Rising Popularity of Interdisciplinary Research – an Analysis of Citation Networks

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***Abstract*—A common consensus among researchers is that interdisciplinarity is one of the key factors in doing research at current time. However, a pertinent question deals with identifying appropriate indicators of interdisciplinarity. Using a set of citation based indicators, here we investigate the evolution of the extent of interdisciplinary research in computer science and physics in the period 1975-2008. For this, we study the citation networks of these two domains from different orthogonal directions, namely citation and reference patterns of a paper, overlapping membership of the papers in different research communities, inclination of the researchers to adopt new fields, and propose several indices to quantify the degree of interdisciplinarity of a field. The new indices of interdisciplinarity corroborate with the hypothesis that the emergence of interdisciplinarity occurs through cross-fertilization of ideas between the sub-fields that otherwise have little overlap as they are studied independently. At the end, we analyze the core-periphery organization of citation networks and arrive to the conclusion that with the advancement of interdisciplinary research, the core part of the network is also changing from theoretical towards more applied fields of research.**

I. Introduction

A discipline is any comparatively self-contained and isolated domain of human experience which possesses its own community of experts, with distinctive components such as shared goals, concepts, facts, tacit skills and methodologies. Interdisciplinarity, on the other hand, is the coalition of distinctive components of two or more disciplines in research or education, leading to new knowledge which would not be possible without this integration. Interdisciplinarity occurs when disciplines intermesh, integrate and collaborate among themselves [1].

Many believe that the great advances disproportionately take place at the interstices between disciplines, and that today's research knowledge "knows no disciplinary boundaries" [2]. Therefore, both the measurements and mapping of cross-disciplinary research interchanges over time are essential to understand the emergence of integrative research activities almost in all the branches of science. The purpose of interdisciplinary research is to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single field of research practice.

The structural and dynamical properties of the networks among researchers have been an important research subject for the last several decades [3] [4]. While earlier studies mostly focused on characterizing citation or collaboration networks within a particular domain, there is a growing body of literature on the characterization and measurement of interdisciplinarity of scientific journals and researchers [5] [6] [7]. Many published attempts try to categorize interdisciplinarity into components such as pluridisciplinarity, crossdisciplinarity, and even metadisciplinarity [8] [9]. But these subdivisions throw little light on the theory and practice of interdisciplinarity. Recently, Pan et al. [10] study the relationships between the fields of physics to show a clear trend towards increasing interactions between different sub-fields. They conclude that the microscopic observation is missing in their study due to the lack of citation information which naturally bears the inherent interaction pattern among the fields and unfolds the evolution of a scientific research field in more systematic way.

In this paper, we systematically unfold large-size citation networks of two major domains of scientific research – computer science and physics, and study the dynamics and emergence of connections across their fields in a longitudinal scale over the last four decades (1975 – 2008). For this, we develop the citation network of the papers of computer science that appeared in DBLP[1], and the citation network of papers appeared in Physical Review series[2] of journals (Physical Reviews A, B, C, D, E, Physical Review Letters and Review of Modern Physics) published by the American Physical Society during this period. These two networks provide the opportunity to study the microscopic behavior of the connectivity patterns across fields and thus reveal the evolutionary landscape of interdisciplinary research.

We exhaustively study the citation networks in different dimension of connectivity that indeed demonstrates the interdisciplinary property of a field. In particular, we propose three indices bearing three different characteristics of citation network – Reference Diversity Index (RDI) using the references (outward citations) of a paper, Membership Diversity Index (MDI) using the membership of the nodes in different communities and Citation Diversity Index (CDI) using inward citations received by a paper. These three measures establish the existence of interdisciplinarity of a field from three different perspectives of citation networks. We also further quantify the inclination of the researchers to join a field which is independent of the citation network structure and complements the previous three measures of interdisciplinarity. We rank the fields separately using these four metrics. The results obtained from the metrics corroborate a consistent ranking of few fields, namely Data Mining, WWW, NLP, Computational Biology in

The first author of the paper is financially supported by the Google India PhD Fellowship Grant in Social Computing.

[1] http://www.informatik.uni-trier.de/~ley/db/
[2] http://prola.aps.org/

978-1-4799-3635-9/14/$31.00 ©2014 IEEE

computer science and Interdisciplinary Physics, General and Optical Physics in physics domain in different time windows that indeed emphasize the sensitivity of the proposed metrics to characterize the interdisciplinarity. Finally, by applying the k-shell decomposition technique, we show that with the emergence of interdisciplinarity over the years, the core region of a domain is gradually occupied mostly by the applied fields rather than the theoretical fields with interdisciplinary fields steadily accelerating towards the core.

The rest of the paper is organized as follows. The description of the datasets and the construction of networks are elaborated in section II. In section III, we describe in detail several indices to quantify the degree of interdisciplinarity of a field from different perspectives of a citation network and some other external evidences. In section 5, we present a core-periphery analysis of the citation network to demonstrate different concentric layers of the network obtained from k-shell decomposition and the position of different fields in different regions. Finally in section V, we conclude the paper mentioning some important insights of this research with few immediate research directions in future.

II. Description of the Dataset and Network Construction

We use the DBLP dataset of the computer science domain[3] developed by Chakraborty et al. [11] for our experiments. The dataset contains 702,973 valid papers and 495,311 authors. It was constructed using the DBLP web repository which contains information about various research papers from different fields of computer science domain published over the years. This information includes the name of the research paper, index of the paper, its author(s), the year of publication, the publication venue, the related field(s) of the paper, the list of research papers the given paper cites and (in some cases) the abstract of the papers. It categorizes papers of computer science domain into the fields as noted in Table I.

TABLE I. The fields (with abbreviations) of computer science domain

Fields	Abbrev.	Fields	Abbrev.
Artificial Intelligence	AI	Algorithms and Theory	ALGO
Networking	NETW	Databases	DB
Distributed Systems	DIST	Hardware & Architecture	ARC
Software Engineering	SE	Machine Learning & Pattern Recognition	ML
Scientific Computing	SC	Computational Biology	BIO
Human-Computer Interaction	HCI	Multimedia	MUL
Graphics	GRP	Computer Vision	CV
Data Mining	DM	Programming Languages	PL
Security and Privacy	SEC	Information Retrieval	IR
Natural Language and Speech	NLP	World Wide Web	WWW
Computer Education	EDU	Operating Systems	OS
Real Time & Embedded Systems	RT	Simulation	SIM

We use all published articles in Physical Review (PR) journals [10] from 1975 till the end of 2008 which are classified into sub-fields using the corresponding PACS codes. We use all such entries which possess the information about their index, title, name of the author(s), year of publication, references and PACS code(s). The filtered dataset contains 325,399 valid papers and 277,154 authors. The PACS[4] is an internationally adopted, hierarchical subject classification system of the American Institute of Physics (AIP) for categorizing publications in physics and astronomy. It is primarily divided into 10 top-level categories that represent broad research areas. Each of these categories is then divided into smaller domains representing more specific fields of physics, which may be further split into even more specific sub-fields. For the purpose of better visualization and analysis, we use only top level hierarchy that contains 10 broad fields of physics shown in Table II.

TABLE II. The fields (with abbreviations) of physics domain

PACS	Fields	Abbrev.
00	General Physics	GEN
10	Elementary Particles and Fields	EP
20	Nuclear Physics	NP
30	Atomic & Molecular Physics	AMP
40	Electromagnetism, Optics, Acoustics, Heat Transfer, Classical Mechanics & Fluid Dynamics	OP
50	Gases, Plasmas & Electric Discharges	GPE
60	Condensed Matter: Structural, Mechanical & Thermal Properties	CMT
70	Condensed Matter: Electronic Structure, Electrical, Magnetic & Optical Properties	CME
80	Interdisciplinary Physics and Related Areas of Science and Technology	INT
90	Geophysics, Astronomy & Astrophysics	GEO

Since our method is primarily based on suitable statistical analysis of various properties of paper-paper citation network, the next task is to construct the citation network from the tagged dataset. From the tagged dataset in each domain, a citation network is constructed by the papers representing nodes and the citations representing directed edges from the citing paper to the cited paper. The citation networks for computer science and physics domains are constructed in longitudinal framework where the papers in each year are arranged vertically and the unidirectional citation edges point to any papers at or before this year.

[3] http://cse.iitkgp.ac.in/resgrp/cnerg/

[4] http://www.aip.org/pacs/

III. Interdisciplinarity Measurements of Fields

To quantify the degree of interdisciplinarity of a field over time, we only concentrate on the topological structure of the time-varying citation network and observe its two essential characteristics – link distribution and community structure. The rest of the section elaborately describes the proposed measurements one by one and the experimental results.

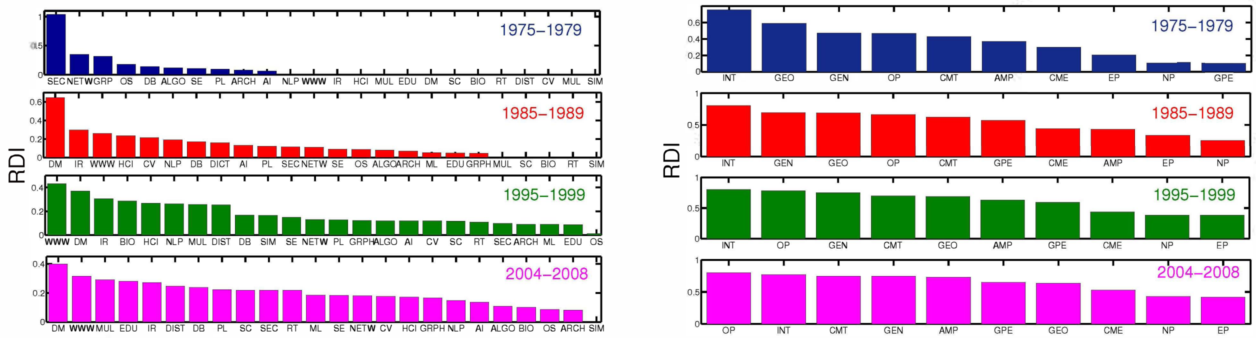
A. Reference Diversity Index (RDI)

It is quite intuitive that the more diverse the references of a paper the more the probability that the paper is of interdisciplinarity nature. Therefore, to formulate the reference diversity, we propose a simple quantitative measure described below.

Let X_i be a paper of field f_i, and it cites papers of k different fields, namely $f_1, f_2, ..., f_k$ (f_i may be one of the fields in f_1 to f_k). The *Reference Diversity Index (RDI)* of paper X_i denoted by $RDI(X_i)$ is defined as follows:

$$RDI(X_i) = -\sum_j p_j log(p_j) \quad (1)$$

where p_j is the proportion of references of X_i citing the papers of field f_j. The average is taken over all the papers in field f_i to get the RDI score of f_i.



(a) Computer science

(b) Physics

Fig. 1. Reference Diversity Index (RDI) of all the fields in computer science and physics domains in four time-windows. The x-axis is sorted (descending order) by the RDI value.

Figure 1 illustrates the results of the RDI metric measured for the fields of two domains. All the results are sorted in descending order to get an idea of the rank of the fields in each time window based on RDI. The more the RDI value of a field the more it shows its interdisciplinarity nature. The result is not so significant in 1975-1979 possibly since interdisciplinarity became popular after 1985. The fields in computer science like Data Mining, World Wide Web, Human Computer Interaction, Information Retrieval consistently remain at the top positions in terms of their RDI values (Figure 1 (left)). Similar pattern is observed in physics domain where the trend is more apparent (Figure 1 (right)). Interestingly, Interdisciplinary Physics that retained the top position over the initial two decades (1975-1995) shows a steady movement towards core after 1995 (we shall discuss this more in section 5). Similar pattern is followed by General Physics (GEN) and Geophysics, Astronomy and Astrophysics (GEO). However, just the reverse pattern is observed for OP, CMT and GPE which gradually exhibit more interdisciplinarity in their citation distributions. Another important observation is that the degree of interdisciplinarity in terms of RDI for all the fields tends to become uniform over the years (the bars for all the fields in each domain gradually attain equal heights over the years). It is a clear indication of increasing rate of interdisciplinary activities started emerging from all fields in the last few decades.

B. *Membership Diversity Index (MDI)*

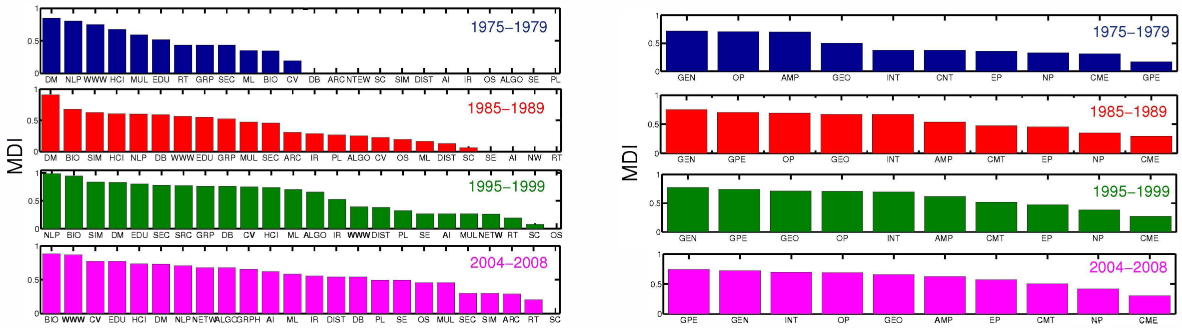
The communities in citation network of a domain generally indicate different areas of research where the intra-community citation density is higher than inter-communities [12]. Therefore, the papers belonging to more than one communities (i.e., overlapping nodes) could signify the interdisciplinary papers adopting ideas from different research areas (communities) where they belong. We hypothesize that the diverse range of membership in different communities of a paper indicates its extent of interdisciplinarity. To verify our hypothesis, we conduct a community-centric measurement on the networks of four dynamic-windows (1975-1979, 1985-1989, 1995-1999 and 2004-2008). We use SLPA (Speaker listener Label Propagation Algorithm) [13] to detect overlapping communities in each dynamic-window. Then based on the membership of the overlapping nodes (papers) in each field, we define another metric called *Membership Diversity Index (MDI)* to measure its extent of interdisciplinarity. The formulation of MDI is as follows.

We run SLPA on the network of each dynamic-window that extracts the overlapping communities (say, $c_1, c_2, ..., c_n$). Since we know the actual field information of the papers, for each community c_i we can then find out the major field f_i such that c_i constitutes most of the papers belonging to f_i (i ranges from 1 to 24 for computer science and 1 to 10 for physics). In this way, we can mark each community with a field tag that roughly signifies the research area indicated by this community. Note that it might be possible that more than one community are marked by the same field tag since we have very few field categories (24 for computer science and 10 for physics) compared to the number of communities in each dynamic-window. Now for the field f_i, we extract only the overlapping papers of f_i in that time-window. Then, we find out the membership of each such overlapping paper to different communities labeled by the fields. Now, the MDI of the field f_i in a particular time-window is defined by the following equation:

$$MDI(f_i) = -\sum_{j=1}^{m} p_j log(p_j) \tag{2}$$

where p_j is the fraction of overlapped-papers of f_i belonging to the communities tagged as f_j and m is the number of fields ($m = 24$ for computer science and $m = 10$ for physics). The more the MDI value of a field the more it shows its interdisciplinarity.

Figure 2 shows the MDI of each field in computer science (left) and physics (right) domains. In computer science, Data Mining achieves the highest MDI in the earlier two time windows (1975-1979 and 1985-1989); then it tends to loose its overlapping nature and gradually moves towards the core region. We will observe similar pattern in Figure 5 discussed in the next section. Recently, Computational Biology and WWW achieve highest rank in terms of MDI that again implies their increasing degree of interdisciplinarity in the recent time period. In all the time windows depicted in Figure 2, top few positions are mostly occupied by the same fields of computer science, namely Data Mining, Computational Biology, Natural Language Processing and WWW. The results are even consistent for physics domain (Figure 2 (right)) where General Physics always holds the top positions. In the latest time window, General Physics and Geophysics swap their



(a) Computer science

(b) Physics

Fig. 2. Membership Diversity Index (MDI) of all the fields in computer science and physics domains in four time-windows. The x-axis is sorted (descending order) by the MDI value.

position. Condensed Matter (PACS 70) and Nuclear Physics (PACS 20) consistently retain their core property throughout the entire time frames.

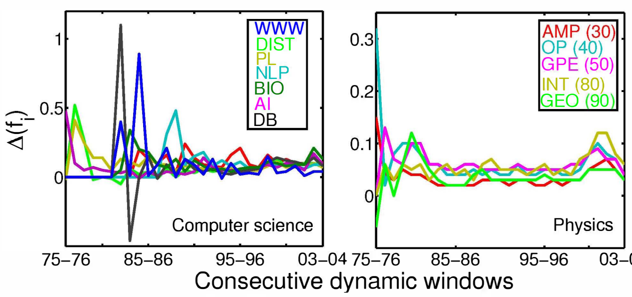


Fig. 3. (Color online) Drift of CDIs in two consecutive time windows for all the fields. The value in y-axis corresponding to $(t_i - t_{i+1})$ in x-axis indicates the difference of the CDI values obtained from the time windows t_i and t_{i+1}. Those fields showing bumps in the temporal spectrum of the drift of citation skewness are shown. Other fields are relatively stable.

C. Citation Diversity Index (CDI)

We define citation diversity of a field as follows. Let X_i be a paper of field f_i published in the time window t_i[5], and it is cited by the papers (also published in t_i) of k different fields, namely $f_1, f_2, ..., f_k$ (f_i may be one of the fields in f_1 to f_k). The *Citation Diversity Index (CDI)* of paper X_i at time window t_i denoted by $CDI_{t_i}(X_i)$ is defined to capture the skew of the inward citation of a field using the following equation.

$$CDI_{t_i}(X_i) = -\sum_{j}^{n} p_j log(p_j) \tag{3}$$

where p_j is the proportion of citations of paper X_i received from the field f_j at t_i. The average is taken over all the papers in field f_i to get the CDI score of f_i.

Similarly, we can find out the CDI of X_i in time window t_{i+1}, i.e., $CDI_{t_{i+1}}(X_i)$. Then for a field f_i, we can calculate the drift of this skew of the citation patterns in two successive time windows t_i and t_{i+1} by the following equation.

$$\Delta_{t_i}(f_i) = CDI_{t_{i+1}}(f_i) - CDI_{t_i}(f_i) \tag{4}$$

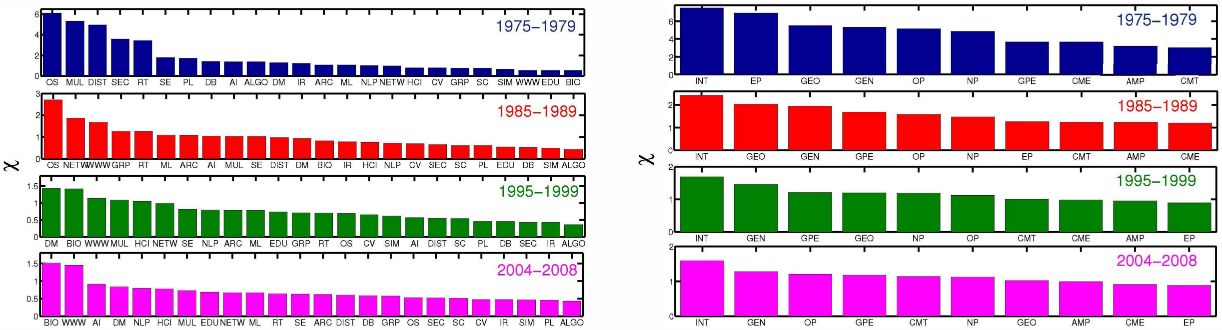
In Figure 3, we plot the Δ values of those fields for which we are able to detect such a large fluctuation at some time point in the entire profile. For instance in Figure 3 (left), WWW achieves a sudden peak between the time windows 1985-1989 and 1986-1990 and then gets stabilized. Similar behavior is observed for NLP between the time windows 1989-1993 and 1990-1994. Therefore, the fields that experience such peaks can be thought of more interdisciplinary in nature. Surprisingly, Databases shows a typical behavior of sudden increase followed by a negative drift in the time windows 1981-1985 and 1982-1986. This behavior implies that there is a sudden citation skewness of Databases peaking at the middle of the two time windows followed by a lower skewness resulting in a negative drift. We notice that at the time window 1982-1986, Databases has received variety of citations from the fields like Computer Vision, Security and Privacy, Operating Systems none of which have cited Databases later. On the other hand, Figure 3 (right) shows similar behavior for the physics domain. The evidence in physics domain is not so distinguishable due to more coarse-grained classification of the fields compared to computer science. However, here also, Interdisciplinary Physics (PACS 80) has a peak in CDI drift between 2000-2004 and 2001-2005 time windows. Atomic and molecular Physics (PACS 30), Geophysics and Astrophysics (PACS 90), Optical Physics (PACS 40) also experience such peaks in the initial time-window.

D. Attraction Index

The metrics discussed above are the consequences of the direct use of topological evidences of the citation network that are only related to the link structure. Here we complement these metrics with a different measure quantifying the degree of the attractiveness of a field in terms of the new researchers joining the field.

For each dynamic window, we measure the number of new authors (suitably normalized by the number of papers in that time window) who started research in a field which signifies the attractiveness of a field in that time window. Let us assume that the number of unique authors from the beginning up to the year t_i and up to the year t_{i+4} publishing papers in field f is n_i and n_{i+4} respectively. The number of papers of field

[5]Note that, by the term time window t_i we mean to say the five-year time period from t_i to $t_i + 4$.



(a) Computer science (b) Physics

Fig. 4. Attraction Index of the fields in computer science and physics domains in four time-windows. The x-axis is sorted (descending order) by the χ value.

f published in time window $(t_i - t_{i+4})$ is p_i. Therefore, the *Attraction Index* of a field f denoted by χ_f is measured by the following equation.

$$\chi_f = \frac{n_{i+4} - n_i}{p_i} \tag{5}$$

In Figure 4, we plot the value of χ for all the fields (in decreasing order of χ) in four different time windows. In computer science domain, though the core fields like OS, Networking hold the top few positions in terms of χ in the first two time-windows (1975-1979 and 1985-1989), gradually these positions got occupied by the interdisciplinary fields like Computational Biology, WWW, Data Mining. This scenario is quite prominent for physics domain where the top field had always remained occupied by Interdisciplinary Physics. In other words, the above mentioned fields consistently exhibit their increasing degree of interdisciplinarity from all corners of studies conducted here. This quantitative measure indeed corroborates the ranking results obtained from the direct use of three citation based measures discussed above and emphasizes the importance of topological structure even in measuring the interdisciplinarity of a field.

IV. K-CORE ANALYSIS

With the emerging trend of interdisciplinarity, we are interested to observe whether the core fields of computer science and physics domains have also got changed over the years. Pan et al. [10] proposed a $k^s - shell$ [14] analysis technique to identify the nuclear fields of a domain. For this, they used individual PACS code as node and a pair of nodes (PACS codes) are connected if there is at least one paper sharing these two PACS codes. As we mentioned earlier, the PACS hierarchy is manually created and manipulated over the years. Furthermore, the impact of a field in terms of its related papers can possibly be better judged by the citation information that is intrinsically created with out any manual intervention and after creation, they remain forever. For this reason, we use citation information for the k-core analysis. Sometimes, both the inward and outward citations play important role to measure the impact of a field since they are significant to estimate the *authoritativeness* and *hubness* of a field respectively. Therefore, we take into account both of them separately to perform the k-core decomposition in four different dynamic windows (i.e., 1975-1979, 1985-1989, 1995-1999, 2004-2008).

We start by recursively removing nodes that have single link until no such nodes remain in the network. These nodes form the 1-shell of the network ($k^s - shell$ index $k^s = 1$). Similarly, by recursively removing all nodes with degree 2, we get the 2-shell. We continue increasing k until all nodes in the network have been assigned to one of the shells. The union of all the shells with index greater than or equal to k^s is called the k^s-core of the network. Since the shell index is assigned to each paper, we calculate the fraction of papers of a field in each k^s-core of the network in each dynamic window to identify the core fields of a domain.

The multi-level pie charts in Figure 5 (a) in four dynamic time-windows show how the different fields of computer science and physics are positioned with respect to the core-periphery organization of the citation network when considering in-degree and how their positions have changed over time. Each level of the pie-chart represents one of the k^s-shell regions, i.e., the innermost layer represents Region I, followed by Region II, Region III, and finally the outermost layer represents the peripheral Region IV. For each layer, we show the fraction of papers belonging to a field. For computer science domain (top panel of Figure 5 (a)), the pie charts for the time windows 1975-1979 and 1985-1989 show that the core region I consists mostly of Databases, Programming Language and Software Engineering; while after that it is dominated by the more applied fields like Networking, Distributed Systems, Data Mining with a small contribution from Hardware and Architecture and Databases. In all other regions, all fields of computer science are present. From these results, we can infer that the core of the computer science is gradually turning from theoretical to more applied. On the other hand, in physics domain (bottom panel of Figure 5 (a)), initially there was only one region covered by Condensed Matter (PACS 70) and Nuclear Physics (PACS 20). After that, a major fraction of the core region is dominated by the fields like Gases, Plasmas and Electric Discharges (PACS 50), Elementary Particles and Fields (PACS 10) with small contributions from General Physics and Condensed Matter (PACS categories 00, 60 and 70). Nuclear physics (PACS 20) always retains the position at the periphery. Interestingly, while Gas, Plasmas and Electric Discharges (PACS 50) has started moving towards periphery, Interdisciplinary Physics (PACS 80) has steadily moved towards the core after 1985.

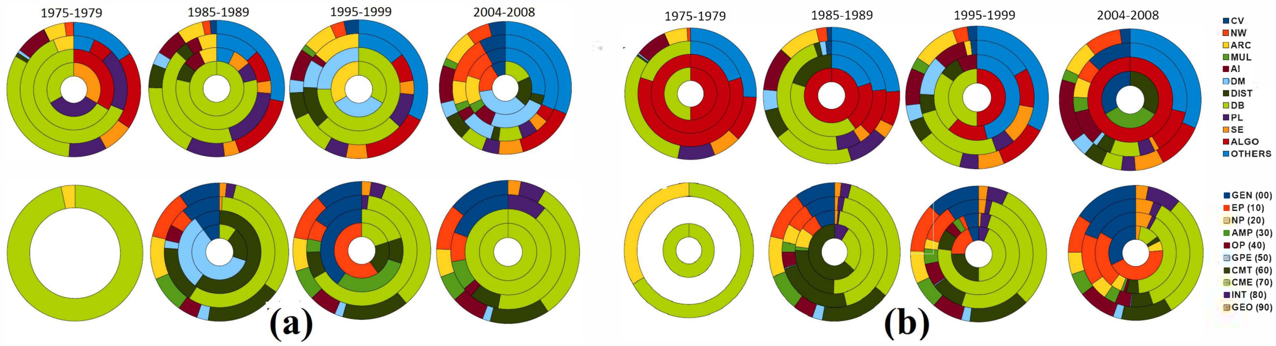


Fig. 5. (Color online) Multilevel pie-chart for the dynamic windows 1975-1979, 1985-1989, 1995-1999 and 2004-2008 showing the core-periphery organization of the citation networks of computer science (top panel) and physics (bottom panel) with respect to the (a) inward and (b) outward citations.

We extract the core-periphery organization of citation network with respect to the outward citations as shown in Figure 5 (b). Surprisingly in computer science domain (top panel of Figure 5 (b)), while Algorithms and Theory has been a consistent contributor at the periphery region in Figure 5 (a), the core regions are heavily dominated by Algorithms and Theory in Figure 5 (b) with a contribution from Databases. Recently, the core region is covered by the emerging fields like Computer Vision, Multimedia and Distributed Systems. On the other hand in physics domain (bottom panel of Figure 5 (b)), there were only two regions covered by Condensed Matter (PACS 70) and Nuclear Physics (PACS 20) in the initial time window. After that, it has been started covered by Condensed Matter (PACS 60), General and Interdisciplinary Physics (PACS categories 00 and 80). Similarity, while Elementary Particles (PACS 10) has steadily moved into the core region, Geophysics, Astronomy and Astrophysics (PACS 90) has shifted towards periphery region. Note that all the results described in this section imply a general conclusion that the core parts of computer science and physics have been evolved over the years when considering the citation information. These results are counterintuitive with the results shown by Pan et al. [10] that even if the interdisciplinary fields emerge over the years, the core region is mainly dominated by Condensed Matter and General Physics in all the time periods.

V. Conclusion

In this article, we have investigated how the degree of interdisciplinarity has changed between 1975 and 2008 for two popular research domains – computer science and physics. In doing so, we have proposed several indicators of interdisciplinarity extracted from the large-scale citation networks. We have demonstrated that the citation information is strong enough to reveal the interdisciplinary characteristics of a field. Few fields such as Data Mining, Natural Language Processing in computer science domain and Interdisciplinary and General Physics, Condensed Matter in physics domain produce constant indications of interdisciplinarity for all the metrics proposed here. Moreover, for already very interdisciplinary fields, such as Data Mining, the indicators may have a certain "saturation" effect forcing it towards the core regions.

The study of the two research domains examined here is not only interesting in their own right to track the evolution of interdisciplinarity over time, but it also provides essential benchmarks for future investigations. Using these diversity indices, one can build up a specialized recommendation system aiming to predict future combination of fields generating new interdisciplinary area of research. It would be especially interesting to see how the availability of research grants in different fields of computer science and physics correlate with our observations, and whether the evolution of interdisciplinarity follows the amount of funding available for its sub-areas or vice versa.

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