Degree, Closeness, and Betweenness: Application of group centrality measurements to explore macro-disciplinary evolution diachronically

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Abstract
Three group centrality measures--degree, closeness, and betweenness--are utilized in this paper to explore the role of disciplines in two journal co-citation networks by using 677 journals from 40 disciplines categorized by Web of Knowledge. The result shows that social science disciplines play a more central role in knowledge communication and interaction among disciplines than science discipline. Some science disciplines, such as Computer Science, have become more dominant in terms of the three centrality measures over time. The use of group centrality measures provides a novel way of exploring role of disciplines in science mapping and provides evidence that a more comprehensive result can be obtained when all three of these measurements are utilized.

Introduction and Background
Science mapping is a growing domain, facilitated by the amount of large-scale data currently available. Of increasing importance in science mapping is the use of social network analysis methods. Network maps, comprised of nodes and links between these nodes, have come to dominate the landscape (see Börner, 2010; Klavans & Boyack, 2009 for a history of science maps). The unit of analysis, or node in the network maps, has largely consisted of one of three items: a single author, document, or journal. The edges between these nodes typically represent citations or co-authorship. Many of these attempt to show interactions between disciplines, by manually superimposing disciplines or domains on top of the document (e.g. Small, 1999, 2010; Small & Garfield, 1985), author (e.g. Moya-Anegón, Vargas-Quesada, Chinchilla-Rodríguez, Corera-Álvarez, & Herrero-Solana, 2007; Perianes-Rodríguez, Olmeda-Gómez, & Moya-Anegón, 2010; Wallace, Gingras, & Duhon, 2009), or journal clustering (Boyack, Klavans, & Börner, 2005; Leydesdorff, Moya-Anegón, & Guerrero-Bote, 2010; Leydesdorff & Probst, 2009; Sugimoto, Pratt, & Hauser, 2008).

This superimposition was noted by Leydesdorff and Rafols (2009) who suggested that aggregation may improve results. Current research has attempted to address this issue by analyzing aggregated units, primarily using aggregations of journal sets as proxies for a discipline (e.g. Leydesdorff & Rafols, 2009; Moya-Anegón, et al., 2007; Vargas-Quesada, Moya-Anegón, Chinchilla-Rodríguez, & González-Molina, 2009; Zhang, Liu, Janssens, Liang, & Glänzel, 2010). For example, Moya-Anegón et al.(2007) used co-citation data of ISI categories to map the world of science. However, mapping directly from co-citation data at the category level contains potential issues. For instance, when the co-citation frequency of two ISI categories is calculated, it is determined by the number of times that publications belonging to these categories are co-cited, regardless of how many papers from these two categories appear in the same reference list. Therefore, better metrics are necessary that incorporate these nuances and the roles of actors within the network.

One basic but essential measure in social network analysis is centrality. Centrality measures, e.g. degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality, have been employed to understand the roles of certain nodes in networks. Historically, all of these nodes are units of documents, authors, and journals. While these previous studies provide an adequate examination of the roles of these actors within the system, the actors have rarely been examined on the group or category level. With the rise of large-scale analyses of interdisciplinarity, it has become increasingly important to find metrics that not only describe the relationships between individual scholars, but also aggregations of these scholars on the discipline or domain level.

Some centrality measures have been employed in scientometric evaluations at the author (e.g. Yan, Ding, & Zhu, 2010) and journal level (e.g. Leydesdorff, 2007) and in evaluation of structural changes diachronically (Leydesdorff & Schank, 2008). However, researchers have not yet exploited the potential for using group centrality measures to examine structural changes in research aggregates (e.g. disciplines). Therefore, this work proposes to examine the application of Everett and Borgatti's (2005) notion of group centrality measures to scientometric data. Group centrality measures were proposed to describe the degree, closeness and betweenness centrality of a group. This method may be able to address some of the issues described above by providing three interpretations of the roles between groups or communities within the network data. This is particularly relevant for scientometric evaluations, but may also have application to other social network and community analysis questions.

The objective of this paper is to introduce the application of group centrality by aggregating journals into disciplines in a co-citation network. Additionally, interpretation is made on the macro-discipline level to describe the use of group centrality measures for exploring structural differences and behaviours between the sciences and social sciences.

Method

Data collection and processing

Data used in this study was collected in December 2010 from Thomson Reuter's Web of Knowledge (WoK). The top 20 journals (ranked by Impact Factor) were selected from each of 40 disciplines (20 science disciplines and 20 social science disciplines) according to the 2009 Journal Citation Report, for a total of 1,828,138 papers from 1960-2010. After data pre-processing, journals that have never been co-cited with any other journals or did not publish consistently for more than 10 years in either time span (1960-1985 or 1985-2010) are excluded. In total, 677 journals from 40 disciplines are analyzed in this paper.

Actor centrality measurements

Centrality is regarded as one of the most important and commonly used conceptual tools for exploring actor roles in social networks. A node's degree centrality, in an un-directed graph, is defined as the number of nodes that are connected to that node. The definition dictates that "central actors must be the most active in the sense that they have the most ties to other actors in the network or graph" (Wasserman & Faust, 1994, p. 178). Closeness centrality, as intuitively indicated by the term, focuses on how close a node is to all the other nodes in a network (Wasserman & Faust, 1994, p. 165). As defined by Freeman (1979), the centrality of a given node is the sum of geodesics distance from all other nodes, which is defined as the length of the shortest path from one node to another. Closeness centrality describes the extent of influence of a node on the network. Betweenness centrality, according to Borgatti (2005), focuses on "the share of times that a node i needs a node k (whose centrality is being measured) in order to reach j via the shortest path" (p.60). The more times a node lies on the shortest path between two other nodes, the more control that the node has over the interaction between these two non-adjacent nodes (Wasserman & Faust, 1994).

Extended Centrality - Group Centrality

Everett & Borgatti (2005) extended the actor/node level centrality measure to a group level. The definition and formulas for group centrality measurements are as follows. According to their definition, the degree centrality of a group is the number of actors outside the group that are connected to the member of that group. Different ties to the same actors by different group members are only counted once. The formula is described below:

$$\text{Group degree centrality} = |N(C)|$$

$$\text{Normalized group degree centrality} = \frac{|N(C)|}{|V| - |C|}$$

Note that C is a group that is a subset of the set of vertices V, *and* $N(C)$ denotes the set of all nodes that are not in C but connected to a member of C.

Group closeness centrality is defined as the normalized inverse sum of distances from the group to all nodes outside the group. Let D denote the set of all shortest paths from a node x to group C. It should be noted that, the average number of x to nodes in C group is used in this research as the distance from node x to group C, taking into account our data feature. Let $d(x,C)$ denote the distance from node x to group C, then

$$\text{Group closeness} = \sum_{x \in V - C} d(x,C)$$

$$\text{Normalized group closeness} = \frac{|V - C|}{\sum_{x \in V - C} d(x,C)}$$

Betweenness centrality measure is extended into a group level in a similar way as closeness centrality was. Group betweenness centrality shows the "proportion of geodesics connecting pairs of non-group members that pass through the group" (Everett & Borgatti, 2005, p.61). Let $g_{u,v}$ denote the number of geodesics between u and v, and $g_{u,v}$ (C) the number of geodesics that pass through group C.

$$\text{Group betweenness} = \sum_{u<v} \frac{g_{u,v}(C)}{g_{u,v}}, u, v \notin C$$

These three group level centrality measures give us a new way of measuring the role of disciplines in a discipline knowledge communication network.

Results and Discussion

Articles, journals and disciplines overview

After data pre-processing, there were 677 journals analyzed in this research. Journals categorized into one discipline by WoK are called unique-discipline journals, and journals categorized into more than one discipline (in this dataset) are called cross-discipline journals. According to this, there are 45 cross-discipline journals in our data. Table 1 displays the number of unique discipline journals (Uni#), cross-discipline journals (Cro#) and articles (paper#) of each discipline from 1960-2010.

On average, science disciplines published more papers than social sciences did. The average number of papers is 73,701 for science disciplines and 21,351 for social science disciplines. The average number of cross-discipline journals in science disciplines (1.65) is smaller than social science journals (2.95). This may indicate that science disciplines are more productive than social science disciplines, but bear less inter-disciplinary features than social science disciplines. Psychiatry is the science discipline that has the largest number of cross-discipline journals among all 40 disciplines analyzed. The possible reason for this is that psychiatry is indexed in both SCI and SSCI (called Psychiatry (social)). Of all the 11 cross-discipline journals that Psychiatry in science has, 10 are categorized in Psychiatry (social) by SSCI. This also explains Psychiatry (social)'s relatively larger number of cross-discipline journals within social science disciplines. Within social science, Business and Management are the two disciplines that hold the largest number of cross-discipline journals, all of which overlap. Most of 45 cross-discipline journals belong to two different disciplines. Two journals, *Psychological Medicine* and *Psychosomatic Medicine*, are categorized in three disciplines by WoK. In addition, there are six journals that are indexed by both SSCI and SCI of WoK.

Table 1. Unique-discipline journals, cross-discipline journals and papers in each discipline

	Science				*Social Science*		
ISI Discipline	*Uni#*	*Cro#*	*Paper#*	*ISI Discipline*	*Uni#*	*Cro#*	*Paper#*
Astronomy	18	2	216,733	Psychiatry_Social	9	8	62,197
Physics	17	1	181,255	Social Psychology	15	4	31,850
Medicine	17	2	161,012	Economics	16	3	27,585
Immunology	20	0	120,836	Law	19	1	26696
Chemistry	20	0	82,118	Anthropology	17	1	24,132
Agriculture	18	0	81,982	Geography	16	4	23,913
Psychiatry	7	11	80,049	Sociology	14	4	22,724
Neuro-Science	17	3	73,406	Social Work	15	2	21,904
Nano-Science	9	2	67,280	Business	10	9	19,905
Zoology	20	0	67,037	Political Science	16	4	19,325
Public Health	19	0	62,012	Linguistics	17	2	18,700
Ecology	19	0	48,838	Demography	16	1	16,310
Biology	15	1	46,454	Education	18	1	16,188
Engineering	19	0	34,402	Management	8	9	15,051
Mathematics	17	1	33,619	LIS	13	2	14,497
Geology	15	3	27,208	History	17	0	14,213
Computer Science	17	1	24,469	History of Science	19	1	13,805
Paleontology	14	3	15,925	Public Administration	17	2	13,368
Nursing	12	0	14,683	Criminology	18	0	12,851
Psychology	15	3	34,695	Communication	16	2	11,808

Constructing journal co-citation networks

Two journal co-citation networks are constructed according to the co-citation relationship between journals pairs (1960-1985 and 1985-2010). If two journals were ever co-cited, then there is an edge between them. The weight of an edge depends on the times they are co-cited. Normalization of co-citation counts is used to get reasonable edge weights for the journal co-citation network. There are many publications regarding proper proximity measurements for co-citation data (e.g. Eck & Waltman, 2009; White, 2003), including Pearons's *r*, Chi-Square, and Cosine similarity. This discussion will not be elaborated on here, due to space. However, in this research, *Pearson's r* is employed as the proximity measure for journal pairs, making this research comparable to other citation studies utilizing this measure[2].

[2] Raw pearson's r is adjusted to eliminate negative values. Adjusted r= (raw r+1)/2.

An overview of the journal co-citation networks

In order to trace the change of interaction and communication between disciplines diachronically, two journal co-citation networks were constructed, by time period. Table 2 shows a brief summary of these two journal co-citation networks. According to the result, the 1985-2010 network has a larger number of total edges, average node degree, density and a smaller number of isolated nodes compared with 1960-1985 network. This indicates that, in the most recent 25 years, journals of different disciplines have become more correlated and are more interconnected.

Table 2. Summary of journal co-citation network

Network	*Isolates*	*Edges*	*Ave. Deg.*	*Density*	*#Nodes in largest Component*
1960-1985	209	43254	127.80	0.19	468
1985-2010	11	77915	230.18	0.34	666

There are 209 isolated nodes in 1960-1985 network and 11 in 1985-2010 network. On the meta-discipline level, 122 isolated journals in the 1960-1985 network are from 20 science disciplines, and 87 isolated journals are from 17 social science disciplines. In the 1960-1985 network, a social science discipline has the largest number of isolated journals (Education) with 13 isolates followed by Communication with 10 isolates. Computer Science and Chemistry have the most isolated journals among all science disciplines, 14 and 13, respectively. In the 1985-2010 network, there are 11 isolated journals: six journals from five science disciplines and five journals from five social science disciplines. It should be mentioned that those 11 isolated journals in 1985-2010 network are also isolates in 1960-1985 network.

Table 3. Isolated journals in both networks

Network	*Science*		*Social Science*	
	#Journals	*#journaldiscipline*	*#Journals*	*#journaldiscipline*
1960-1985	122	20	87	17
1985-2010	6	5	5	5

Journal co-citation and discipline partition network

The networks are visualized in Figure 1 (1960-1985) and Figure 2 (1985-2010). Three groups are partitioned by color in the networks: social science journals (green), science journals (yellow) and cross-science journals (red)[3]. After removing isolates in both networks, the average node degree is 185 in the 1960-1985 network and 234 in the 1985-2010 network. This indicates that of all the journals, on average, those in 1985-2010 network are more interconnected than those in 1960-1985 network.

Visually, journals from social science disciplines stay in a more central position in both networks compared with those from science disciplines. This may provide evidence of a higher degree of interdisciplinarity in social science. As can be expected, the cross-disciplinary journals play a central role in both networks. Additionally, a visual comparison provides insights on the isolates, as we note less social science discipline components and isolates in Figure 2 than in Figure 1, which implies that social science journals are increasingly interconnected in recent years.

[3] It should be noted that only edges with weights larger than 0.6 are shown in the network visualizations.Recall that we adjusted the raw pearson's *r* by plus 1 and then divided by 2. Therefore, the adjusted *r* value lower than 0.6 means that its corresponding raw pearson's *r* is lower than 0.2, which indicates small proximity between the journal pair.

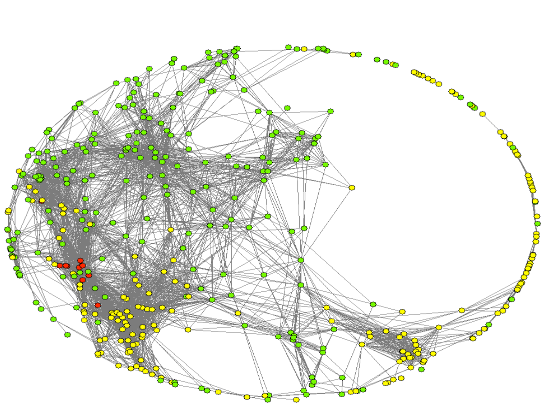

Figure 1. 1960-1985 network by journal

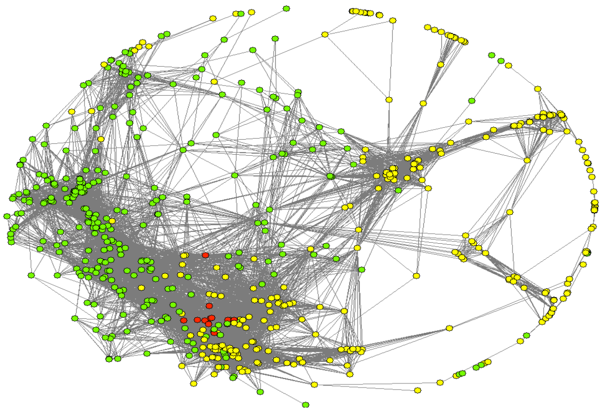

Figure 2. 1985-2010 network by journal

In order to explore the structure of the networks on the disciplinary level, we then aggregated all journals by ISI category. Therefore, journals are put into 41 categories: one for each of the 40 disciplines and one cross-disciplinary category. Figure 3 and 4 display the disciplinary co-citation networks for 1960-1985 and 1985-2010, respectively. These are labelled on the macro level, with green denoting social sciences and yellow denoting sciences. The size of the circle is dictated by the number of journals in the corresponding discipline.

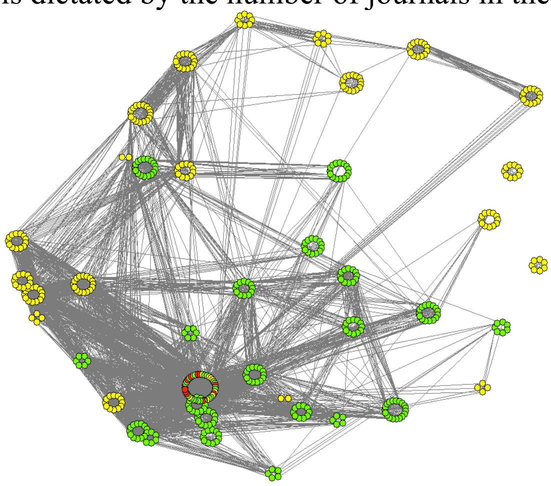

Figure 3. 1960-1985 network by discipline

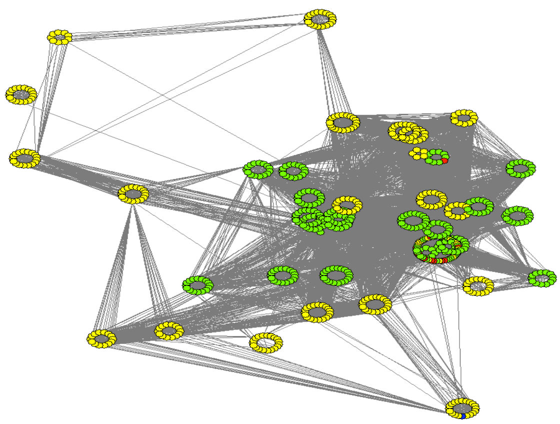

Figure 4. 1985-2010 network by discipline

Some details can be examined between these two networks. As with the journal networks, the earlier time period is less connected than the later time period, indicating greater convergence in the 1985-2010 between all disciplines. Additionally, we see closer connections between some science and social sciences in 1985-2010 than in 1960-1985. However, many science disciplines remain removed from the center of the network.

Centrality of disciplines in 1960-1985 period and 1985-2010 period

The journal and aggregated journal co-citation networks give us a general view of how interaction and communication between disciplines changed in the two time periods. For a closer look at how the role of each discipline changed, group centrality measures are employed. In this case, journals indexed in the same discipline by WoK are treated as a group (partition). The degree centrality, closeness centrality and betweenness centrality for each discipline are calculated according to Everett and Borgatti's (2005) group centrality definitions. A program in C++ was developed and employed to calculate the degree centrality, closeness centrality and betweenness centrality for each disciplines in two different time periods. It should be noted that all isolated nodes in both networks are removed in order to calculate the degree, closeness and betweenness centrality, leading to 468 journals in 1960-1985 network and 666 in 1985-2010 network.

Appendix A shows us the values of each centrality measure and corresponding rankings. Table 3 shows the correlation between the centrality measures in both networks. It shows that the group degree centrality in both networks is significantly correlated, while the closeness centrality and betweenness centrality in these two networks is not.

Table 3. Kendall's tau_b correlation result on centrality ranks

			Degree		*Closeness*		*Betweenness*	
			1960-1985	*1985-2010*	*1960-1985*	*1985-2010*	*1960-1985*	*1985-2010*
Degr	*1960-1985*	*Cor.*	1.000					
	1985-2010	*Cor.*	.569**	1.000				.
Clos	*1960-1985*	*Cor.*	.182	.131	1.000			
	1985-2010	*Cor.*	.110	-.003	.097	1.000		
Betw	*1960-1985*	*Cor.*	.48	.019	-.191	-.055	1.000	
	1985-2010	*Cor.*	.031	.183	-.039	-.129	-.110	1.000

*Correlation is significant at the 0.01 level (2-tailed).

Specifically, degree centrality of social science disciplines seems to be significantly correlated, but their betweenness and closeness centrality appears not correlated within these two networks. Similar analysis was done to look into the centrality change of science disciplines within these two networks. The results show that, for science disciplines, their degree centrality is significantly correlated, but closeness and betweenness centrality are not, which is the similar case for social science disciplines.

Discipline degree centrality

Group degree centrality, according to the definition, shows the number of nodes outside the group that are connected to that group. The larger the group degree is, the more central position the discipline is in the network. Appendix A shows us the degree centrality of all 40 disciplines. It should be noted that degree centrality here is the normalized group centrality. The average discipline degree in the 1960-1985 network is 0.431, and in 1985-2010 network is 0.612. The following table indicates that social sciences disciplines and science disciplines show significant difference in both networks. In other words, science disciplines and social science disciplines demonstrate significant changes diachronically.

Table 4. t-test for science and social Science disciplines degree centrality in both network

	t	*df*	*Sig.(2-tailed)*
1960-1985 network	-4.313	38	0.000
1985-2010 network	-3.652	38	0.001

Overall, social science disciplines rank higher than science discipline do by degree centrality. For social science disciplines, History of Science ranks first by degree centrality in both networks, showing its consistent central roles among disciplines. Economics and Library and Information Science begin to show high degree centrality in 1985-2010 network, which indicates their increasing interrelatedness among disciplines. There are some social science disciplines that show less central roles in the 1985-2010 network than in 1960-1985 network, such as Social Psychology and Public Administration. Some social science disciplines, however, rank consistently lower in both networks, such as Geography, Political Science, and Social Psychiatry. According to the definition of degree centrality, these disciplines are those disciplines that, generally, do not have dominant positions in interdisciplinary knowledge communication and interaction.

For science disciplines, Biology and Public Health rank consistently higher in degree centrality among science disciplines. Some disciplines rank consistently lower in both networks, such as Mathematics, Palaeontology, Chemistry, Astronomy, Geology, and Physics, all of which are also lower ranked disciplines among all 40 disciplines in this research. Computer Science, according to degree centrality in this paper, experienced abrupt increasing in degree centrality ranking through these two networks. This can be explained by increasingly wide range of application in other field and great importance to other disciplines in today's world, for both science and social science.

Based on our assumption that co-citation tells something about journal/discipline similarity, the more disciplines to which a discipline is similar, the more cross discipline features the discipline shows. Therefore, we can say that some science disciplines bear less cross-disciplinary features than some social science disciplines, and this does not change significantly between the two time periods.

Discipline closeness centrality

Closeness centrality indicates the influence of a node on the entire network, and thus discipline centrality in this research can tell how "close" each discipline is to the other disciplines and the influence that a discipline puts on the entire network. Our result shows that the average normalized discipline closeness in 1960-1985 network (0.934) is slightly lower than 1985-2010 network (0.937), which indicates that, on average, disciplines in 1985-2010 network are closer to other disciplines than in 1960-1985 network. In this case, we might conclude that these 40 disciplines are more interconnected over time.

On the other hand, social science and science disciplines have different behaviours in these two networks, regarding their closeness centrality in the co-citation network. Among the top 20 disciplines by closeness centrality in 1985-2010 network, 13 are social science disciplines, which is the same case as in 1960-1985 network. As shown in Table 5, social science disciplines and science disciplines do not show significant difference in 1960-1985 network, but do in 1985-2010 network. If we regard the meaning of closeness centrality as it is defined, then we would say that, on average, social science disciplines are more similar to each other than science disciplines are.

Table 5. t-test for science and social science disciplines closeness centrality in both networks

	t	*df*	*Sig.(2-tailed)*
1960-1985 network	.250	38	.804
1985-2010 network	-2.340	38	.025

For social science disciplines, there are some that rank consistently higher in both networks, such as Criminology and Social Psychology, and some rank consistently lower in both networks, such as Demography and Law. Linguistics has the largest number of closeness centrality in 1960-1985 network, but declined to a lower rank in 1985-2010 network.

For science disciplines, Mathematics and Computer Science increased in closeness ranking from the 1960-1985 network to the 1985-2010 network, which indicates that they are moving closer to other disciplines and thus bear more interdisciplinary features. On the other hand, some science disciplines, such as Public Health, Nursing, Neuroscience and Engineering, have a lower rank in the 1985-2010 network. This can mean that their influence is weakened and they are sharing similarities with fewer disciplines in recent 25 years.

Discipline betweenness centrality

According to the definition of group betweenness, discipline betweenness centrality in this paper reflects the bridge role of a discipline in a knowledge communication network. The larger the discipline betweenness, the more control that the discipline has over the interaction between other disconnected disciplines. As shown in Appendix A, the average betweenness centrality in the 1960-1985 network is 0.0049, which is slightly lower than that in 1985-2010 network (0.0050). Of the top 10 betweenness centrality disciplines in 1985-2010 network, nine of them rank in the lower half by betweenness in 1960-1985 network. Thus, we can say that, on average, each of these 40 disciplines in 1985-2010 network are more likely to serve as bridges for communicating between other disciplines, implying a more interconnected network in current years.

On the other hand, social science and science disciplines behave differently in these two networks, regarding their betweenness centrality in the co-citation network. Among the top 20 disciplines by betweenness centrality in 1985-2010 network, 13 are social science disciplines, which is the same case as in 1960-1985 network. The results shows that social science disciplines and science disciplines do not show significant difference in 1960-1985 network, but do in 1985-2010 network. If we regard the meaning of betweenness centrality as it is defined, then we would say that, on average, social science disciplines are more bridged in the current time periods than science disciplines are.

Table 6. t-test for science and social science disciplines betweenness centrality in both networks

	t	*df*	*Sig.(2-tailed)*
1960-1985 network	-1.885	38	.121
1985-2010 network	-.396	38	.694

Business holds comparatively higher rank than other social science disciplines in 1960-1985 network, and declines a little in 1985-2010 network. Thus, we might conclude that Business takes a less important role in knowledge communication among disciplines as time goes by. In contrast, Public Administration ranks higher in 1985-2010 network then in 1960-2010 network. Public Administration ranks 36th by betweenness in 1960-1985 network but ranks first in 1985-2010 networks, showing that more and more disciplines rely on it to communicate and interact with other disciplines. Some science disciplines have a relatively higher rank in 1985-2010 network than in 1960-1985 network, such as Computer Science, Ecology, Nanoscience, while some disciplines are in the opposite direction, such as Agriculture, and Palaeontology.

Conclusion and Future work

The innovative use of group centrality measure reveals the role of each discipline in discipline knowledge communication and interaction networks. By using co-citation information of 677 journals from 40 disciplines from WoK, group centrality measures are employed in this research. Two networks, representing two time periods, are constructed using journal co-citation information. An overview of our data set shows that science disciplines are more productive than social science disciplines; journals are more interconnected in recent years; and social science disciplines bear more cross-disciplinary features than science disciplines.

The discipline knowledge communication network based on journal co-citation information is dynamic between the first and second time periods, in terms of degree, closeness and betweenness centrality. The result shows that only degree centrality in the two time periods are correlated, and both closeness and betweenness centrality of disciplines in these two networks are not correlated. Science and social science disciplines experienced changes between these two networks. Degree centrality of social science disciplines seems to be significantly correlated, but their betweenness and closeness centrality seems not correlated within these two networks. Similar analysis was done to look into the centrality change of science disciplines within these two networks. It shows that degree centrality is significantly correlated, but closeness and betweenness centrality are not, which is the similar case as social science disciplines. According to the definition of three centrality measures, a possible reason for this might be that disciplines of both science and social science might have a similar number of disciplines that they seem to be alike, but the extent to which these disciplines are similar to others might change a lot.

Social science disciplines hold and keep a more central role in knowledge communication network compared with science disciplines, which can be approved by degree, closeness and betweenness centrality. In both networks, most of the top 20 disciplines in degree, closeness and betweenness centrality are social science disciplines. Most disciplines experienced increasing ranking between networks are from social science. Therefore, it seems that social science disciplines, according to group centrality measures, are more cross-disciplinary than science disciplines are. It should be noticed that Computer Science experienced abrupt increasing in rankings by all three centrality measures, indicating its increasingly important role in the entire academic network, which is an exception of science disciplines.

Group centrality measures of network analysis, including degree, closeness and betweenness centrality are employed in this paper to explore the role of each discipline in knowledge communication and interaction among disciplines. According to group centrality result, degree, closeness and betweenness centrality can tell different aspects of group's role in network analysis. Our result shows that degree, closeness and betweenness are not correlated when they used to analyze discipline roles. Discipline degree centrality measures the number of nodes that are directly connected to this discipline, and put emphasis on how many disciplines are similar to this discipline regardless of the extent to which this discipline is similar to others. Discipline closeness and betweenness centrality, however, takes into account the weight of edges, i.e. the similarity of each journal pair. Closeness measures how geographically close on average a discipline is to other disciplines in the discipline network, while betweenness tells us the probability that a discipline serves as a bridge between disciplines. These three measurements tell different things about a discipline's role in networks. Therefore, comprehensive analysis of a group's role in a network might require all three in order to get a comprehensive analysis.

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Appendix A

Field	Discipline	Degree				Closeness				Betweenness			
		1960		2010		1960		2010		1960		2010	
		Val.	R.	Val.	R.	Val.	R.	Val.	R.	Val.	R.	Val.	R.
SS	HISTORYSCIENCE	0.908	1	0.941	1	1.025	5	1.005	6	0.0002	30	0.0015	19
SS	ANTHROPOLOGY	0.869	2	0.843	5	1.004	16	0.994	8	0.0001	34	0.0311	2
SS	HISTORY	0.77	5	0.726	9	1.003	21	0.955	15	0.0196	3	0	36
SS	SOCIOLOGY	0.768	6	0.722	11	0.784	35	0.942	18	0.007	9	0.0008	22
SS	DEMOGRAPHY	0.767	7	0.843	4	0.721	37	0.802	37	0.0065	11	0.0035	12
SS	EDUCATION	0.766	8	0.725	10	0.984	26	0.913	24	0.0001	32	0.0007	25
SS	SOCPSYCH	0.762	9	0.691	17	1.008	10	1.426	1	0.0017	19	0	36
SS	PUBLICADMIN	0.733	12	0.67	20	1.004	18	1.317	2	0	36	0.0356	1
SS	MANAGEMENT	0.729	13	0.677	19	0.498	39	0.911	26	0.0065	10	0.0027	16
SS	LAW	0.728	14	0.619	25	0.478	40	0.831	34	0.0131	5	0.0007	23
SS	SOCWORK	0.727	15	0.654	21	1.005	15	1.111	4	0.0015	21	0.0009	21
SS	LINGUISTICS	0.724	16	0.711	14	1.132	2	0.932	19	0.0256	2	0.0011	20
SS	CRIMINOLOGY	0.715	17	0.645	23	1.01	7	1.184	3	0.0045	14	0.0002	29
SS	COMMUNICATION	0.709	19	0.704	15	1.003	20	1.004	7	0.0012	24	0	36
SS	ECONOMICS	0.695	21	0.809	7	1.006	13	1.009	5	0.0004	28	0.0096	9
SS	PSYCHIATRY_SOC	0.693	22	0.56	29	1.004	19	0.912	25	0	37	0.0091	10
SS	LIS	0.687	24	0.839	6	0.855	32	0.822	36	0.0021	18	0.0003	28
SS	BUSINESS	0.684	25	0.683	18	1.004	17	0.77	38	0.0373	1	0.0035	13
SS	POLISCI	0.681	26	0.647	22	1.029	4	0.963	13	0.0088	7	0	34
SS	GEOGRAPHY	0.679	27	0.616	26	1.009	8	0.944	17	0	38	0.0097	8
S	PUBLIC HEALTH	0.796	3	0.691	16	1.008	9	0.883	29	0.0051	13	0.0018	17
S	PSYCHOLOGY	0.785	4	0.727	8	1.134	1	0.951	16	0	38	0.0027	15
S	BIOLOGY	0.761	10	0.719	12	0.99	24	0.928	22	0.0054	12	0.0001	32
S	ZOOLOGY	0.738	11	0.716	13	1.007	11	0.971	12	0.0115	6	0.0108	7
S	MEDICINE	0.712	18	0.576	28	0.955	28	0.874	30	0.0012	23	0	35
S	NEUROSCIENCE	0.708	20	0.641	24	1.056	3	0.647	39	0.0001	35	0.0016	18
S	NURSING	0.688	23	0.552	30	1.013	6	0.842	31	0	38	0	33
S	PSYCHIATRY	0.646	28	0.545	31	1.006	14	0.985	11	0.0001	33	0.0005	26
S	ENGINEERING	0.634	29	0.849	3	1.002	23	0.633	40	0.0016	20	0.0113	6
S	ECOLOGY	0.608	30	0.263	37	0.988	25	0.929	21	0.0029	15	0.0139	4
S	IMMUNOLOGY	0.547	31	0.488	32	0.894	31	0.825	35	0.0021	17	0.0032	14
S	NANOSCIENCE	0.545	32	0.581	27	0.788	34	0.836	33	0.0008	27	0.0131	5
S	AGRICULTURE	0.412	33	0.386	35	0.605	38	0.89	28	0.0141	4	0.005	11
S	COMPUTER SCIENCE	0.287	34	0.937	2	0.805	33	0.987	10	0.0011	26	0.0244	3
S	MATHEMATICS	0.255	35	0.314	36	1.007	12	0.994	9	0.0003	29	0	36
S	PALEONTOLOGY	0.241	36	0.21	39	1.002	22	0.917	23	0.008	8	0	36
S	CHEMISTRY	0.21	37	0.409	34	0.937	29	0.91	27	0.0001	31	0.0001	31
S	ASTRONOMY	0.205	38	0.25	38	0.975	27	0.963	14	0.0013	22	0.0007	24
S	GEOLOGY	0.196	39	0.205	40	0.733	36	0.931	20	0.0011	25	0.0003	27