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# Insight into the Disciplinary Structure of Nanoscience & Nanotechnology

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## Abstract

**Purpose:** This paper aims to gain an insight into the disciplinary structure of nanoscience & nanotechnology (N&N): What is the disciplinary network of N&N like? Which disciplines are being integrated into N&N over time? For a specific discipline, how many other disciplines have direct or indirect connections with it? What are the distinct subgroups of N&N at different evolutionary stages? Such critical issues are to be addressed in this paper.

**Design/methodology/approach:** We map the disciplinary network structure of N&N by employing the social network analysis tool, Netdraw, identifying which Web of Science Categories (WCs) mediate nbetweenness centrality in different stages of nano development. Cliques analysis embedded in the Ucinet program is applied to do the disciplinary cluster analysis in the study according to the path of "Network-Subgroup-Cliques," and a tree diagram is selected as the visualizing type.

**Findings:** The disciplinary network structure reveals the relationships among different disciplines in the N&N developing process clearly, and it is easy for us to identify which disciplines are connected with the core "N&N" directly or indirectly. The tree diagram showing N&N related disciplines provides an interesting perspective on nano research and development (R&D) structure.

**Research limitations:** The matrices used to draw the N&N disciplinary network are the original ones, and normalized matrix could be tried in future similar studies.

**Practical implications:** Results in this paper can help us better understand the disciplinary structure of N&N, and the dynamic evolution of N&N related disciplines over time. The findings could benefit R&D decision making. It can support policy makers from government agencies engaging in science and technology (S&T) management or S&T strategy planners to formulate efficient decisions according to a perspective of converging sciences and technologies.

**Originality/value:** The novelty of this study lies in mapping the disciplinary network structure of N&N clearly, identifying which WCs have a mediating effect in different developmental

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stages (especially analyzing clusters among disciplines related to N&N, revealing close or distant relationships among distinct areas pertinent to N&N).

**Keywords** Nanoscience & nanotechnology (N&N); Disciplinary structure; Social network analysis; Cluster analysis; Cliques analysis; Dynamic evolution

## 1 Introduction

As a typical emerging and converging technology field, nanoscience & nanotechnology (N&N) has attracted tremendous governmental funds and scientific efforts. Articles in the field of N&N have grown explosively. With the rapid development of N&N, studies on N&N have been widely conducted by information scientists worldwide.

Disciplinary analysis of N&N as a major research area has drawn many scholars' interests. Numerous topics of N&N have been studied, such as impact evaluation of N&N (Bartol & Stopar, 2015; Kostoff, Barth, & Lau, 2008; Leydesdorff, 2013), nano-competition or "nanorace" among countries or regions or institutions (Gorjiara & Baldock, 2014; Guan & Wei, 2015; Leydesdorff & Wagner, 2009; Wong, Ho, & Chan, 2007), technological life cycle of N&N (Anick, 2007; Milanez et al., 2013), and mapping of N&N (Bartol & Stopar, 2015; Kostoff, Koytcheff, & Lau, 2007; Mohammadi, 2012).

Investigations into the interdisciplinarity of N&N have been explored from a wide range of aspects. From the view of author collaboration, hypotheses, such as whether the collaboration in the area of N&N is of an obvious nature, have been proposed (Schummer, 2004), yet the results have not verified the assumption. As far as the toxicology and environmental risks of N&N are concerned, some approaches from interdisciplinary angles have been presented; some examples are an interdisciplinary approach for a comprehensive analysis of the impacts and ethical acceptability of nano technologies (Patenaude et al., 2015); and an interdisciplinary challenge for nanotoxicology has also been pointed out (Krug & Wick, 2011). Actually, various fields related to N&N from the perspective of interdisciplinarity have been studied, such as environmental areas (Bottero et al., 2015), chemistry and physics (Lindquist, 2014), material science (Mody & Choi, 2013), and biotechnology & genomics (Heimeriks, 2013).

Studies concerning the disciplinary structure of N&N are warranted to help set context for analyses of N&N research patterns and knowledge exchange. Porter and Youtie have explored the disciplinary structure of N&N by using Science Citation Index (SCI) journals' Subject Categories (SCs). They selected nano-related papers by means of a Boolean search in SCI: "nano*," less exclusions, then plus seven additional modules, detailed by Porter et al. (Porter et al., 2008; Porter & Youtie, 2009). Following this approach, we note that Subject Categories (SCs, WoS version 4) have been supplanted by "Web of Science Categories" (WCs, WoS version 5) launched in August, 2011. We address WCs to accomplish the analysis of the disciplinary structure of N&N in this paper. Compared to SCs, the 222 ISI Subject Categories (SCs) for SCI & Social Sciences Citation Index (SSCI)'s two databases in version 4 of Web of Science (WoS) were renamed and extended to 225 WoS Categories (WCs) (also, a new set of 151 Subject Areas were added, but a higher level of aggregation) (Leydesdorff, Carley, & Rafols, 2013). Thus, we use WCs to detect the disciplinary structure of N&N, further conducting a comparison with conclusions of Porter and Youtie (2009) with the predecessor SCs.

Besides analysis from the perspective of the social network analysis of the disciplinary structure of N&N, cluster analysis by employing cliques embedded in Ucinet software has also been conducted in this paper. This can help understand the disciplinary structure evolution of N&N.

It is of great significance to study the disciplinary structure of N&N both for theory and practice. Theoretically, this study can help us understand the disciplinary and knowledge origins from the beginning of N&N development and trace the trajectory of related subjects' convergence over time. Practically, it will support research and development (R&D) policy-makers to formulate decisions according to a perspective of converging sciences and technologies.

This paper is organized as follows: Following the introduction, Section 2 introduces data and methods; Section 3 shows the analyses and results; Section 4 states the discussions and conclusions.

## 2 Data and Methods

### 2.1 Data

Data in this study are retrieved from the database of Science Citation Index-Expanded, SCI-E. N&N has been listed as a WC in SCI-E nowadays, so it is convenient for us to capture articles belonging to the research area of N&N. Articles in the WC of N&N have been searched in the SCI-E database. Our search strategy is as follows: document types = article; WC for nanoscience nanotechnology; time span: 1900–2014; limited to SCI-E. The date of data search and download is July 1, 2015. We retrieved 249,596 resulting records. The yearly distribution of N&N articles is shown in Figure 1.

The WC called *nanoscience nanotechnology* is used as the search strategy for N&N in this study. One reason is that we believe this WC employed here is likely to capture a core of N&N publications more crisply than other strategies. Another reason is that WC-based searching has been employed in some recent studies

(Herranz & Ruiz-Castillo, 2012; Sweileh et al., 2014). There is possibly a third reason: though a sophisticated "nano" search strategy was presented by Arora and Porter et al. (2013), times change and topical emphases shift. WoS indexers, in associating journals to WCs may have some advantages over topical term based determinations. Readers should recognize that there may be advantages and disadvantages in studying term-based *versus* WC-based search results. For one, we note that our results are more selective. Applying the Arora et al.'s strategy in September, 2016, we retrieved some 144,000 articles *versus* about 33,000 articles from our N&N WC-based search. Our results here are more selective; arguably more representative of "core" nano R&D.

In order to gain an insight into the evolution of the disciplinary structure of N&N in different developmental phases, Statistical Product and Service Solutions (SPSS) software is employed to do the phase-dividing work. Three variables, (different years, the amount of N&N articles published in each year, and the number of distinct WCs of N&N articles in each year) are selected according to the method of Hierarchical Cluster Analysis embedded in SPSS, combining significant events during the N&N developing history, such as the Scanning Tunneling Microscope invented in 1981 (Tersoff & Hamann, 1983; Tersoff & Hamann, 1985), the Atomic Force Microscope invented in 1986 (Binnig, Quate, & Gerber, 1986; Martin, Williams, & Wickramasinghe, 1987), and the US National Nanotechnology Initiative (NNI) taken in 2000 (Roco, 2001; Jung & Lee, 2014). Three stages have been obtained: Stage I: 1966–1980, the infancy phase; Stage II: 1981–1999, the preliminary development phase; and Stage III: 2000–2014, the fast development phase (Figure 1).

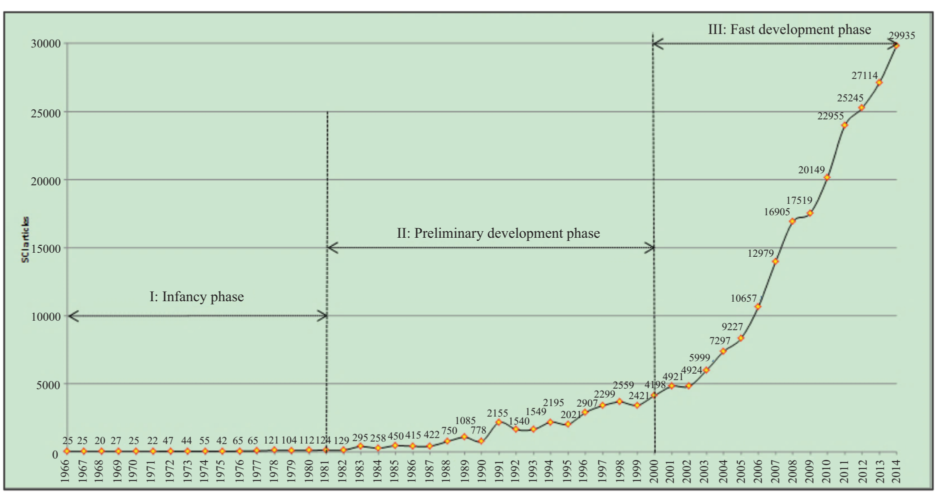


Figure 1. Development phases of nanoscience and nanotechnology (1966–2014).

We recognize that nanoscience does not really get started in any reasonable way until the advent of the Scanning Tunneling Microscope in 1981 and the Atomic Force Microscope in 1986, so we begin at the second stage timeframe. The evolution of the N&N disciplinary structure during stage II and stage III will be explored, respectively.

## 2.2 Methods

### 2.2.1 Construction of Disciplinary Co-occurrence Matrix

Disciplinary co-occurrence matrix reports the relationship among different disciplines of N&N, as operationalized as WCs. The matrix construction is the basic work for analyzing disciplinary network structure and disciplinary cliques here. WCs provide an effective level of measurement of discipline for the study of interdisciplinary processes (National Academies Committee on Facilitating Interdisciplinary Research, 2005). The 225 or so WCs (the number is adjusted slightly over time) reflect sub-disciplines (e.g. Organic Chemistry). WCs have been selected to map science disciplines (Leydesdorff, Carley, & Rafols, 2013), and to do many other bibliometric analyses (Fu & Ho, 2015; Garner, Porter, & Newman, 2014; Lin & Ho, 2015).

An article may involve contributions from two or more disciplines. Keep in mind that the classification into WCs is based on the journal of publication, not on analysis of the individual article. In the SCI-E database, some 40% of journals are associated with multiple WCs; for example, there are six WCs in the following article in the area of N&N.

*TI: Thermally stable, efficient polymer solar cells with nanoscale control of the interpenetrating network morphology*

- *Chemistry, Multidisciplinary;*
- *Chemistry, Physical;*
- *Nanoscience & Nanotechnology;*
- *Materials Science, Multidisciplinary;*
- *Physics, Applied;*
- *Physics, Condensed Matter*

These six WCs in this record (this is an extreme example; recall that nearly 60% of journals are associated with a single WC) represent the co-occurrence relationship. That is, the record is associated with multiple disciplines (WCs). Bibexcel (Persson & Dastidar, 2013) and Ucinet (Borgatti & Everett, 1999; Freeman, Borgatti, & White, 1991) are jointly employed to get the WC co-occurrence matrix as follows (Table 1). Take the cell crossed by 5 and 8 with value of 1,794 for an example, it means that the co-occurrence frequencies of 5 (Chemistry_Applied) and 8 (Chemistry_Physical) are 1,794 times.

Table 1. Web of Science category, WC co-occurrence matrix (Partial).

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0 | 22 | 0 | 0 | 0 | 0 | 800 | 0 | 0 | 0 |
| **2** | 22 | 0 | 1,685 | 1,685 | 0 | 0 | 0 | 0 | 0 | 1,685 |
| **3** | 0 | 1,685 | 0 | 1,685 | 0 | 0 | 0 | 0 | 0 | 1,685 |
| **4** | 0 | 1,685 | 1,685 | 0 | 0 | 0 | 0 | 0 | 0 | 1,685 |
| **5** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,794 | 0 | 0 |
| **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | 800 | 0 | 0 | 0 | 0 | 0 | 0 | 7,878 | 0 | 0 |
| **8** | 0 | 0 | 0 | 0 | 1,794 | 0 | 7,878 | 0 | 0 | 0 |
| **9** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **10** | 0 | 1,685 | 1,685 | 1,685 | 0 | 0 | 0 | 0 | 0 | 0 |

*Note.* 1: Biochemical_Research_Methods; 2: Biophysics; 3: Biotechnology_&_Applied_Microbiology; 4: Chemistry_Analytical; 5: Chemistry_Applied; 6: Chemistry_Inorganic_&_Nuclear; 7: Chemistry_Multidisciplinary; 8: Chemistry_Physical; 9: Computer_Science_Hardware_&_Architecture; 10: Electrochemistry.

### 2.2.2 Analysis of Disciplinary Network Structure and Each Discipline's Mediating Effect

After obtaining the WC co-occurrence matrix, we can map the disciplinary network by employing Netdraw (Johnson et al., 2009). The WC co-occurrence matrix we used here is the original matrix derived from the bibliographic data, and the Jaccard index method proposed by Leydesdorff (2008) has not been employed here, for the total disciplines (WCs) concerning N&N are not more than 40, and the disciplinary network structure can be visualized clearly by mapping directly from the original WC co-occurrence matrix. The disciplinary networks help us identify the ties among disciplines engaged in N&N and the evolution of the disciplinary network structure over time. It is simple for us to find out which disciplines have connections with a specific discipline in the network (Figure 2).

The indicator of betweenness centrality (Equation 1) is applied to measure each discipline's mediating effect according to the path of Network-Centrality-Freeman Betweenness-Node Betweenness, embedded in the Ucinet program, and to further help us understand the mechanism of the evolution of N&N. Betweenness is a centrality measure of a vertex within a graph. Betweenness centrality quantifies the number of times a node acts as a bridge along the shortest path between two other nodes (Freeman, 1977).

If $g_{jk}$ denotes the number of geodesics between $j$ and $k$, the probability is $1/g_{jk}$ when all the geodesics are equally selected to be the communicative paths among each node. $g_{jk}(n_i)$ represents the number of geodesics between two nodes including $n_i$, and the betweenness centrality of $n_i$ can be calculated by Equation (1):

$$C_B = \sum_{j<k} g_{jk}(n_i) / g_{jk}. \quad (1)$$

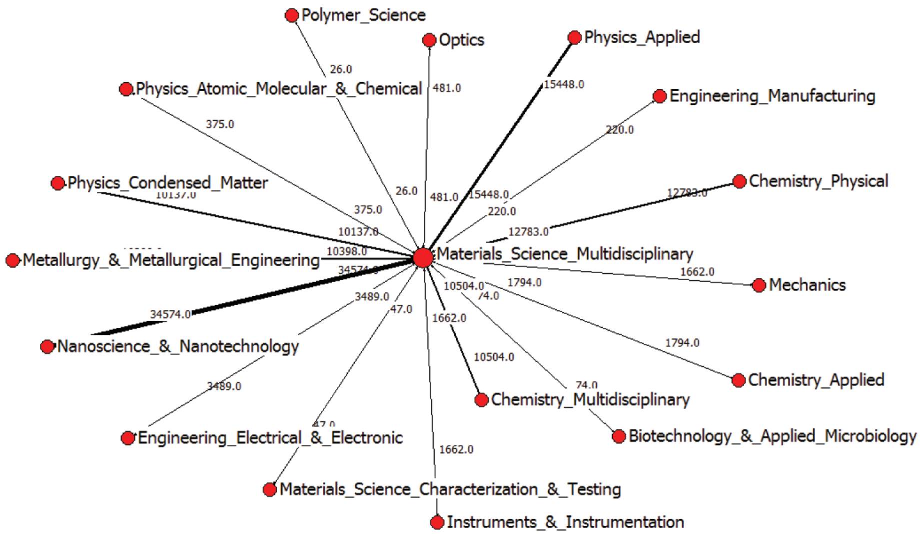


Figure 2. Ego-network: Disciplines connected with a specific discipline.

The higher the betweenness centrality of a specific discipline concerning N&N is, the more contribution this discipline has made to the development of N&N.

### 2.2.3 Analysis of Disciplinary Clusters

Cliques analysis embedded in the Ucinet program is employed to do the disciplinary cluster analysis in the study according to the path of "Network-Subgroup-Cliques." Cliques are one of the basic concepts of graph theory and are used in many other mathematical problems and constructions on graphs. Since the numbers of disciplines concerning N&N are comparatively limited (no more than 40), and the disciplinary network is composed of a whole component, cliques analysis is found out doing well in a subgroup, and cluster analysis is found after exploring several other schemes (e.g. N-Clan, K-Plex, Lambda Set, Factions, f-Groups, etc.).

The disciplinary network structure of N&N, mapped by employing the social network analysis tool, helps us better understand the dynamic evolution of N&N over time from the perspective of the evolution of the network structure, such as nodes and links added over time. Tree diagrams of N&N disciplines inform the dynamic evolution of N&N from a logical view by showing relationships among different disciplines near or far.

# 3 Analyses and Results

## 3.1 Mapping Disciplinary Network Structure and Measuring Each Discipline's Mediating Effect by Betweenness Centrality

According to the methods illustrated in Section 2.2, we first mapped the disciplinary network structure in two stages: Stage II, the preliminary development phase (1981–1999), and Stage III, the fast development phase (2000–2014); and then we measured each discipline's mediating effect by selecting the indicator of betweenness centrality in each network.

### 3.1.1 Stage II, the Preliminary Development Phase (1981–1999)

In this technology's early development phase (1981–1999), there are a total of 22 WCs participating in the N&N related disciplinary network (Figure 3), and these WCs are connected with each other, forming a whole network.

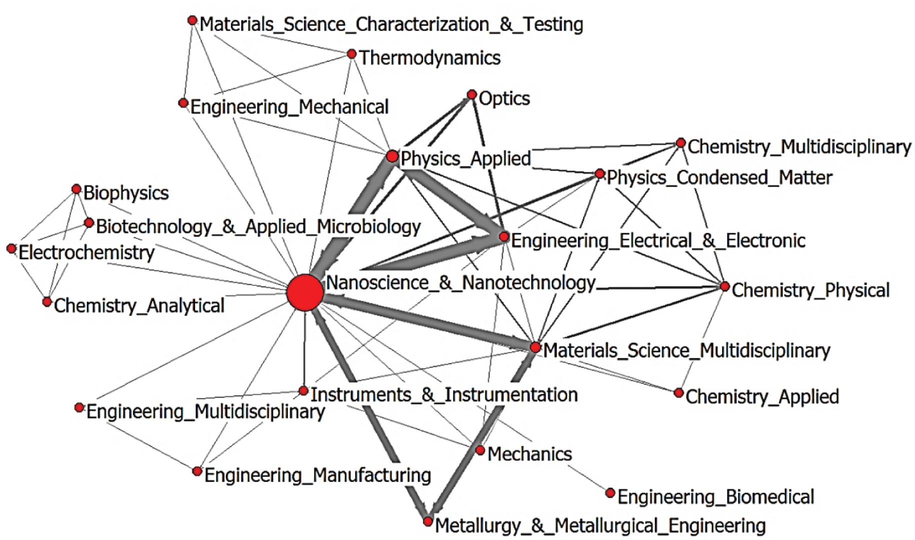


Figure 3. Disciplinary network structure of nanoscience & nanotechnology in Stage II, the preliminary development phase (1981–1999) in terms of betweenness centrality. Tie strength: Minimum line width of 1 and maximum line width of 2. Totally 22 nodes.

The map of the disciplinary network of Stage II, 1981–1999, in Figure 3 seems very dense, and the disciplinary network structure appears to be comparatively obvious, with concentrations relating to *Nano-Biotechnology*, *Nano-Manufacturing*, *Nano-Materials*, *Nano-Electronics*, *Nano-Physics*, *Nano-Chemistry*, *Nano-Biomedical*, and *Nano-Thermodynamics*.

In Figure 3, not only can we easily identify those WCs connected with N&N directly or indirectly but also determine if those WCs are also linked to any specific discipline (WC) directly or indirectly. In fact, each WC in Figure 3 can be mapped as an ego-network of disciplinary structure, as shown in Figure 2.

In Figure 3, the relationships among *Physics Applied*, *Engineering Electrical & Electronic*, and *Nanoscience & Nanotechnology* are the strongest ones in the network; the links among *Materials Science Multidisciplinary*, *Metallurgy & Metallurgical Engineering*, and *Nanoscience & Nanotechnology* are much stronger than the rest.

In Stage II, during 1981–1999, a total of seven WCs have played mediating effects (Table 2). The discipline of *Nanoscience & Nanotechnology* plays the highest mediating effect, with a normalized betweenness centrality of 68.095; the discipline of *Physics Applied* has the second highest nbetweenness centrality[①] of 5.317; *Materials Science Multidisciplinary* has an nbetweenness centrality of 4.921, the 3rd; and *Engineering Electrical & Electronic* has an nbetweenness centrality of 1.429; also *Instruments Instrumentation* has an nbetweenness centrality of 1.429; the other two disciplines with mediating effects are *Chemistry Physical* (0.476) and *Physics Condensed Matter* (0.238)[②].

Table 2. Values of betweenness and nbetweenness centrality over 0 of each discipline in Stage II: 1981–1999.

| Rank | ID | Betweenness | nBetweenness |
|---|---|---|---|
| 1 | Nanoscience_&_Nanotechnology | 143.000 | 68.095 |
| 2 | Physics_Applied | 11.167 | 5.317 |
| 3 | Materials_Science_Multidisciplinary | 10.333 | 4.921 |
| 4 | Engineering_Electrical_&_Electronic | 3.000 | 1.429 |
| 5 | Instruments_&_Instrumentation | 3.000 | 1.429 |
| 6 | Chemistry_Physical | 1.000 | 0.476 |
| 7 | Physics_Condensed_Matter | 0.500 | 0.238 |

### 3.1.2 Stage III, the Fast Development Phase, 2000–2014

In Stage III, the fast development phase from 2000 to 2014, more disciplines are added into the disciplinary network (Figure 4). The core N&N network expands to 34 WCs. These WCs are connected with each other, forming a whole network.

The density of the disciplinary network in Stage III is much higher than that of Stage II, especially the left part of the network. 12 new WCs are added in Figure 4 compared to Figure 3; they are *Biochemical Research Methods*, *Chemistry Inorganic & Nuclear*, *Computer Science-Hardware & Architecture*, *Environmental Sciences*, *Materials Science-Biomaterials*, *Medicine-Research & Experimental*,

① nBetweenness refers to normalized betweenness centrality.
② But keep in mind that the set of records was determined by a search on the N&N WC as such.

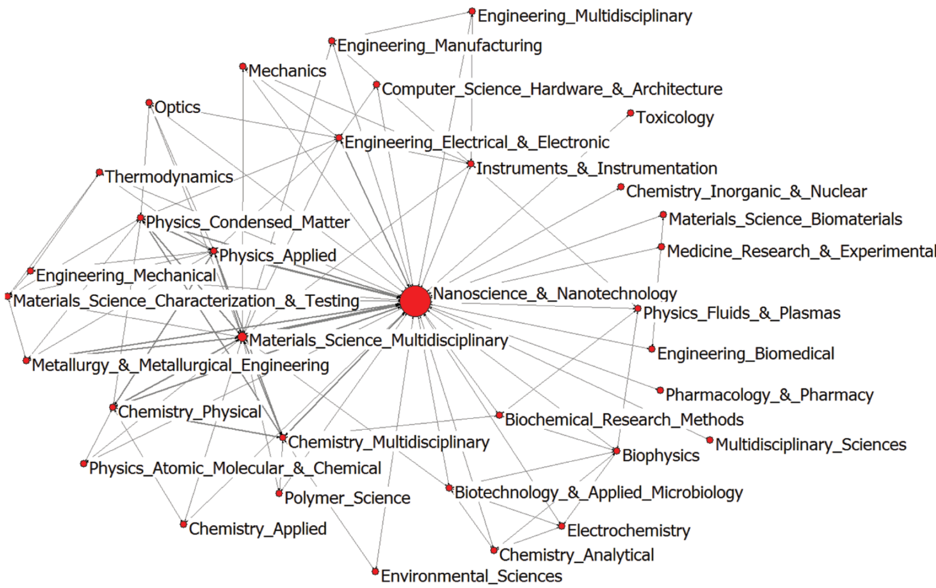


Figure 4. Disciplinary network structure of nanoscience & nanotechnology in Stage III, the fast development phase 2000–2014: betweenness centrality. Tie strength: Minimum line width of 2 and maximum line width of 4. Totally 34 nodes.

*Multidisciplinary Sciences*, *Pharmacology & Pharmacy*, *Physics- Atomic-Molecular & Chemical*, *Physics-Fluids & Plasmas*, *Polymer Science*, and *Toxicology*. A total of 14 WCs have played mediating effects in Stage III: 2000–2014 (Table 3).

Table 3. Values of betweenness and nbetweenness centrality over 0 of each discipline in Stage III: 2000–2014.

| Rank | ID | Betweenness | nBetweenness |
|---|---|---|---|
| 1 | Nanoscience_&_Nanotechnology | 394.833 | 74.779 |
| 2 | Materials_Science_Multidisciplinary | 35.000 | 6.629 |
| 3 | Physics_Applied | 9.000 | 1.705 |
| 4 | Chemistry_Multidisciplinary | 6.500 | 1.231 |
| 5 | Engineering_Electrical_&_Electronic | 5.000 | 0.947 |
| 6 | Instruments_&_Instrumentation | 4.500 | 0.852 |
| 7 | Biophysics | 3.000 | 0.568 |
| 8 | Physics_Condensed_Matter | 3.000 | 0.568 |
| 9 | Chemistry_Physical | 2.333 | 0.442 |
| 10 | Materials_Science_Characterization_&_Testing | 2.000 | 0.379 |
| 11 | Biotechnology_&_Applied_Microbiology | 1.500 | 0.284 |
| 12 | Physics_Fluids_&_Plasmas | 1.000 | 0.189 |
| 13 | Biochemical_Research_Methods | 1.000 | 0.189 |
| 14 | Engineering_Manufacturing | 0.333 | 0.063 |

It is notable that *Material Science Multidisciplinary* plays a very important role with a much higher nbetweenness value than the other WCs—except for *Nanoscience*

*& Nanotechnology*. It becomes a critical mediating point bridging other disciplines. In Stage III, the discipline of *Nanoscience & Nanotechnology* still plays the highest mediating effect with an nbetweenness centrality of 74.779; *Materials Science Multidisciplinary* has an nbetweenness centrality of 6.629; there are two other disciplines with an nbetweenness value exceeding 1.0—*Physics Applied* with 1.705 and *Chemistry Multidisciplinary* with 1.231.

### 3.1.3 Comparisons of Stage II and Stage III

In order to have an overview of the two development stages, Stage II and Stage III, three indicators (density, average distance, and mean nbetweenness (m-nbetweenness)) are selected to do the comparison, and the results are shown in Table 4.

Table 4. Comparison between two stages: Density, avg. distance, and m-nbetweenness.

| | Density (Avg. value) | Avg. distance | M-nbetweenness |
|---|---|---|---|
| Stage II | 518.636 | 1.745 | 3.723 |
| Stage III | 804.373 | 1.836 | 2.613 |

Table 4 shows that the value of density is higher in Stage III than in Stage II, indicating closer relationships among N&N related disciplines over time. As far as average distance is concerned, the average distance becomes further as time goes on, which is mainly due to more and more subjects that have appeared. In terms of mean nbetweenness, the value is smaller over time, which is also because of more WCs participating in the arena of N&N over time.

## 3.2 Cluster Analysis of N&N Related Disciplines

Though the disciplinary networks of N&N in Section 3.1 can tell us what the whole network structure is like, they also help us identify which WCs are connected to a specific discipline. Yet, sometimes the clustering of WCs is not so clear. Thus, clique analysis embedded in the Ucinet program is employed to do cluster analysis, and this will further help us detect the main domains of N&N by selecting the tree diagram display of a subgroup analysis.

### 3.2.1 Stage II-Preliminary Development Phase (1981–1999)

According to the method illustrated in Section 2.2, and following the path of Network-Subgroup-Cliques of Ucinet, selecting *tree diagram* as the diagram type, nine cliques (Figure 5) have been found in Stage II, the preliminary development phase (1981–1999), as follows.

*A: Chemistry Multidisciplinary*, *Chemistry Physical Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Physics Condensed Matter*

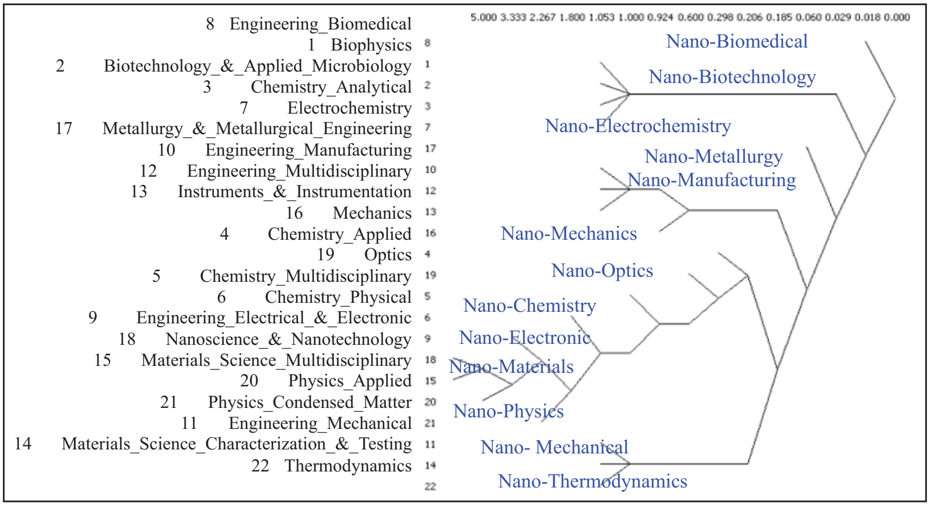


Figure 5. Cliques of nanoscience & nanotechnology in Stage II: 1981–1999.

B: *Chemistry Applied*, *Chemistry Physical*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*

C: *Engineering Electrical & Electronic*, *Instruments & Instrumentation*, *Materials Science Multidisciplinary*, *Mechanics*, *Nanoscience & Nanotechnology*

D: *Engineering Electrical & Electronic*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Physics Condensed Matter*

E: *Materials Science Multidisciplinary*, *Metallurgy & Metallurgical Engineering*, *Nanoscience & Nanotechnology*

F: *Biophysics*, *Biotechnology & Applied Microbiology*, *Chemistry Analytical*, *Electrochemistry*, *Nanoscience & Nanotechnology*

G: *Engineering Manufacturing*, *Engineering Multidisciplinary*, *Instruments & Instrumentation*, *Nanoscience & Nanotechnology*

H: *Engineering Mechanical*, *Materials Science Characterization & Testing*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Thermodynamics*

I: *Engineering Electrical & Electronic*, *Nanoscience & Nanotechnology*, *Optics*, *Physics Applied*

Figure 5 shows that the cliques of N&N are clearly identified in Stage II: 1981–1999. There are six branches from the root in the tree diagram, and they are (1) *Nano-Biomedical*, *Nano-Biotechnology*, (2) *Nano-Metallurgy*, (3) *Nano-Manufacturing*, (4) *Nano-Material*, (5) *Nano-Mechanical*, and (6) *Nano-Thermodynamics*. This indicates that in this phase, many branches of N&N have come into being. The linking branch with *Nano-Material* is the biggest one in the map associated with some other sub-branches, such as *Nano-Chemistry*, *Nano-Electronic*, *Nano-Physics*, and *Nano-Optics*.

#### 3.2.2 Stage III: Fast Development Phase (2000–2014)

By using the same method, we get 18 cliques (Figure 6) in Stage III, the fast development phase, 2000–2014, as follows.

*A: Chemistry Multidisciplinary*, *Chemistry Physical*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Physics Condensed Matter*

*B: Engineering Electrical & Electronic*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Optics*, *Physics Applied*, *Physics Condensed Matter*

*C: Materials Science Characterization & Testing*, *Materials Science Multidisciplinary*, *Metallurgy & Metallurgical Engineering*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Physics Condensed Matter*

*D: Chemistry Applied*, *Chemistry Physical*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*

*E: Engineering Manufacturing*, *Instruments & Instrumentation*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*

*F: Engineering Electrical & Electronic*, *Instruments & Instrumentation*, *Materials Science Multidisciplinary*, *Mechanics*, *Nanoscience & Nanotechnology*

*G: Biotechnology & Applied Microbiology*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*

*H: Chemistry Physical*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Physics Atomic Molecular & Chemical*

*I: Chemistry Multidisciplinary*, *Materials Science Multidisciplinary*, *Nanoscience & Nanotechnology*, *Polymer Science*

*J: Biophysics*, *Biotechnology & Applied Microbiology*, *Chemistry Analytical*, *Electrochemistry*, *Nanoscience & Nanotechnology*

*K: Computer Science Hardware & Architecture*, *Engineering Electrical & Electronic*, *Nanoscience & Nanotechnology*

*L: Engineering Biomedical*, *Materials Science Biomaterials*, *Nanoscience & Nanotechnology*

*M: Engineering Mechanical*, *Materials Science Characterization & Testing*, *Nanoscience & Nanotechnology*, *Physics Applied*, *Thermodynamics*

*N: Engineering Manufacturing*, *Engineering Multidisciplinary*, *Instruments & Instrumentation*, *Nanoscience & Nanotechnology*

*O: Chemistry Multidisciplinary*, *Environmental Sciences*, *Nanoscience & Nanotechnology*

*P: Biochemical Research Methods*, *Biophysics*, *Nanoscience & Nanotechnology*, *Physics Fluids & Plasmas*

*Q: Biochemical Research Methods*, *Chemistry Multidisciplinary*, *Nanoscience & Nanotechnology*

*R: Instruments & Instrumentation*, *Nanoscience & Nanotechnology*, *Physics Fluids & Plasmas*

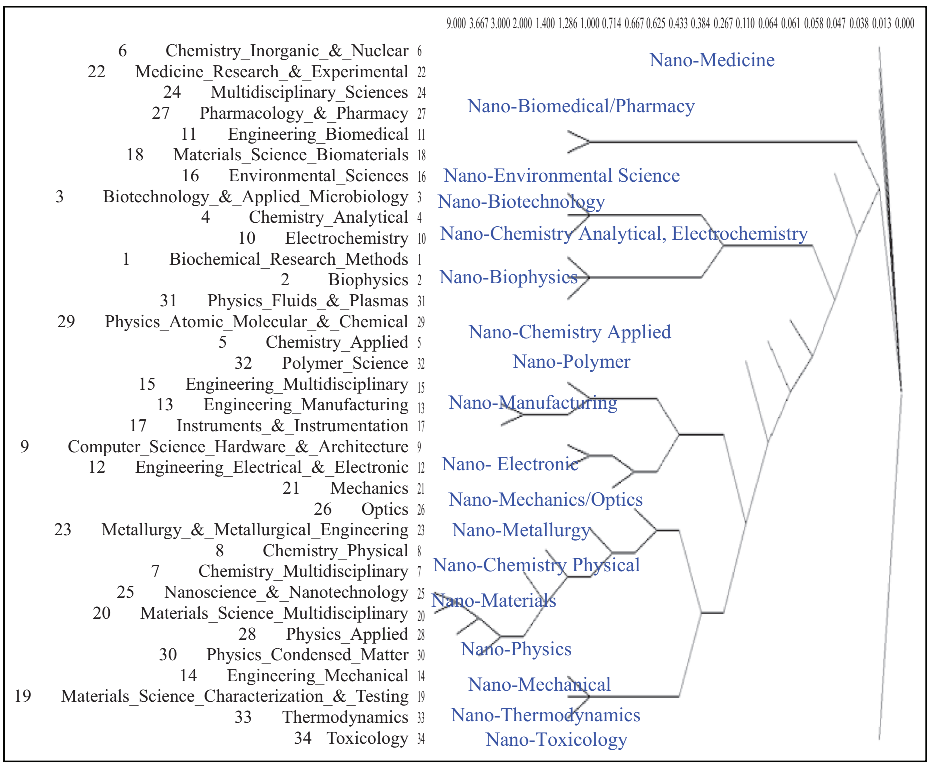


Figure 6. Cliques of nanoscience & nanotechnology in Stage III: 2000–2014.

Figure 6 demonstrates two imbalanced domains of N&N: A smaller one is about *Nano-Biomedical/Pharmacy*; the much bigger one is covering *Nano-Manufacturing*, *Nano-Metallurgy*, *Nano-Electronic*, *Nano-Mechanics*, *Nano-Biotechnology*, *Nano-Chemistry Analytical*, *Nano-Electrochemistry*, *Nano-Biochemical*, *Nano-Environmental Science*, *Nano-Chemistry Physical*, *Nano-Chemistry Applied*, *Nano-Optics*, *Nano-Materials*, *Nano-Physics*, *Nano-Mechanical*, *Nano-Thermodynamics*, and *Nano-Toxicology*.

## 4 Discussion and Conclusion

In this study, some extant studies pertinent to N&N were reviewed, and it was proposed that studies regarding the disciplinary structure of N&N were insufficient. Next, the research purpose and significance were stated, as well as data sources and methods. The data in this paper are from SCI-E with a WC of N&N; a total of 249,596 results of N&N articles are obtained. The methods in this study mainly involve social network analysis and cluster analysis by employing the Ucinet program and Bibexcel software.

The disciplinary network structure reveals relationships among different disciplines in the N&N developing process. We identify the disciplines that are connected with N&N directly or indirectly (and even the disciplines that are linked to a specific discipline). In general, more N&N related disciplines converge into the N&N developing process over time in stages; also, the density of the disciplinary network is closer as time goes on and the average distance is further over time. The value of mean nbetweenness is also smaller. More WCs play a mediating effect with the evolution of different phases of N&N; *Materials Science* and *Physics Applied* play a very critical mediating role in the course of development of N&N, besides N&N itself.

The results of N&N cluster analysis show logical relationships among different disciplines related to N&N. The analysis can reveal the original knowledge source at the beginning stage of N&N, the dynamic evolution of N&N over time and also show us relative strength of connections among the different disciplines. With the development of N&N, besides *Nano-Engineering* and *Nano-Manufacturing*, more and more other branches have come into being gradually, such as *Nano-Materials*, *Nano-Chemistry Applied*, *Nano-Polymer*, *Nano-Optics*, *Nano-Metallurgy*, *Nano-Mechanical*, and *Nano-Thermodynamics*, *Nano-Electrochemistry*, *Nano-Biotechnology*, *Nano-Biomedical*, and *Nano-Environmental Science.*

The novelty of this research lies in mapping the disciplinary network structure of disciplines related to N&N, based on a search using WC in SCI-E. That is also both the strength in focusing on one version of an N&N core, and the limitation in that it does not address the wider swath of R&D that can be identified by a broad, term-based search in such databases. Here, we identify the WCs playing a mediating effect in two stages (especially, analyzing clusters among disciplines related to N&N, revealing close or distant relationships among distinct areas pertinent to

N&N). The results help better understand the knowledge sources of N&N at the beginning stage, and also the dynamic evolution of N&N over time.

Compared to similar previous research, core data of the domain of N&N have been selected and analyzed in this paper. There are many studies concerning the interdisciplinary structure of N&N and various subfields and further research could compare results and their implications with such studies to better understand the disciplinary network structure and dynamics (c.f. Porter & Youtie, 2009; Souminen, Li, & Youtie, 2016; Wang & Shapira, 2011).

Another point in this paper is that the WCs (version 5) launched by Thomson Reuters in August 2011 are selected to accomplish the analysis of the disciplinary structure of N&N, supplanting the ISI Subject Categories (SCs) for SCI & SSCI (two databases in version 4 of Web of Science).

Cluster analysis of disciplines related to N&N by employing cliques function embedded in the Ucinet program helped understand the evolutionary mechanics of N&N. The results help illuminate how the area of N&N developed, and which disciplines have converged into N&N over time.

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## Author Contributions

The study was derived from Chunjuan Luan's (julielcj@163.com, corresponding author) curiosity who intended to find out what the disciplinary structure of nanoscience nanotechnology was like. Alan L. Porter (alan.porter@isye.gatech.edu) has complemented a number of new thoughts and improved the methodologies in detail, and edited the paper entirely. Both authors contributed to the final manuscript.

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