) (Van Looy et al., 2003; Van Looy, Magerman, & Debackere, 2007; Verbeek, Debackere, & Luwel, 2003). In particular, *science intensity* appears to be relevant for scientific sectors having a sufficient body of knowledge (Tamada, Naito, Kodama, Gemba, & Suzuki, 2006).

As outlined above, in this work we add to the current discussion with the research aim of measuring and comparing the influence that the publication output of national scientific systems has on the global scientific and technological knowledge development. To task, we use two refined bibliometric indicators, based on citation that research papers accrued either from other papers or from patents. The first indicator, which we introduced in a previous work (Cimini, Zaccaria, & Gabrielli, 2016) in line with standard bibliometric impact metrics, is the average number of papers citations received by research articles

[1] A limited number of studies explicitly consider the motivations for patent inventors/examiners to cite scientific literature. Grupp and Schmoch (1992) identify a number of reasons: the limited availability of patents describing prior art due to the fast development of certain technology fields; the examiner's willingness to cite scientific literature; the influence of other actors (such as inventor's colleagues and attorneys) in the patent shaping process. Meyer and Persson (1998) observe that citations to scientific literature found in patents provide relevant background information, whereas, Tussen, Buter, and van Leeuwen (2000) claim that such citations represent genuine, direct, observable links between research and technical inventions. Sternitzke (2009) suggests that scientific references in patents qualify the inventive step rather than novelty, while Roach and Cohen (2013) argue that they reflect knowledge originating from public research.

[2] The inverse feedback, namely the influence of technology on science, has been proxied using patents cited by scientific publications (Glänzel & Meyer, 2003; Hicks, 2000), which have however a less clear interpretation than references in the opposite direction (Bar-Ilan, 2008).