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RESEARCH ARTICLE

Co-citations in context: disciplinary heterogeneity is relevant

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ABSTRACT

Citation analysis of the scientific literature has been used to study and define disciplinary boundaries, to trace the dissemination of knowledge, and to estimate impact. Co-citation, the frequency with which pairs of publications are cited, provides insight into how documents relate to each other and across fields. Co-citation analysis has been used to characterize combinations of prior work as conventional or innovative and to derive features of highly cited publications. Given the organization of science into disciplines, a key question is the sensitivity of such analyses to frame of reference. Our study examines this question using semantically-themed citation networks. We observe that trends reported to be true across the scientific literature do not hold for focused citation networks, and we conclude that co-citation analysis requires a contextual perspective.

INTRODUCTION

Citation and network analysis of scientific literature reveals information on semantic relationships between publications, collaboration between scientists, and the practice of citation itself (de Solla Price, 1965; Garfield, 1955; Newman, 2001; Patience, Patience, Blais, & Bertrand, 2017; Shi, Leskovec, & McFarland, 2010). Co-citation, the frequency with which two documents are cited together in other documents provides additional insights, including the identification of semantically related documents, fields, specializations, and new ideas in science (Boyack & Klavans, 2010; Marshakova-Shaikevich, 1973; Small, 1973; Zuckerman, 2018).

Uzzi, Mukherjee, Stringer, and Jones (2013) used a novel approach for co-citation analysis to characterize a subset of highly cited articles with respect to both novel and conventional combinations of prior research. The frequency with which references were co-cited in 17.9 million articles and their cited references from the Web of Science (WoS) was calculated and expressed as journal pair frequencies (observed co-citation frequencies). Expected co-citation values were generated from Monte Carlo simulations under a random graph model. Observed frequencies were then normalized (shifted and scaled) to averaged expected values from ten simulations and termed as *z-scores*. Consequently, every article was associated with multiple z-scores corresponding to co-cited journal pairs in its references. For each article, positional statistics of z-scores were calculated to set thresholds for

a binary classification of conventionality using the median z-score of an article and novelty using the tenth percentile of z-scores within an article. Thus, HCLN would denote high conventionality (HC) and low novelty (LN), with all four combinations being possible. The authors observed that HCHN articles were twice as likely to be highly cited, suggesting that novel combinations of ideas flavoring a body of conventional thought were a feature of impact and that 'science follows a nearly universal pattern.'

Key to Uzzi *et al.*, is their random graph model and its underlying assumptions. The citation switching algorithm used to generate expected values from random substitutions is designed to preserve the number of publications, the number of references in each publication, the year of publication of both publications and references, and the disciplinary composition of the references cited in these publications. However, a critically important feature of the model is that all references published in the same year have equal probability of being cited by any given publication. Thus, in particular, subject matter and citation count do not impact the probability that the reference will be cited, so that a reference in quantum physics can be substituted, with equal probability, by a reference in quantum physics, quantum chemistry, classical literature, entomology, or anthropology. Such substitutions poorly model the disciplinary nature of scientific endeavor and citation behavior (Garfield, 1979; Klavans & Boyack, 2017; Moed, 2010; Wallace, Lariviere, & Gingras, 2012). In addition, under this random model, a reference cited over 100 times in a given year is selected with the same probability as a reference cited only once, which appears inconsistent with the power law or lognormal citation distributions described in the literature (Perline, 2005; Stringer, Sales-Pardo, & Amaral, 2010). Accordingly, model misspecification is likely to arise on account of the simulated values not modeling the empirical data very well.

A follow-up study by Boyack and Klavans (2014) explored the impact of discipline and journal effects on these definition of conventionality and novelty. While their study had some methodological differences in the use of Scopus data rather than WoS data, a smaller dataset, and a χ^2 calculation rather than Monte Carlo simulations to generate expected values of journal pairs, Boyack and Klavans noted strong effects from both disciplines and journals that were not reported by Uzzi et al. While they reported the trend that HCHN is more probable in highly cited papers, they observed that "only 64.4% of 243 WoS subject categories" in the Uzzi *et al.* study met the criterion of having the highest probability of hit papers in the HCHN category. Further, they observed that journals vary widely in terms of size and influence and that 20 journals accounted for nearly 15% of co-citations in their measurements. Lastly, they noted that three multidisciplinary journals accounted for 9.4% of all atypical combinations.

Despite different methods used to generate expected values, both of these key preceding studies (*vide supra*) measured co-citation frequencies across the scientific literature (the WoS superset) and normalized them without disciplinary constraints before subsequently analyzing disciplinary subsets. In other words, the concerns raised above about misspecification resulting from treating all references as equiprobable, independent of discipline, apply to Boyack and Klavans (2014) as well. We hypothesized that modifying the normalization to constrain references to be drawn only from the disciplinary citation subnetwork, rather than all of WoS, would reduce model misspecification. Consequently, we used keyword searches of the scientific literature to construct exemplar citation networks themed around academic disciplines: *applied physics, immunology, and metabolism*. Within these disciplinary frameworks, we calculated observed and expected co-citation frequencies using a refined random graph model and an efficient Monte Carlo simulation algorithm.

Our analyses, using multiple techniques, provides substantial evidence that constraining the reference substitutions to the disciplinary subnetwork reduces model misspecification compared to treating all substitutions within WoS as equiprobable. Furthermore, reanalyses of these three semantically-themed citation networks under the improved model reveals strikingly different trends than those observed by Uzzi *et al.* For example, while Uzzi *et al.* claimed that highly cited articles are more likely to be both HC and HN than expected, and that this trend held across all subdisciplines, we find that these trends vary with the subdiscipline so that no universal trends can be established. Specifically, HC remains highly correlated with highly cited articles in the immunology and metabolism datasets but not with applied physics, and HN is highly correlated with highly cited articles in applied physics but not with immunology and metabolism. Thus, disciplinary networks are different from each other, and trends that hold for the full WoS network do not hold for even large subnetworks (such as metabolism). Furthermore, we also found that the categories HC, HN, etc., demonstrating the highest percentage of highly cited articles are not robust with respect to varying thresholds for high citation counts or for highly novel citation patterns. Overall, our study, although limited to three disciplinary subnetworks, suggests that co-citation analysis that inadequately considers disciplinary differences, may not be very useful at detecting universal features of impactful publications.

MATERIALS AND METHODS

Bibliographic data

We have previously developed ERNIE, an open source knowledge platform into which we parse the Web of Science (WoS) Core Collection (Keserci, Davey, Pico, Korobskiy, & Chacko, 2018). WoS data stored in ERNIE spans the period 1900-2019 and consists of over 72 million publications. For this study, we generated an analytical dataset from years 1985 to 2005 using data in ERNIE. The total number of publications in this dataset was just over 25 million publications (25,134,073), which were then stratified by year of publication. For each of these years, we further restricted analysis to publications of type Article. Since WoS data also contains incomplete references or references that point at other indexes, we also considered only those references for which there were complete records (Table 1). For example, WoS data for year 2005 contained 1,753,174 publications, which after restricting to type Article and considering only those references described above resulted in 916,573 publications, 6,095,594 unique references (set of references), and 17,167,347 total references (multiset of references). Given consistent trends in the data (Table 1), we analyzed the two boundary years (1985 and 2005) and the mid-point (1995). We also used the number of times each of these articles was cited in the first 8 years since publication as a measure of its impact.

We constructed three disciplinary datasets in areas of our interest based on the keyword searches: immunology, metabolism, and applied physics. For the first two, rooted in biomedical research, we searched Pubmed for the term 'immunology' or 'metabolism' in the years 1985, 1995, and 2005 (Table 2). Pubmed IDs (pmids) returned were matched to WoS IDs (wos_ids) and used to retrieve relevant articles. For the applied physics dataset, we directly searched traditional subject labels in WoS for 'applied physics.' While applied physics and immunology represent somewhat small subnetworks (roughly 2-6% of WoS), metabolism represents approximately 22% of WoS, making them interesting and meaningful test cases. We also examined publications in the five major research areas in the Web of Science: life sciences & biomedicine, physical sciences, technology, social sciences, and arts

Table 1. Summary of base WoS Analytical Dataset. The number of unique publications of type Article, unique references (UR), total references (TR), and the ratio of total references to unique references increases monotonically with each year indicating that both the number of documents and citation activity increase over time. Only publications of type Article with at least two references and references with complete publication data were included.

year	Unique Publications	Unique References (UR)	Total References (TR)	TR/UR
1985	391,860	2,266,584	5,588,861	2.47
1986	402,309	2,316,451	5,708,796	2.46
1987	412,936	2,427,347	5,998,513	2.47
1988	426,001	2,545,647	6,354,917	2.50
1989	443,144	2,673,092	6,749,319	2.52
1990	458,768	2,827,517	7,209,413	2.55
1991	477,712	2,977,784	7,729,776	2.60
1992	492,181	3,134,109	8,188,940	2.61
1993	504,488	3,278,102	8,676,583	2.65
1994	523,660	3,458,072	9,255,748	2.68
1995	537,160	3,680,616	9,875,421	2.68
1996	663,110	4,144,581	11,641,286	2.81
1997	677,077	4,340,733	12,135,104	2.80
1998	693,531	4,573,584	12,728,629	2.78
1999	709,827	4,784,024	13,280,828	2.78
2000	721,926	5,008,842	13,810,746	2.76
2001	727,816	5,203,078	14,261,189	2.74
2002	747,287	5,464,045	15,001,390	2.75
2003	786,284	5,773,756	16,024,652	2.78
2004	826,834	6,095,594	17,167,347	2.82
2005	886,648	6,615,824	19,036,324	2.88

& humanities, using the extended subcategory classification of 153 sub-groups to categorize disciplinary composition of cited references in the datasets we studied.

Table 2. Disciplinary Datasets. PubMed and WoS were searched for articles using search terms, 'immunology', 'metabolism', and 'applied physics.' Counts of publications are shown for each of the three years analyzed and expressed in parentheses as a percentage of the total number of publications in our analytical WoS dataset (Table 1) for that year. Note that Applied Physics and Immunology each represent about 4% of the publications in WoS, but Metabolism occupies nearly one-fourth of WoS.

Year	Applied Physics	Immunology	Metabolism
1985	10,298 (2.7%)	21,606 (5.5%)	78,998 (20.2%)
1995	21,012 (3.9%)	29,320 (5.5%)	121,247 (22.6%)
2005	35,600 (4.0%)	37,296 (4.2%)	200,052 (22.6%)

Monte Carlo simulations, normalization of observed frequencies, annotations, and 'hit' papers

We performed analyses on publications from 1985, 1995, and 2005. Building upon prior work (Uzzi et al., 2013), all $\binom{n}{2}$ reference pairs were generated for each publication, where n is the number of cited references in the publication. These reference pairs were then mapped to the journals they were published in using ISSN numbers as identifiers. Where multiple ISSN numbers exist for a journal, the most frequently used one in the WoS was assigned to the journal. In addition, publications containing fewer than two references were discarded. Journal pair frequencies were summed across the dataset to create observed frequencies (F_{obs}).

For citation shuffling, we developed a performant citation switching algorithm, *runtime enhanced permuting citation switcher (repcs)* (Korobskiy, Davey, Liu, Devarakonda, & Chacko, 2019), that randomly permuted citations grouped by year of publication to switch citations

while preserving the year of publication for both articles and references, the number of publications and the number of references in each dataset and the disciplinary composition of the references in each dataset. In implementing this approach, our approach differs from the approach in Uzzi et al. (2013), in the following ways (i) we sampled citations proportional to their citation frequency (equivalently, from a multiset rather than a set) in order to better reflect citation practice, (ii) we permitted a substitution to match the original reference in a publication when the random selection process dictated it rather than attempting to enforce that a different reference be substituted, and (iii) we introduced an error correction step to delete any publications that accumulated duplicate references during the substitution process. As a benchmark, we used the citation switching algorithm of Uzzi et al. (2013), henceforth referred to as *umsj* (as also done in Boyack and Klavans (2014)), using code kindly provided by the authors. A single comparative analysis showed that while 10 simulations of the WoS 1985 dataset (391,860 publications) completed in 2,186 hours using the *umsj* algorithm, it completed in less than one hour using the our implementation of the *repcs* algorithm on a Spark cluster. We also tested *repcs* under comparable conditions to *umsj* and estimated a runtime advantage of at least two orders of magnitude. Using either the *repcs* or *umsj* algorithms for 10 simulations resulted in expected value coverage of 75% of the observed journal pair frequencies. Subsequent rounds of development and testing resulted in 99% coverage of observed journal pairs when 1,000 simulations were conducted. The runtime advantage was significant enough that we chose to use the *repcs* algorithm in our study and generated expected values averaged from 1,000 simulations for improved coverage of every dataset we analyzed.

Averaging the result of 1,000 simulations for each dataset studied, z-scores were then calculated for each journal-pair using the formula $(F_{obs} - F_{exp})/\sigma$ where F_{obs} is the observed frequency, F_{exp} is the averaged simulated frequency, and σ is the standard deviation of the simulated frequencies for a journal pair. As a result of these calculations, each publication becomes associated with a set of z-scores corresponding to the journal pairs derived from pairwise combinations of its cited references. Positional statistics of z-scores were calculated for each publication, which was then labeled according to conventionality and novelty: (i) HC if the median z-score exceeded the median of median z-scores for all publications and LC if the median z-score was equal to or less than the median of median z-scores for all publications, and (ii) HN if the tenth percentile of z-scores for a publication was less than zero, and LN if the tenth percentile of z-scores for a publication was greater than zero.

To consider the relationship between citation impact, conventionality, and novelty we calculated percentiles for the number of accumulated citations in the first 8 years since publication for each article we studied and stratified. We also investigated multiple definitions of hit articles with hits defined as the 1%, 2%, 5%, and 10% top-cited articles. Also, mention different thresholds, 1st and 10th, for novelty threshold.

RESULTS

Model Misspecification and the Attributes of Disciplinary Context

A source of misspecification in the Uzzi *et al.* model arises from not accounting for disciplinary heterogeneity by treating all references as equiprobable substituents. Under this model, the probability of replacing a reference in one discipline by another reference in a second discipline is identical to the proportion of the articles in WoS that from the second discipline. If the Uzzi *et al.* model accurately reflects citation practice, the expected propor-

tion of references within papers published in a given discipline D would be equal to the proportion of references in D, and conversely, the degree to which the proportion deviates from the expected value would reflect the extent of model misspecification.

To study the disciplinary composition of references in our custom datasets, we first used the high level WoS classification of five major research areas: life sciences and biomedicine, physical sciences, social sciences, technology, and arts and humanities. The two largest of these research areas are physical sciences and life sciences and biomedicine, which contribute on average approximately 35.1% and 62.8%, respectively, of the references in WoS over the three years of interest. While there is some variability over the years, according to the Uzzi *et al.* model, we would expect close to 35.1% of the references cited by the publications in any large network to be drawn from the physical sciences and roughly 62.8% of the references to be drawn from the life sciences and biomedicine. Yet the empirical data present a very different story: 79.6% of the references cited in physical sciences publications are from the physical sciences and 89.9% of the references cited in life sciences and biomedicine publications are from the life sciences and biomedicine. In other words, the empirical data shows a strong tendency of publications to cite papers that are in the same major research area rather than in some other research area. Thus, there is a strong bias towards citations that are *intra-network*. Our observations are in agreement with Wallace et al. (2012) who found that, often, a majority of an article's citations are from the specialty of the article, even though that percentage varied among disciplines in the eight specialties they investigated (from approximately 39% to 89% for 2006). Furthermore, these findings argue that a discipline-indifferent random graph model would exhibit misspecification (in deviating substantially from the empirical data), and supports the concern about definitions of innovation and conventionality that are based on deviation from expected values.

We also analyzed disciplinary composition at a deeper level of the 153 Subjects in WoS extended classification and examining the consequences of citation shuffling within a disciplinary set or all of the Web of Science. References in publications belonging to these three datasets were classified into 153 subject areas and summarized as a frequency distribution. A single shuffle of the references in these datasets or all the references in the corresponding WoS year slice was performed, using either the *repcs* or *umsj* algorithms, after which subject frequencies were computed again. The fold change in subject frequencies of references before and after shuffling was calculated for these groups using all 153 subject categories and are summarized as boxplots in Fig 1. For example, the applied physics dataset contained one reference labeled Genetics and Heredity, but after the shuffle (using the WoS background), there were 1496 references labeled Genetics and Heredity. Similarly, the metabolism dataset contained one reference labeled Philosophy, but after a single shuffle (again using the WoS background), there were 661 occurrences with this label. The data show convincingly that the disciplinary composition of references in a network is preserved when citation shuffling is constrained to the subnetwork, but is significantly distorted when the WoS superset is used as a source of substitution. A second inference is that the two algorithms, except for running time considerations, have equivalent effects in this experiment.

We tested the conjecture that model misspecification would be reduced by constraining the substitutions to disciplinary subnetworks by examining the Kullback-Leibler (K-L) Divergence (Kullback & Leibler, 1951) between observed and predicted citation distributions, restricted to the set of journals in a given disciplinary subnetwork. The results (Table 3) confirm this prediction: simulations under the constrained model (which constrains substitutions to the disciplinary subnetwork) consistently have a lower K-L divergence compared

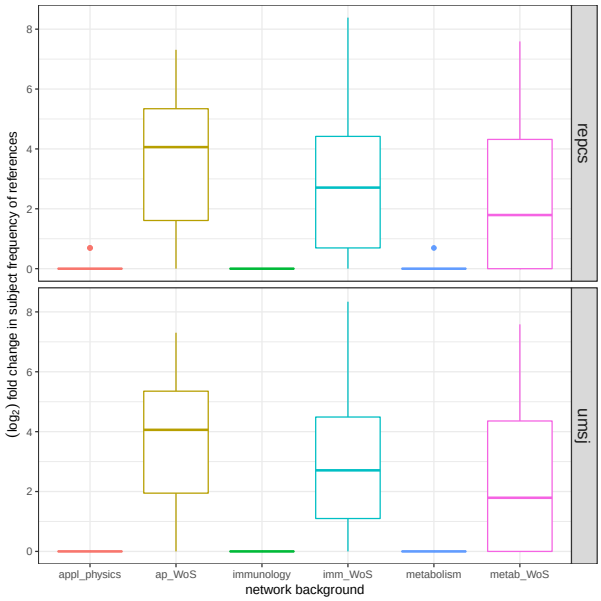


Figure 1. Intra-network citation shuffling preserves the disciplinary composition of references. Publications of type Article belonging to the three disciplinary networks (Applied Physics, Immunology, and Metabolism) were subject to a single shuffle of all their cited references using either the cited references in these networks as a source of random substitutions (bg_local) or references from all articles in WoS (bg_allWoS). Citation shuffling was performed using either our algorithm (*repcs*) or that of Uzzi et al. (*umsj*). The disciplinary composition of cited references before and after shuffling was measured as frequencies for each of 153 subdisciplines (from the extended subject classification in WoS) and expressed as a fold difference between citation counts grouped by subject for original (o) and shuffled (s) references using the formula (fold_difference = $ifelse(o > s, o/s, s/o)$) and rounded to the nearest integer. A fold difference of 1 indicates that citation shuffling did not alter disciplinary composition. Data are shown for articles published in 1985. All eight boxplots are generated from 153 observations each. Null values were set to 1. Note y-axis: log_2 scale.

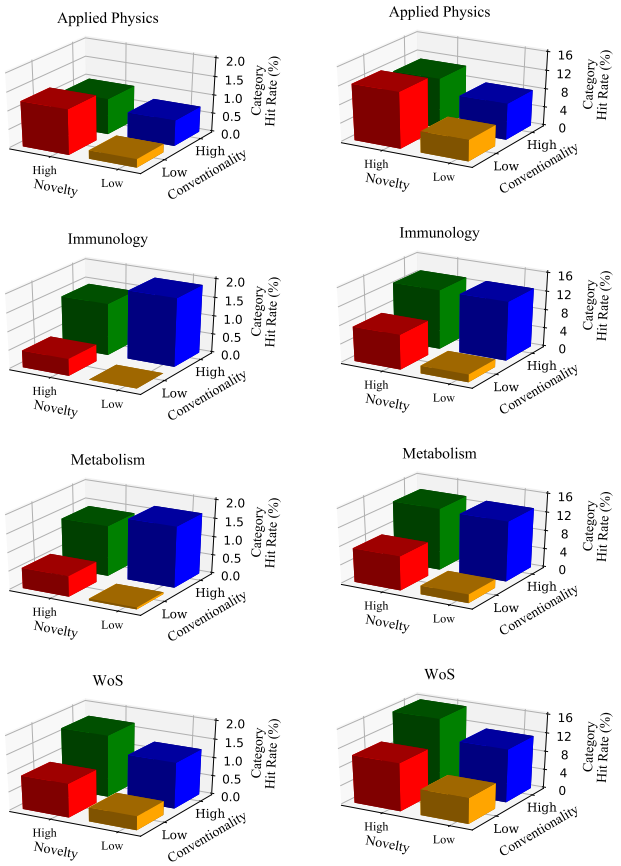
Table 3. Model misspecification is reduced by constraining substitutions to disciplinary subnetworks. For the set of journal pairs in common between a disciplinary network and the full WoS dataset, Kullback-Leibler (K-L) divergences between empirical and simulated journal pair frequencies were computed for the years 1985, 1995, and 2005 for the three disciplinary datasets (applied_physics, immunology, and metabolism) using either the disciplinary network as background or the WoS superset (all_wos) to generate the null model (Background). K-L divergence was calculated using the R seewave package (Sueur et al., 2008). The reduction in K-L divergence between simulated and observed data shows that model misspecification is reduced by restricting the reference substitutions to the disciplinary subnetwork (our model), as compared to treating all substitutions within WoS as equiprobable.

Disciplinary Network	Year	Background	K-L Divergence	Ratio
appl_physics	1985	appl_physics	1.21	
	1985	all_wos	2.37	1.96
	1995	appl_physics	0.86	
	1995	all_wos	2.37	2.77
	2005	appl_physics	0.95	
	2005	all_wos	2.35	2.47
immunology	1985	immunology	0.75	
	1985	all_wos	1.68	2.24
	1995	immunology	0.78	
	1995	all_wos	1.70	2.19
	2005	immunology	0.73	
	2005	all_wos	1.92	2.63
metabolism	1985	metabolism	1.11	
	1985	all_wos	2.24	2.02
	1995	metabolism	1.07	
	1995	all_wos	2.33	2.17
	2005	metabolism	1.19	
	2005	all_wos	2.60	2.18

to simulations under the unconstrained model, where all references in WoS for a given year are equiprobable. Furthermore, the K-L divergence for the unconstrained model is generally twice as large as the K-L divergence for the models where the references are constrained to the disciplinary subnetworks (ratios range from 1.96 to 2.77, and are greater than 2.0 in eight out of nine cases). These results clearly demonstrate that constraining reference substitutions to the given disciplinary network better models the observed data.

Calculation of Novelty and Conventionality using the constrained model

Since the constrained model better fits the observed data, we evaluated the distribution of highly cited articles (i.e., "hit articles") in the four categories (HCHN, LCHN, HCLN, LCLN), for different thresholds for hit articles. Figure 2, Panels (a) and (b), compares hit rates for the four categories among the Immunology, Metabolism, Applied Physics, and WoS datasets for 1995, where the hit rate is defined as the number of hit articles in each category divided by the number of articles in the category. The calculation for the hit rates for the WoS dataset (bottom row, Figure 2) mirrors Uzzi et al.'s results, whereby the largest hit rates were for the HNHC category, despite our methodological changes in sampling citations in proportion to their frequency. However, the trends for all three disciplinary subnetworks are different from those for WoS. Specifically, the highest hit rates for the 1995 immunology and metabolism datasets are in the LNHC category for the top 1% of cited



(a) Top 1% of cited articles (b) Top 10% of cited articles

Figure 2. Effect of using the improved model on categorical hit rates for Immunology, Applied Physics, and WoS for 1995. Panels (a) and (b) show hit rates for the LNLC, LNHC, HNLC, and HNHC categories for the applied physics, immunology, metabolism, and WoS datasets when hit articles are defined as the top 1% and top 10% of articles, respectively. Novelty in both panels is defined at the 10th percentile of articles' z-score distributions. The results for the WoS data set mirror results from Uzzi et al. (2013), where the highest hit rate was for the HNHC category. Results for the three disciplinary subnetworks all differ from the overall WoS results: the highest hit rates for the immunology and metabolism datasets are in the LNHC category and the highest hit rate for the applied physics datasets are in the HNLC category. Need numbers for metabolism for the next sentence: The number of data points in the immunology, applied physics, and WoS data sets are 21,917, 18,305, and 476,288, respectively.

articles (and tied between LNHC and HNHC for the top 10%), and the highest hit rates for the 1995 applied physics datasets are in the HNLC category for both the top 1% and top 10% of all cited articles. Thus, the category exhibiting the highest hit rate (among highly cited papers) depends on the specific disciplinary network and to some extent on the threshold for being highly cited. Furthermore, the categories displaying the greatest hit rate vary to some extent with the year (data not shown).

I did not review the next two paragraphs. I did–JRB

We evaluated the statistical significance of the categorical hit rates using multiple methods. Our first test was based on the null hypotheses that hits were distributed randomly among the four categories with uniform probability in proportion to the number of articles in each category. Rejecting the null hypothesis, using a Chi-Square Goodness of Fit test, supports a non-uniform dispersion of hits with some of the four categories being associated with higher or lower than expected expected hit rates. The null hypothesis was rejected at a $p < 0.001$ in all cases in Figure 2, with the exception of the immunology and applied physics datasets where hit articles are designated as the top 1% of articles: valid tests were not possible in those instances due to too few expected hits. The null hypothesis was rejected with $p < 0.001$ for all valid tests for all parameter settings, all datasets, and all years: hypotheses tests were valid in 73 of 96 instances. We conclude that it is likely that the distribution of hits among categories is not uniform and that, instead, hit rates vary among the categories in all datasets.

We also tested the explanatory power of each framework dimension by classifying articles as LN or HN and, separately, as LC or HC. We tested the null hypothesis that hits are distributed between LN and HN (LC and HC) in proportion to the total number of articles assigned to those categories. That null hypothesis was rejected for the WoS data along both dimensions. Consistent with the findings in Uzzi et al. (2013), hit articles were overrepresented in the HC category in every instance of WoS data at a $p < 0.001$ and also overrepresented in the HN category at a $p < 0.001$ in all but two cases: the p-values in those exceptions were 0.002 and 0.007. Hits in the immunology and metabolism data were overrepresented in the HC category with the same statistical significance as for WoS. The relationship of novelty with hits in the immunology and metabolism data differed dramatically from the WoS, however, with statistically significant findings of hit articles being sometimes overrepresented in the LN category, and sometimes being underrepresented. In applied physics, hit articles were positively related with HN with a statistical significance of at least $p < 0.10$ in all 12 parameter sets, and at $p < 0.05$ in 10 of 12 cases. Furthermore, a strong positive relationship was found between LC and hit articles in applied physics in 5 of 12 instances with $p < 0.10$. These results suggest that (1) both conventionality and novelty are strongly related to hits in the WoS, (2) the conventionality dimension is strongly related with hits in immunology and metabolism and novelty is not, (3) novelty is more strongly related with hits in applied physics than is conventionality. More generally, we find that the dimensions most strongly related with hit articles vary between disciplinary and broad data sets, and also among disciplines.

DISCUSSION

needs to be expanded

Our study shows strong evidence that constraining the model to a disciplinary subnetwork reduces model misspecification. Furthermore, using the constrained model instead

of the unconstrained model to redefine high (or low) novelty and conventionality produces different trends, depending on the subnetwork. In particular, while Uzzi *et al.* found that highly cited papers were most likely to be in the HNHC category, this observation does not consistently hold when using the improved model. Instead, we find that conventionality flavored with novelty is *not* generally a feature of impactful research. In particular, high novelty (as defined by Uzzi *et al.*) is not always indicative of impactful research (as reflected in citation counts), as shown by both Immunology and Metabolism having their highest hit rates for low novelty (Figure 2). More generally, these results show that the conclusions of universal trends in highly cited papers may be the consequence of using a random model that has a poor fit to the observed data.

Placement and relevance to be determined. This paragraph is not yet well written... still working on it. We described concerns with model misspecification at the outset along two general dimensions: the background dataset and sampling methodology for the random graph. The differences we found from prior research in terms of which categories demonstrated the highest hit rates were caused both by using disciplinary datasets and our sampling methodology through the article z-score distributions. When z-scores are shifted downward using one algorithm versus another, for example, then the former algorithm can result in an increased percentage of HN articles. We thought it important to determine the extent to which each of our methodological differences contributed to our observations. We found that z-scores of 28.6% of the journal pairs changed signs with our sampling algorithm, for example, when computed with respect to the WoS dataset versus the immunology dataset. In contrast, 2.8% of z-scores changed signs in the WoS dataset depending on whether Uzzi et al.'s or our random model was used and x% z-scores changed signs in the case of the immunology dataset. Need to insert data for the immunology dataset here also for an apples-to-apples comparison. We conclude that the choice of background datasets is the source of a majority of differences we observed the categories demonstrating the highest hit rates, although our sampling approach, most notably sampling from a multiset so as to reflect the observed frequencies of individual citations as well as their associated journals and disciplines, can also create material differences.

Of relevance, we found the category displaying the highest hit rate to be sensitive to the study parameters, which are the percentage of articles classified as hits and the z-score percentile threshold that delineates LN and HN. (data not shown). This lack of robustness makes parameter selection of the utmost importance. However, the most appropriate definitions of novelty, conventionality, and hit articles in the framework that we have applied are not clear. More research might be done in that regard or, further, in investigating whether the current approach of defining novelty, conventionality, and impactful research sufficiently captures the complexity of the issue at hand.

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code used in this study is freely available from a Github site (Korobskiy et al., 2019). Access to the bibliographic data analyzed in this study requires a license from Clarivate Analytics, which had no role in funding, experimental design, review of results, and conclusions presented.

AUTHOR CONTRIBUTIONS

This study was designed by GC, JB, SD, and TW. Simulations and analysis were performed by AD, DLH, GC, JB, and SD. Infrastructure and workflows used to generate data used in this study were developed by AD, DK, SL, SD, and GC. All authors reviewed and commented on the manuscript, which was written by GC, JB, and TW.

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RESIDUAL

these remaining sentences require some work The varying citation patterns when sampling from a disciplinary-focused dataset versus a broader dataset due, was a cause of journal pair z-scores changing signs in 28.6% of instances: the effect of any one of these journal pairs on an article's novelty or conventionality is contradictory between broad and, more narrow disciplinary datasets. We contend that the interpretation due to a disciplinary dataset, which preserved citation patterns, is more appropriate and an improvement on current methods.

We addressed this consideration by analyzing disciplinary subsets of the scientific literature, thereby restricting random selection of references to only those references in the disciplinary network being studied. *What about z-scores?* We have conjectured that the approach of Uzzi et al. for generating journal-pair z-scores is misspecified in its sampling from a broad dataset and its disregard for the frequency with which journal pairs are citedOur principal consideration was to restrict model misspecification arising from disciplinarily irrelevant references. We addressed this consideration by analyzing disciplinary subsets of the scientific literature, thereby restricting random selection of references to only those references in the disciplinary network being studied.As observed in the Introduction, Monte Carlo simulations that use references from all publications do not account for observed citation practice (sentence needs to be made more eloquent)...

This paragraph needs work, but I wanted to create a placeholder for the introduction to this subsection. It uses some of the passages form the former Chacko subsection. . Like Uzzi et al., we also used a Monte Carlo approach to simulate under a random graph model, although our principal consideration was to restrict model misspecification arising from disciplinarily irrelevant references. We addressed this consideration by analyzing disciplinary subsets of the scientific literature, thereby restricting random selection of references to only those references in the disciplinary network being studied. In this subsection we demonstrate the effects of model misspecification or Uzzi et al.'s approach and the effectiveness of using disciplinary datasets in resolving the concomitant issues with the former.

Note also in Figure 4 that many z-scores values are significantly different between the WoS and Immunology datasets, although the density of points near the origin in Figure 4 indicates that some journal pairs change signs between the datasets while their magnitudes are not significantly different. While no metric is without downside, this observation points to a weakness of measuring novelty based simply on the sign of z-scores where no distinction is made between a small negative value and a large negative value, but a negative value of small magnitude is viewed as being significantly different than a small positive value.

We used the criteria of Uzzi to calculate normalized journal pair frequencies (z-scores) and classify publications according to conventionality and novelty. We observe that z-score calculations are sensitive to the background network (disciplinary or WoS). Figure 4 shows that the z-scores for the same journal pair can be positive (negative) when computed with respect to one data set but be negative (positive) for another data set. The journal-pair z-scores in Figure 4 have consistent signs for both Immunology and WoS data sets in 71.4% of the instances and different signs for 28.6% of the journal pairs. When a journal-pair z-score is negative with respect to one dataset and positive with respect to another dataset, articles citing that pair are more likely to be deemed novel in the first instance and less likely to be deemed novel in the second instance. It seems that any journal pair should either be indicative of novelty or not, but it should never have contradictory implications that

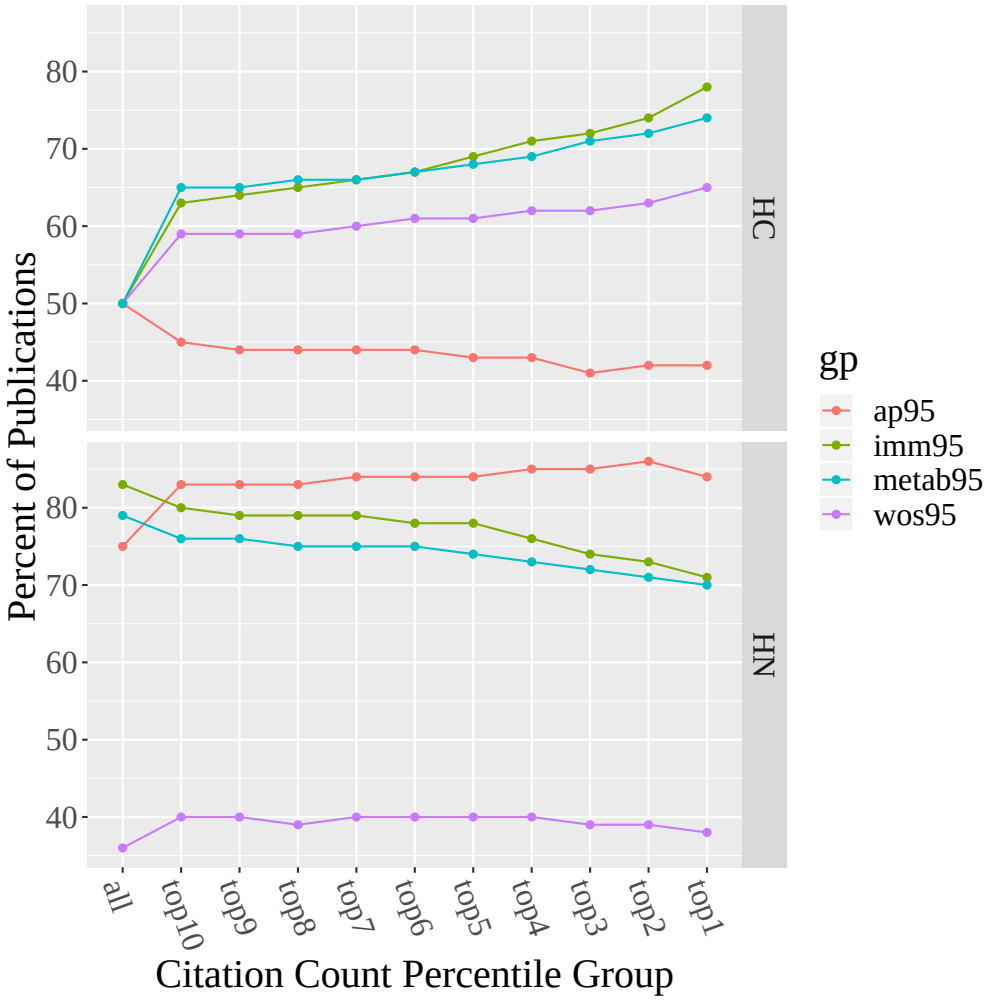

Figure 3. Effect of Research Discipline, Background Network, and Citation Count on Conventionality and Novelty. Data are shown for the applied physics (18,305), immunology (21,917), metabolism (97,405) and WoS (476,288) networks for 1995. The number of publications in each network is shown in parentheses. Citation counts shown are cumulative over the first 8 years since publication. X-axis: publications were classified into percentile groups based on citation counts (e.g., Top 1 indicates those publications in the top 1%). Y axis: The percent of applications in each group that are high conventionality (HC) and high novelty (HN). The z-scores are computed for each disciplinary network based on the selected background network; thus, *imm* denotes the immunology network with immunology z-scores and *imm_wos* denotes the immunology network with z-scores from WoS z-scores. The figure shows striking differences between the WOS network compared to the metabolism and immunology networks: across all networks, the percentage of high conventionality (HC) publications increases with citation counts, while the percentage of high novelty (HN) publications decreases with citation counts for the biological networks but not for WOS.

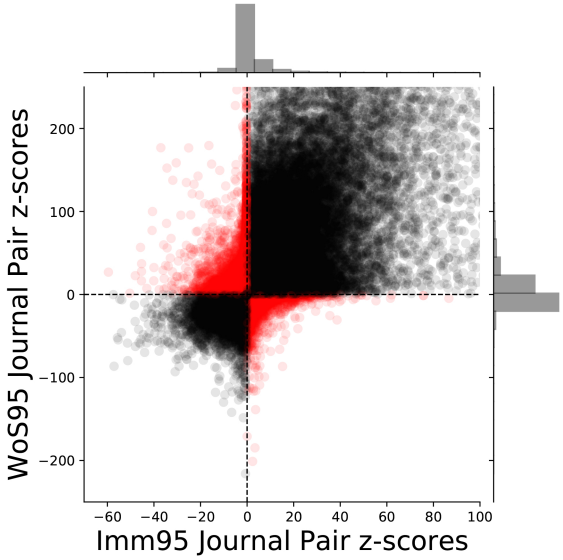

Figure 4. Journal pair z-scores vary with background network. Scatter plot points (319,005) indicate journal pair z-scores for the 1995 Immunology dataset with two different background networks: the x-axis is based on the local network (1995 Immunology) and the y-axis is based on the entire Web of Science network. Black indicates journal pairs whose z-scores have the same sign when computed for both background networks, while red points indicate the 28.6% of journal pairs whose z-scores change sign across networks. Regions with deeper hues indicate higher point densities.

depend on the reference dataset. We view, therefore, these contradictions as symptomatic of inappropriately sampling from a broad dataset and ignoring observed citation patterns. Figure 4 reflects that the WoS data set has approximately 44,000 fewer negative z-scores than does the immunology data set, which contributes to its significantly lower percentage of high-novelty articles. *The plots I made of the cumulative z-score distributions for Immunology and WoS also could be used to demonstrate this phenomenon, although the scatter plot does this more clearly, and it is more striking. The scatter plot also encodes more data, that is, the matched z-scores for each journal pair.*

The variation in z-scores with respect to the reference datasets causes the percentages of articles denoted as highly conventional and highly novel to be significantly different, as demonstrated in Figure 3. *Insert text about Figure 3.*

Table 4. Hit Rates by Category for the 1995 datasets. The last four columns indicate the proportion of publications that are hits for each respective category.

Data Set	Hits as % of Articles	Novelty Percentile	LNLC	LNHC	HNLC	HNHC
Imm95	1%	10%	0.000	0.019	0.005	0.014
Imm95	10%	10%	0.017	0.128	0.076	0.129
Metab95	1%	10%	0.001	0.017	0.006	0.014
Metab95	10%	10%	0.019	0.130	0.074	0.133
AP95	1%	10%	0.002	0.007	0.012	0.010
AP95	10%	10%	0.047	0.079	0.123	0.109
WoS95	1%	10%	0.004	0.013	0.009	0.017
WoS95	10%	10%	0.056	0.115	0.104	0.156