Does diversity of papers affect their citations? Evidence from American Physical Society Journals

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Abstract—In this work, we study the correlation between interdisciplinarity of papers within physical sciences and their citations by using meta data of articles published in American Physical Society's Physical Review journals between 1985 to 2012. We use the Weitzman diversity index to measure the diversity of papers and authors, exploiting the hierarchical structure of PACS (Physics and Astronomy Classification Scheme) codes. We find that the fraction of authors with high diversity is increasing with time, where as the fraction of least diversity are decreasing, and moderate diversity authors have higher tendency to switch over to other diversity groups. The diversity index of papers is correlated with the citations they received in a given time period from their publication year. Papers with lower and higher end of diversity index receive lesser citations than the moderate diversity papers.

Keywords-Diversity; PACS codes; Citation; interdisciplinarity;

I. INTRODUCTION

In the second half of the twentieth century many scientific disciplines became more interconnected. Scientists working in varied fields felt the need to connect with people across different disciplines to study phenomena which required insights and expertise from multiple fields [1]. This process has been accelerated in the last three decades as the advent of internet made people instantly discover the work done by other people world wide, and interact with people irrespective of their geographic location. Digital revolution has also enabled generation of enormous data on scientific articles published by various journals. This generated tremendous interest among scientists working in scientometric and bibliometric studies, to understand the evolution of scientific disciplines, measure the impact of articles through citation analysis, discover the pattern of scientific collaboration etc [2], [3], [4]. In recent years, many studies have focused on understanding the interdisciplinarity through variety of approaches [5], [6], [7], [8], and [9], but primarily using citation data and measures based on entropy, simpson index etc [10]. A recent special issue of Nature summarizes the work on measuring interdiscplinarity and tracks the trend in interdisciplinary work across different fields from 1950 onwards [11]. General conclusion has been that the interdisciplinary research is on the rise, especially since mid 1980's, they take time to have an impact and too much interdisciplinarity can decease the citations received.

Interdisciplinary work is characterized by the diversity of inputs from different fields that contribute to making it. Consequently measuring the diversity of paper (author) captures the degree of interdisciplinarity of work (person). Diversity measures can then be used to understand whether more diverse papers generate greater impact?, are authors who work in diverse research areas necessarily have better publication record with higher citations? Thanks to the availability of large data sets of journal papers, such questions can be addressed. For example: using DBLP database of computer science, Chakraborty et al. [12] studied the diversity of researcher's scientific publications to understand the features that lead to triumphant career, and using co-citation cluster analysis on electrochemistry journal database Schmidt et al. [13] studied dynamics of diversity across six different countries in electrochemistry. Diversity measures can be used to characterize behaviors of individuals in complex networks. Lu Liu et al. [14] gave an efficient algorithm to find the top-k diverse nodes on a dynamic network. Quan Shi et al. [9] found that local (global) diversity of authors in DBLP network tend to decay as an exponential (Gaussian) distribution. They also found that authors with more diverse social ties are more competitive. The interdisciplinarity in physical science research has been studied by Pan et al. using American Physical Society journals (APS) [15], and observed that over time from 1980's there is a steady increase in interactions between the different fields and subfields of Physics. Chakraborty et al. [16] developed supervised classification model to distinguish between core and interdisciplinary fields in DBLP database and studied their evolution and impact on the field. Using the APS Physical review database, Martin et al. [17] and Redner et al. [18] studied correlation between authorship and citation, and found that individuals cite their collaborators work more quickly compared to others work.

In this work, we study the interdisciplinarity of papers and authors using Weitzman diversity [19] measure on hierarchical structure of Physics and Astronomy Classification Scheme (PACS) codes of papers published in American Physical Society (APS) journals. We examine the relation between the diversity and citation of papers and authors. We discovered that papers with extreme low and high diversity receive low citations compared to papers with moderate diversity.

II. DATASET

The American Physical Society (APS) started publishing Physical Review journal from 1893. APS added other journals like Reviews of Modern Physics (1929), Physical Review Letters (1958), Physical Review A,B,C and D (1970), Physical Review E (1993) and most recently Physical Review X in 2011. In this paper we use all scientific papers published in APS Physical Review (PR) Journals (Physical Reviews A through E, Review of Modern Physics and Physical Review letters) from 1985 to 2012 to study diversity profile and citations. For each paper, the data set contains unique digital object identifier (DOI), paper title, authors of paper, date of publication, affiliations of each author, Physical Review references of the paper and PACS codes. Along with the meta data of journal papers, we also have citations of papers published in APS from journals published in Physical Review (hence excludes citations received from non APS journals). In Table.I, we show the basic descriptive statistics of the data.

Table IBASIC STATISTICS OF DATA 1985-2012

Number of authors	343055
Number of papers	399713
Average number of papers by an author	9.07
Average number of authors per paper	7.59
Average number of PACS codes per author	10.04
Average number of PACS codes per paper	2.92
Average diversity of author	13.16
Average diversity of paper	3.59
Average citation per paper	10.22



Figure 1. Fraction of papers with PACS codes from 1975 to 2012

A. PACS classification

PACS is a hierarchical classification scheme representing different field and subfields of Physics up to five levels. A PACS code consists of two pairs of numbers followed by a pair of non numeric characters, separated by dots. For example in PACS code 04.25.dg, the first digit 0 represents General Physics, 4 - General relativity and gravitation, 25 - Approximation methods; equations of motion and d represents *Numerical relativity* and *g* represents *Numerical studies of black holes and black-hole binaries*. PACS codes are regularly revised and updated overtime by American Institute of Physics (AIP), new codes are introduced and some codes are deleted. In our analysis we consider PACS codes up to third level (first four digits) of hierarchy as they are reasonably stable upto this level and represents all subfields of physics. We ignore the higher level hierarchy to maintain consistency PACS codes of all papers in our analysis. PACS codes were introduced 1975 and in use since then. But large fraction of papers published between 1975 and 1984 have not assigned any PACS codes (see Fig. 1). We choose the period from 1985 onwards, as the compliance towards PACS code jumped to more than 90% and have been consistently high since then.



Figure 2. Fraction of authors contributing to different number of PACS codes.

In Fig. 2, we show the fraction of authors using different number of PACS codes (plotted in log-log scale) in the papers published between 1985-2012. Large fraction of authors have used only 1 to 4 PACS codes. We can observe a power law decay till PACS of 60, there after, we see the slope changing. The overall pattern seems to follow double pareto distrbution [20], but detailed study is yet to be carried out. Distribution of papers using different PACS codes (in Fig.3) does not show any specific trend and reaches peak at four PACS codes, local minima at seven and there after it is fluctuating.

III. DIVERSITY

PACS data contains rich information on the multiple fields and subfields a papers addresses. The hierarchical structure of PACS can be exploited to understand the diversity of papers and authors. Various measures based Shannon entropy, Simpson index, Gini-Simpson index have been used to study the diversity in bibliographic studies [10] [13]. These studies primarily use citations of papers received from journals of different fields as inputs to these measures. They implicitly assume that diversity is determined by importance of the work as perceived by other disciplines. However, it neglects authors own



Figure 3. Fraction of papers contributing to different number of PACS codes.

perspective on the different fields and sub fields their paper belongs to.

PACS numbers in papers contain information on how authors perceive their paper to be belonging to different fields. On PACS hierachical tree, it is easy to define a distance metric between nodes specified at the same level in the hierarchy from the root. The Weitzman's diversity index [21], [22], [19] is used to characterize degree of dissimilarities between the elements of a set. Weitzman diversity $\mathcal{D}(S)$, measure can be used whenever a clear metric distance is defined between elements of a set S. It is defined as the sum of distances from each element to its nearest neighbor as below:

Definition 1. Weitzman Diversity [21]

Let \mathbb{U} denote the set of PACS codes, and $S, X \subseteq \mathbb{U}$. Let $S = \{u_i, i = 1, 2, ..., N\}$ and $S_k = \{u_i, i = 1, 2, ..., k\}$ with $k \leq N$, the distance metric d(u, v) between two elements of a set. The distance between element u and set X is defined as $\overline{d} : u \times X \to \mathbb{R}$ such that $\overline{d}(u, X) = \min_{v \in X} \{d(u, v)\}$. The Weitzman diversity \mathcal{D} of set S is defined as:

$$\mathcal{D}(S) = \sum_{i=1}^{N} \bar{d}(u_i, S_{i-1})$$

The $\bar{d}(u_i, S_k)$ measures the increase in diversity of S_k after the addition of one element u_i [22]. The algorithm to find Weitzman Diversity [19] is as below:

Definition 2. The Weitzman diversity, $\mathcal{D}(S)$ of a set of elements (or types) given a distance function $\overline{d}(u, X)$ is constructed recursively as follows:

- **1:** Let $X = \emptyset$ and initialize $\mathcal{D}(X) = 0$.
- **2:** Randomly choose an element, $u \in S \setminus X$, to add to *X*.
- **3:** Find the distance between u and its closet neighbor according to distance d. i.e, $\overline{d}(u, S) = \min_{v \in S} d(u, v)$. Increase $\mathcal{D}(X)$ by the $\overline{d}(u, X)$ and add u to the set X.
- 4: If $X \neq S$ go to 2.

Consider the following illustration on PACS tree (defined up to 3 level) in Fig. 4. Consider the PACS set $S = \{a, b, c\}$, where a = 04.25, b = 07.05, c = 04.30. Initialize $S_0 = \{a\}, \mathcal{D}(S_0) = 0$. Let $S_1 = \{a, b\}, \mathcal{D}(S_1) = \mathcal{D}(S_0) + \bar{d}(b, S_0) = 0 + d(a, b) = 2$, as we need to move two steps backwards to reach a common ancestor (i.e. 0). Then $\mathcal{D}(S) = \mathcal{D}(S_1) + \bar{d}(c, S_1) = \mathcal{D}(S_1) + \min\{d(a, c), d(b, c)\} = 2 + 1 = 3$. Hence $\mathcal{D}(S) = 3$.



Figure 4. Subtree of PACS hierarchical tree

A. Diversity of Papers and Authors

In this section we compute the diversity of papers published between 1985-2012 in APS journals and their authors using PACS codes. Diversity of a paper is the Weitzman diversity of a set S, where S is the collection of PACS codes (paper PACS) mentioned in that paper.

In Fig 5, we show the diversity distribution of papers on a log-linear scale. Fraction of papers with $\mathcal{D} > 15$ rapidly declines, and for $\mathcal{D} \geq 25$, it fluctuates around 10^{-6} to 10^{-5} .



Figure 5. Fraction of papers versus diversity

To calculate the diversity of an author A, we take union of all PACS codes S_A of papers published by A during a specified time period, and compute the diversity $\mathcal{D}(S_A)$. In Fig. 6, Weitzman diversity of authors from 1985-2012 is plotted on a log-log scale. We observe that the fraction of authors with diversity less than ten fluctuates. From diversity ten to about 100 we observe a power law, and for $\mathcal{D} > 100$, the decay is more rapid. A detailed statistical investigation is yet to be undertaken.



Figure 6. Fraction of authors versus diversity



Figure 7. Evolution of authors diversity and flows across diversity groups $(G_1 = [0,3], G_2 = [4,9], G_3 = [10,27], G_4 = [28+])$ for every 5 years.

Unlike the diversity of papers, authors diversity changes overtime as they publish more papers. In Fig.7, we show the time evolution (from 1985-2010) of diversity of authors and their transition from one diversity level to another using alluvial diagram. We have binned the authors based on their diversity index G_i = $\{[0,3], [4,9], [10,27], [28+)\}, i = 1, 2, 3, 4$. The first and last intervals representing lowest $(G_1, \text{ in red})$ and the highest diversity levels (G_4 , in blue) and middle levels G_2 and G_3 are in yellow and green respectively. The size of a block indicates the fraction of authors present in that group. The width of shaded flows corresponds to the fraction of authors moving from one group to another. When the width of a group is larger than the incoming flow, the gap indicates the new authors joined in the community. We observe that fraction of high diversity authors are increasing over time, where as the proportion of low diversity authors is decreasing with time. Most of the authors have switched to intermediate diversity, including the new authors.

Table II, we show the fraction of authors in different diversity groups from 1985 to 2010. We observe that over time there is a steady decrease in fraction of low diversity authors and increase in high diversity authors, an indication of trend towards interdisciplinary research. The movement of high diversity authors is less compared to low diversity authors.

	Diversity Groups			
Year	G_1	G_2	G_3	G_4
1985-90	0.30	0.37	0.29	0.03
1990-95	0.27	0.39	0.29	0.05
1995-00	0.23	0.38	0.32	0.06
2000-05	0.19	0.37	0.34	0.09
2005-10	0.16	0.36	0.35	0.13

Table II FRACTION OF AUTHORS IN DIFFERENT GROUPS

IV. CITATIONS AND DIVERSITY

Recently several studies have focused on the statistical characterization of temporal variations of citation received by papers [23], [24], [25]. Wang *et al.* have shown that the age at which a paper receives maximum citations follow a log-normal distribution [26]. In this section we analyze the citations of papers over time and their correlation with diversity. In our data, citations are limited to only those cited by Physical Review(PR) journals. The actual number of citations of papers may be higher, but we assume that there is substantial correlation between PR and non PR citations.



Figure 8. Average number of citations received by a paper at the t^{th} year of its publication.

In Fig. 8, we plot the average number of citations received by papers published in PR journals between 1985-2012. It takes about a year for papers to be discovered and cited, there after the number of citations per year continually decreases. In Table III, we show the percentage of papers corresponding to each diversity index between 1985-1994 and 1994-2003. We see that in both the cases, maximum number of papers have diversity three.



Figure 9. Diversity and Citations: Panels a, b, c and d, shows the cumulative average citations for articles of various diversities for the time periods 1985-1994 and 1994-2003. Diversity groupings [0,4] as in {a,c} and [4,8+] as in {b, d} have been separated for capturing the trend clearly. Panels (e) and (f) show average number of citations received by a paper from publication year, with diversities grouped into three categories: low($D = \{0, 1, 2\}$), medium ($D = \{3, 4, 5\}$) and high ($D = \{6, 7, 8, 8+\}$).



Figure 10. Fraction of papers versus their citations for different diversities. (a) 1985-1994 (b) 1994-2003.

 Table III

 PERCENTAGE OF PAPERS FOR DIFFERENT DIVERSITIES

Year	1985-1994	1994-2003
Diversity	papers (%)	papers (%)
0	13.9	9.7
1	10.2	9.0
2	15.5	13.6
3	19.8	19.0
4	14.6	16.3
5	12.5	14.5
6	8.0	9.8
7	3.3	4.7
8	1.7	2.5
9 and above	0.5	0.9

Based on this data we try to investigate whether the diversity of papers have strong influence on their citations. We have grouped papers published between 1985-1994 and 1994-2003 according to their diversity index and analyzed their citation pattern for each diversity group for ten years from their publication time. In Fig. 9 panels (a) and (c), cumulative average citations for diversities zero to four is shown. We notice that citations monotonically increase with the diversity across ten years from their date of publication. In panels (b) and (d), we plot the same for diversities four to eight and above. In Panel

(b), for years 1985-1994, the cumulative average number of citations received increases till diversity 4 and then begins to decline. It shows that *papers which are too diverse are likely to gather fewer citations*. Such papers may be difficult to follow by focused research groups, and are likely to have lesser depth and relevance to a specific discipline. For papers published between 1994-2003 (Panel c), the citations monotonically increase with the diversity from zero to four. For diversity four to seven (Panel d), the cumulative increase in average citations is roughly the same. Maximum citations is received for diversity eight, from then on wards it declines. This may be partly due to average shift towards higher diversity in 1994-2003 compared to 1985-1994.

To capture the aggregate trends of diversity and citations, we further grouped the diversity index into three bins $\{[0, 1, 2], [3, 4, 5], [6, 7, 8, 8+]\}$ denoting low, medium and high diversity respectively. The average citations received by these groups of papers from their published year is plotted in Fig. 9, panels (e) and (f). We see that for 1985-1994, medium diversity papers receive on an average higher citations than the high diversity in the initial years (0-5 yrs) from their publication time, where as high diversity papers receive more citations in later years (5 and above). This indicates that more diverse papers take time to gather citations, in agreement with a recent Nature special issue report [11]. For the years, 1994-2003, if we use the same bins for diversity grouping, the trend seems to be different. Higher diversity groups receive on an average higher citations in all years from their publication year. However, this trend may require careful analysis with a clear definition of groupings.

The analysis so far, depended on the average citations received for papers at a given diversity. However, this does not capture the effects of diversity on citation distribution. Generally large fraction of papers have zero or low citations, and citation distribution is unimodal and single tailed. We study the citation distribution for each diversity in Fig. 10 panels (a) and (b), for time periods 1985-1994 and 1994-2003. Almost 95% of the papers have citations below 50 in their first 10 years after their publication. Up to 25 citations, distributions follow exponential decay and later the fall is not as steep. This feature is similar across different diversities. A detailed statistical investigation is needed to understand the type of distribution and its parameters for different diversities.

V. SUMMARY AND FUTURE DIRECTIONS

In this work we have used Weitzman diversity measure to study the diversity profile of scientific articles and authors by using hierarchical structure of PACS codes in APS journals. We have studied the evolution of diversity of authors using alluvial diagram and observed that there is significant monotonic increase in high diversity authors from 1985 to 2010. The main purpose of our current work is to understand whether being more diverse means having more impact on scientific literature or not? To address this, we studied the correlation between the diversity of papers and their citations. We find that in general high diversity papers receives more citations, but too much diversity can reduce their total citations. We also find that among papers published between 1985-1994, higher diversity paper take longer time to gather citations than the medium and low diversity papers. However, this trends was not found to be universal and depended on the time period and binning of diversity.

Our work was restricted to only Physical Review journal articles which had hierarchical subject classification through PACS codes. Also, the diversity measure we used are based on the existence of distance metric on the subject classifications. It would be interesting to see whether these conclusions are valid even for other data sets such as DBLP, and when we use other diversity measures.

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