



## Regular article

# Unraveling the dynamics of growth, aging and inflation for citations to scientific articles from specific research fields



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## ABSTRACT

We analyze the time evolution of citations acquired by articles from journals of the American Physical Society (PRA, PRB, PRC, PRD, PRE and PRL). The observed change over time in the number of papers published in each journal is considered an exogenously caused variation in citability that is accounted for by a normalization. The appropriately inflation-adjusted citation rates are found to be separable into a preferential-attachment-type growth kernel and a purely obsolescence-related (i.e., monotonously decreasing as a function of time since publication) aging function. Variations in the empirically extracted parameters of the growth kernels and aging functions associated with different journals point to research-field-specific characteristics of citation intensity and knowledge flow. Comparison with analogous results for the citation dynamics of technology-disaggregated cohorts of patents provides deeper insight into the basic principles of information propagation as indicated by citing behavior.

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## 1. Introduction

Peer-reviewed publications in scientific journals and patents issued by the national patent offices both serve to codify and document knowledge advances. To delineate clearly the reported scientific (technological) progress that has been achieved by the authors (inventors), citations to prior work (art) are necessary. While the detailed mechanisms and motivations governing the use of citations to scientific articles (Bornmann & Daniel, 2008; Garfield, 2006; Garfield & Sher, 1963) are generally different from those applying to patents (Cotropia, Lemley, & Sampat, 2013; Hall, Jaffe, & Trajtenberg, 2002; Jaffe & de Rassenfosse, 2017; Jaffe, Trajtenberg, & Fogarty, 2000), all citing behavior is widely believed to be indicative of, at least some kind of, knowledge flow or information transfer. Furthermore, both for scientific articles and patents, citations are considered to be a (more or less noisy) proxy measure of impact (Garfield, 2006; Griliches, 1990; Hall, Jaffe, & Trajtenberg, 2005; Lane, 2010; von Wartburg, Teichert, & Rost, 2005). This has motivated the quantitative study of citations, especially their distributions across suitably defined cohorts (Golosovsky, 2017; Price, 1965; Radicchi & Castellano, 2011; Radicchi, Fortunato, & Castellano, 2008; Redner, 1998, 2005; Seglen, 1992; Sheridan & Onodera, 2017; Stringer, Sales-Pardo, & Amaral, 2010; Valverde, Solé, Bedau, & Packard, 2007; Vieira & Gomes, 2010; Waltman, van Eck, & van Raan, 2012), as well as the dynamics of how citations are acquired over time (Avramescu, 1979; Colavizza & Franceschet, 2016; Csárdi, Strandburg,

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Zalányi, Tobochnik, & Érdi, 2007; Della Briotta Parolo et al., 2015; Glänzel, 2004; Golosovsky & Solomon, 2012, 2017; Higham, Governale, Jaffe, & Zülicke, 2017; Pan, Petersen, Pammolli, & Fortunato, 2016; Price, 1976; Redner, 2005; Scharnhorst, Börner, & van den Besselaar, 2012; Simkin & Roychowdhury, 2007; Valverde et al., 2007; Wang, Song, & Barabási, 2013; Yin & Wang, 2017). The ultimate goal of such investigation is the establishment of a basic generative model that captures the fundamental mechanisms governing citation dynamics and can thus reproduce the empirically observed time evolution and general statistical properties of citation accrual. Ideally, a properly validated model would be applicable to inform rational science and innovation policies (Lane, 2010).

Recent progress towards realistic, and potentially predictive, descriptions of citation dynamics (Csárdi et al., 2007; Golosovsky & Solomon, 2012, 2017; Higham et al., 2017; Pan et al., 2016; Redner, 2005; Valverde et al., 2007; Wang et al., 2013) has capitalized on advances in complex-network theory (Albert & Barabási, 2002; Dorogovtsev & Mendes, 2002; Newman, 2003). In particular, the concept of preferential attachment (PA) (Barabási & Albert, 1999; Dorogovtsev, Mendes, & Samukhin, 2000; Kravivsky & Redner, 2001) governing the rate at which citations are distributed has been very influential almost from the beginning (Price, 1976). However, the fruitful application of PA to understand citation behavior is predicated on the understanding of two other basic temporal influences: obsolescence and overall growth of research fields. Here we understand *obsolescence* to be reflected in the tendency for the citation rate to articles or patents to decay over time because of their reduced relevance for ongoing knowledge generation. Acting in parallel to the basic trend towards obsolescence, the overall growth of research fields provides another important mechanism that influences the rate at which citations are acquired. Empirical studies have observed a steady increase over time in the production of scientific articles (Price, 1965; Sinatra, Deville, Szell, Wang, & Barabási, 2015) and patents (Hall et al., 2002). As every article and patent will generally have to cite the knowledge stock that is current at the time of their creation, an increase in article and patent production will likely lead to an increase in the rate at which prior work is cited. The need for a careful disentangling of obsolescence and *citation inflation* due to growth was discussed early on, both for scientific articles (Egghe & Rousseau, 2000) and patents (Hall et al., 2002). The most widely adopted method to address growth consists of introducing normalization factors based on citation counts (Radicchi & Castellano, 2011; Radicchi et al., 2008; Wang et al., 2013; Yin & Wang, 2017), which is partly a result of the desire to find robust bibliometric impact measures for individual authors or institutions.

Here our motivation is different. We are interested in characterizing the *intrinsic* dynamics of knowledge generation and propagation that can be revealed by citation behavior if purely exogenous factors such as changes in article and patent productivity are appropriately accounted for. Our approach is inspired by its success in the context of patent-citation dynamics (Higham et al., 2017) and also a recent study (Šubelj & Fiala, 2017) where normalization by the number of articles published per year led to the observation of universal citation distributions for a large body of articles from physics and computer science, respectively. Furthermore, exponential growth was used as one ingredient in a successful network-model simulation of citations to scientific articles (Wang et al., 2013). Similar to our previous work on patents (Higham et al., 2017), we analyze citations within different research fields/subfields of physics as defined by the scope of individual journals published by the American Physical Society. The obtained journal-specific characteristics for the PA mechanism and obsolescence function are indicative of special features associated with knowledge generation and propagation in different physics-researcher communities.

## 2. Data, methods and results

The bibliometric and citation data set used in our work is provided by the American Physical Society (APS) and, in its entirety, consists of article metadata and citation pairs dating back to 1893 (American Physical Society, 2017). The subset of this data set that we focus on here are the cohorts of articles published in the year 2000<sup>1</sup> in the research-field-specific APS journals Physical Review A, B, C, D, and E (from this point onwards abbreviated as PRA, PRB, etc.), as well as the APS's multidisciplinary-physics letters journal Physical Review Letters (PRL). Citation rates are measured using all citation pairs whereby the cited article in one of these cohorts is linked to a citing article published in the years 2000–2015 in any APS journal. Table 1 provides an overview of the journal-specific article cohorts, with citation-number totals and other relevant citation-related statistical information. For all of the specialized journals (i.e., PRA–E), the fraction of citations originating from articles published in the same journal is quite high, justifying our approach to use these journals to be representative of different research fields. As expected, this is not the case for the multi-disciplinary letters journal PRL, which we include in our study as a benchmark for useful comparison.

To be able to separate the various mechanisms that together determine the rate at which citations are gained by scientific articles, we first devise a procedure to account for temporal variations in citeability arising from purely exogenous driving forces. Both the number of articles produced and the average number of citations made by each article vary over time (Pan et al., 2016; Radicchi & Castellano, 2011; Sinatra et al., 2015; Wang et al., 2013). In the long term, the combined effect of these factors causes a citation inflation that can mask the trend of obsolescence. In this work, we consider the changing rate at which articles are published an exogenous factor, as such changes in research productivity can be expected to be largely

<sup>1</sup> Our choice of this particular year constitutes a compromise between us capitalising on the increase over time in publication rates to maximise the article-cohort sizes while, at the same time, keeping a large-enough time window for articles to garner citations and facilitate the reliable observation of citation growth and obsolescence.

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