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Trajectory patterns of technology fusion: Trend analysis and taxonomical grouping in nanobiotechnology

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ABSTRACT

The potential of technology fusion has been advanced as a promising breakthrough function to create hybrid technologies. Despite its importance, however, the evolutionary path of technology fusion is yet unexplored. In this paper, by employing the case of nanobiotechnology, we attempt to deepen understanding of the development trajectories of technology fusion in three important aspects. The first aspect is the development of an index that measures the degree of fusion of cross-disciplinary technology at the meso level. The second aspect is to classify the trajectory patterns of technology fusion in terms of fusion degree. We analyze fusion mechanism by utilizing citation network analysis. The third aspect is to visualize the relationship between patents and their backward and forward patent citations, at the patent class level, with their direction on a citation map. This facilitates understanding of the overview as well as fusion patterns. The changes in fusion patterns are analyzed using time series comparisons. An empirical analysis in the nanobiotechnology field shows no positive relationship between the inflow and outflow degree of fusion. We also observe changes in the trajectory patterns of fusion over time. Analysis demonstrates that each fusion pattern has evolved in such a way that technologies focus more on their niche technologies, and that those technologies which cannot incorporate the technology fusion have been eliminated during the development process.

1. Introduction

Amidst the ever faster pace of technological innovation, there have been a number of noteworthy changes in recent innovation trends. They are (a) the complexity of new products, (b) the miniaturization of new products, (c) the digitalization of products, and (d) the changes in architecture of products due to the appearance of new materials [1]. These changes emphasize the importance of the merging and overlapping of technologies [2]. Consequently, technological diversification such as technological convergence or technology fusion began to assume an important role in technology development across almost every industry in the past decade. With the increased interest in cross-disciplinary technologies, many activities that promote collaboration among different scientific and technological fields increased sharply in the anticipation that cross-disciplinary research would generate a higher rate of breakthroughs in recent years [3].

Moreover, techno-paradigm shifts [4] – from production companies to thinking (R&D) organization, from single business dynamics to multitechnologies base, from R&D activities against visible (within the same industry) competitors to invisible (in other industries) competitors, from linear (supply side) technology development to demand articulation process – have stimulated technology fusion even further. Despite the increasing interest in cross-disciplinary/interdisciplinary technology, the

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lack of data on cross-disciplinary/interdisciplinary research being a major impediment, relatively less research has been done on measuring interdisciplinarity with a few exceptions [5,6].

No one would argue that a proper understanding of the trajectory patterns of technology fusion is critical in making policies, decisions and plans in technology management. Researches in technological trajectories have been focused mostly on tracking emerging or key technologies [7–9], and many were limited to historical and descriptive analyses [9–11]. Although quantitative attempts have been made recently to trace trajectories [12–14], these quantitative methods were conducted at the levels of individual patent or sectoral discipline, or at the industrial level.

This paper introduces an index of fusion degree to measure the extent to which the precedent or following technology spreads across diverse technological fields at the meso level, i.e., technology patent class level. Based on the degree of fusion, the patterns of technology fusion mechanisms are defined. Subsequently, the technologies are grouped taxonomically into six patterns based on the inflow degree of fusion and outflow degree of fusion. The changes in fusion patterns over time are analyzed and compared. We develop a way to track the trajectory of technology fusion from its source technologies to its nozzle technologies, using both backward and forward patent citation. The trajectory is mapped with a citation network which shows the citation's direction as well. This visualized map displays an overview of the relationship between technologies and their sources or nozzles in relation to the fusion degree and number of sources or nozzles while it also represents conspicuous comparison between fusion patterns. We utilize both backward and forward patent citations in mapping and measuring the extent of technology fusion.

2. Background studies

2.1. Cross-disciplinary researches, taxonomy and citation network analysis

Long before Kodama [15] used the term ‘technology fusion’ to describe a type of innovation that leads to breakthrough functions by combining at least two or more existing technologies into hybrid technologies, technological convergence [16,17] and other terms such as technological diversification, interdisciplinary and cross-disciplinary technology have been used to describe similar phenomena [3,5,6]. Despite its attractiveness, the study of this phenomenon has been limited due to insufficient data on cross-disciplinary research. Although there are some debates on whether or not bibliometric tools are the most appropriate indicators [18], bibliometric tools have been used as the one of the most straightforward methods of assessing the extent of cross-disciplinarity since the 1980s [5,19,20].

Taxonomies have been widely applied to the studies of technological change, patterns of innovation and knowledge assets [21–24]. As taxonomies classify and name many different items into groups that share common traits, taxonomy can reduce the complexity of empirical phenomena to few and easy-to-remember categories [25]. Well-classified taxonomy of technological trajectories can be used as a predictive tool of the determinants of innovative performance [26].

Among other important virtues of patent citations such as an ability to trace multiple linkages among inventions, inventors, scientists, firms, locations, etc., an ability to trace spillovers and to create indicators of the importance of an individual patent has allowed patent citations to be used to trace the technological trajectories [27]. As citations provide good evidence on links between innovations and their technological ‘antecedents’ and ‘descendants’ [28], they have increasingly become one of the main indicators of the technological relationships among inventions. Numerous studies utilize citations to measure knowledge flows between technologies, technology trends, and so forth [29,30]. Backward citation is used to measure the inflow knowledge from other technologies while forward citation is used to measure the inventive quality in terms of technological and/or economic values [28,31,32]. These unique linking properties of citation provide useful information on what is vital in studying technology fusion, which is greatly influenced by relationships among other technologies. Porter et al. [5] establish an indicator of cross-disciplinary research with citations and references by using journal citation data. There are many other researches using citations to study the diffusion of technological information and to measure technological quality and its influence [33].

Using patent citations in network analysis, individual patents are represented by nodes, and citations among patents are denoted as edges which refer to interactions among nodes [34]. Citation network analysis has been developed starting from a mere counting of the number of citations to more sophisticated methods, such as using weights on citations. The citation network analysis, which is weighted by citation links, is utilized to map technological trajectories and track emerging technologies [7,12,13,35].

3. Methods

3.1. Research framework

To overview the big picture of the technology development trajectory of technology fusion, the development path is examined with patent citation information at the patent class level since bibliometric indicators based on citations and references more accurately capture the generation of cross-disciplinary knowledge than do approaches tracking co-authors' disciplinary affiliations [3]. Although there are many researches on patent citation networks, most of them use a frequency of citations that technology patent received or cited individual patent itself. We use the occurrence frequency of citation classes among patent classes, on which no previous studies have been done at this level, to the best of the authors' knowledge.

To classify the development patterns of technology fusion, technology trajectories are mapped by using a patent citation network. Backward citations, which reflect the influence of prior art on a particular technology, are used to track past trajectories;

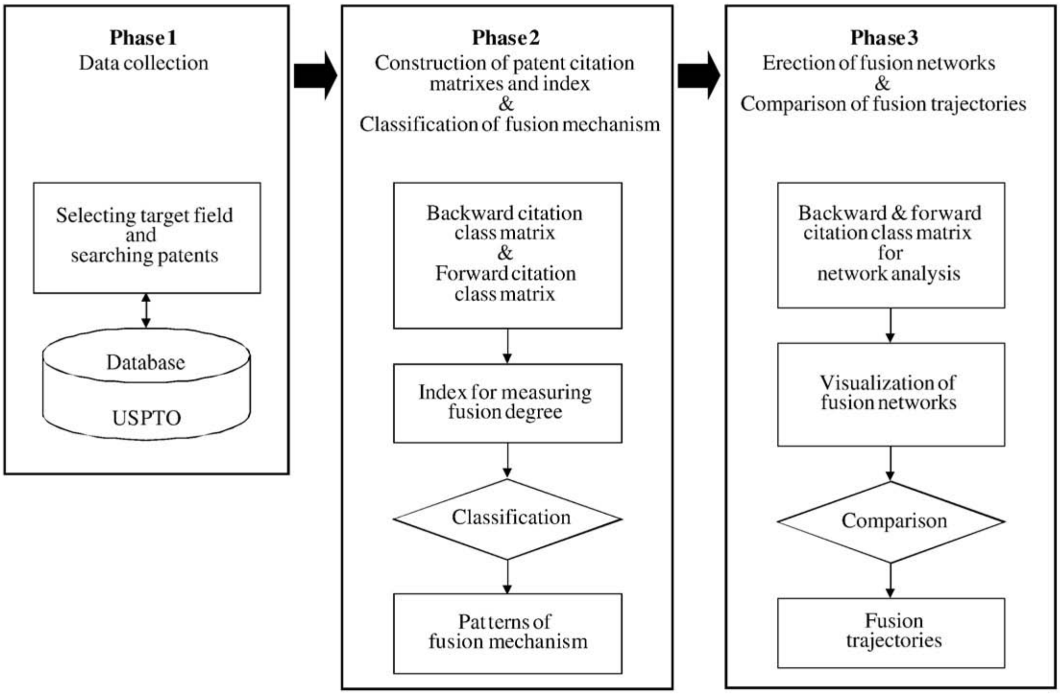
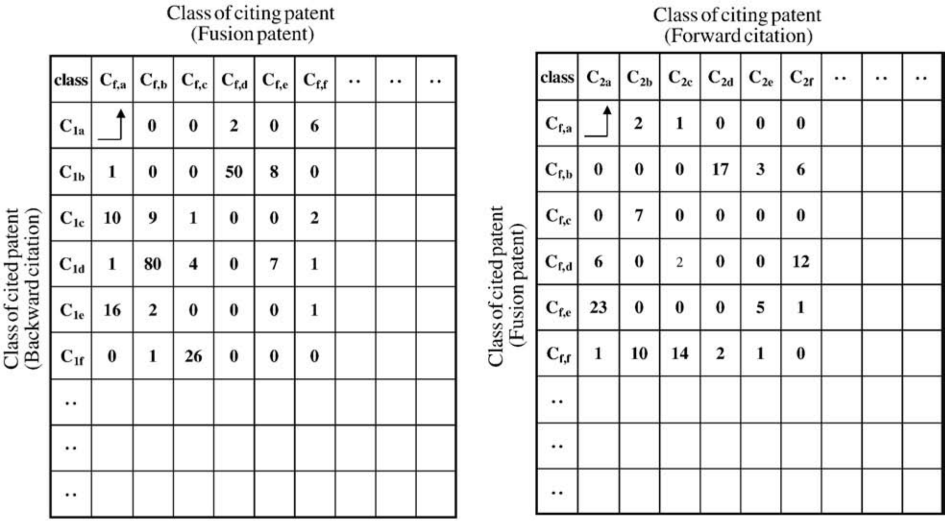


Fig. 1. Overall process of approached algorithm.

and forward citations, which indicate the influence of a technology on successive inventions, are used to estimate future trajectories.

We suggest the following process to map the development trajectory, as shown in Fig. 1. Patent data, including the classes of both backward and forward patent citations, are retrieved from the public patent database. From there, two $n \times m$ matrices are constructed with backward and forward patent citations data, respectively, as shown in Fig. 2. In the backward citation matrix, elements are the citation occurrence frequency in class i, which is cited by class h of technology F, and in the forward citation matrix, elements are the number of citations in class i, which cites class h. The fusion degree of each patent technology class is estimated to be used as a weight in citation networks. In phase 3, the fusion network is erected from the ‘backward and forward citation class matrix,’ which combines backward and forward citation class matrices. Fusion trajectories are classified according to fusion degree in the fusion network.



class	$C_{f,a}$	$C_{f,b}$	$C_{f,c}$	$C_{f,d}$	$C_{f,e}$	$C_{f,f}$	··	··	··
C_{1a}	↑	0	0	2	0	6			
C_{1b}	1	0	0	50	8	0			
C_{1c}	10	9	1	0	0	2			
C_{1d}	1	80	4	0	7	1			
C_{1e}	16	2	0	0	0	1			
C_{1f}	0	1	26	0	0	0			
··									
··									
··									

class	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	··	··	··
$C_{f,a}$	↑	2	1	0	0	0			
$C_{f,b}$	0	0	0	17	3	6			
$C_{f,c}$	0	7	0	0	0	0			
$C_{f,d}$	6	0	2	0	0	12			
$C_{f,e}$	23	0	0	0	5	1			
$C_{f,f}$	1	10	14	2	1	0			
··									
··									
··									

Fig. 2. Backward citation matrix and forward citation matrix.

3.2. Fusion degree

3.2.1. Indicator

In previous research, most indicators that borrow the concept of Herfindal index or Porter's out of category citations to measure the cross-disciplinarity/interdisciplinarity use the portion of citations which is in category *i*. However, we count the number of citation categories (class) in category *i* to measure the extent of its degree of fusion (diversity). This way, we can avoid the multiple counting of the number of categories that are already involved, and correctly measure the number of different fields that are integrated.

The fusion degree of each patent class is measured based on the idea used in Porter and Chubin [5] that computed cross-disciplinary research using a notion of citations/references outside category. The measure using backward citations verifies the breadth of how broadly technology sources are spread across various technological fields. The measure using forward citations computes the extent to which a technology class influences diverse technological fields. Fusion degree would be a reasonable measure to capture the diversity of technology fields that are cited, or cites during technology fusion. The indicators, $C_{\mathrm{IF},h}$ and $C_{\mathrm{OF},h}$ that measure the inflow and outflow degree of fusion of a specific patent class belong to cross-disciplinary technology F varying in the condition are defined by the following equations:

If class *h* is included in the classes cited by class *h*, then

$$C_{\mathrm{IF},h} = \frac{N_{\mathrm{BC},h} - 1}{\left(N_{\mathrm{BC}} - N_{\mathrm{LBC},h}\right) \times n_h} \quad C_{\mathrm{OF},h} = \frac{N_{\mathrm{FC},h} - 1}{\left(N_{\mathrm{FC}} - N_{\mathrm{LFC},h}\right) \times n_h}$$

if class *h* is not included in the classes cited by class *h*, then

$$C_{\mathrm{IF},h} = \frac{N_{\mathrm{BC},h}}{\left(N_{\mathrm{BC}} - N_{\mathrm{LBC},h}\right) \times n_h} \quad C_{\mathrm{OF},h} = \frac{N_{\mathrm{FC},h}}{\left(N_{\mathrm{FC}} - N_{\mathrm{LFC},h}\right) \times n_h}$$

where $N_{\mathrm{BC},h}$ is the number of backward citation classes that is cited by technology class *h* of cross-disciplinary technology F, N_{BC} is the number of all backward citation classes of cross-disciplinary technology F, $N_{\mathrm{LBC},h}$ is the number of the citation classes that is cited only once (cut-off value) by class *h*, and n_h is the number of patents in class *h*. For the calculation of outflow degree of fusion, the number of forward citation classes is used instead of backward citations. The n_h is applied for normalization purposes that avoid the high degree of fusion merely due to the large number of patents in class *h*.[1,2]

Although the different measures of cross-disciplinarity/interdisciplinarity have been used in several papers, there is yet no widely agreed interdisciplinarity indicator. Amongst many measures, the concept of Herfindahl index is probably the most commonly used in the indicators of cross-disciplinarity/interdisciplinarity. Although Herfindahl index is quite suitable for diversity measure, it neglects the degree of differences such as size, distance or similarities [36], and the strength/intensity of the relationship [19] between categories. When measuring the diversity of cross-disciplinarity (degree of fusion), it is important not to disregard the influence of patent size which is a basic, but a critical factor. We estimate how extensively diverse fields of technological fields are integrated while the difference of patent size between categories does not affect the degree of fusion. Consequently, our indicator includes the number of patents that account for the degree of difference due to the size of patents.

The patterns of technology fusion on patent class level are classified according to the relationships between the fusion degree of inflow and outflow that are measured by index of fusion degree.

Each calculated value of the fusion degree for each technology class under cross-disciplinary technology F is applied to the backward and the forward patent citation matrices as an indicator of weight.

3.2.2. Validation

For the validation of the indicator, we compared the biochips field, which is one of the well-known nanobiotechnology fields, with the light bulb field. Although the biochips field was in the beginning stage of development, the difference in the fusion degree was noticeable as seen in Table 1. Even though the citation frequency in the field of light bulb is about twice of that in the biochips field, the number of citation classes is only about three quarters of that in the biochips field. All citation classes belonging to the light bulb field include their own classes, and a significant portion of citations are from their own classes. From the validation, it is shown that the biochips field is developed with more diverse fields of technologies than the fields of light bulb even though there

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[1] The suggested indicator formula appears as though the fusion degree, *C*, may be overestimated whenever the number of patents, *n*, is small. This is true only if the size of patents have a direct and a positive relationship with the fusion degree. However, there is no positive relationship between the number of patents and the fusion degree in the real data. The fusion degree is dependent on the distribution patterns between patents and their citations. The number of patents in a class merely indicates the level of patent activity within the class. More patents in a technology class do not necessarily imply a higher degree of fusion. Therefore, we may not need to worry about the possibility of overestimation of the fusion degree.

[2] There may be a need for different indices for normalization according to the distribution patterns between patents and their citations. Even though our indicator is not perfectly mathematically correct in terms of dealing with size effect, our indicator is quite efficient in eliminating the effect of patent activity between class comparisons.

Table 1
Validation sample.

	No. of patent class	No. of citation	No. of citation class	Fusion degree in each patent class i								
Bio chips	9	127	34	0.33333	0.16667	0.10714	0.0968	0.0968	0.09091	0.07083	0.0625	0.03030
Light bulb	8	247	26	0.29545	0.13043	0.09722	0.08000	0.02666	0.01449	0.00000	0.00000	

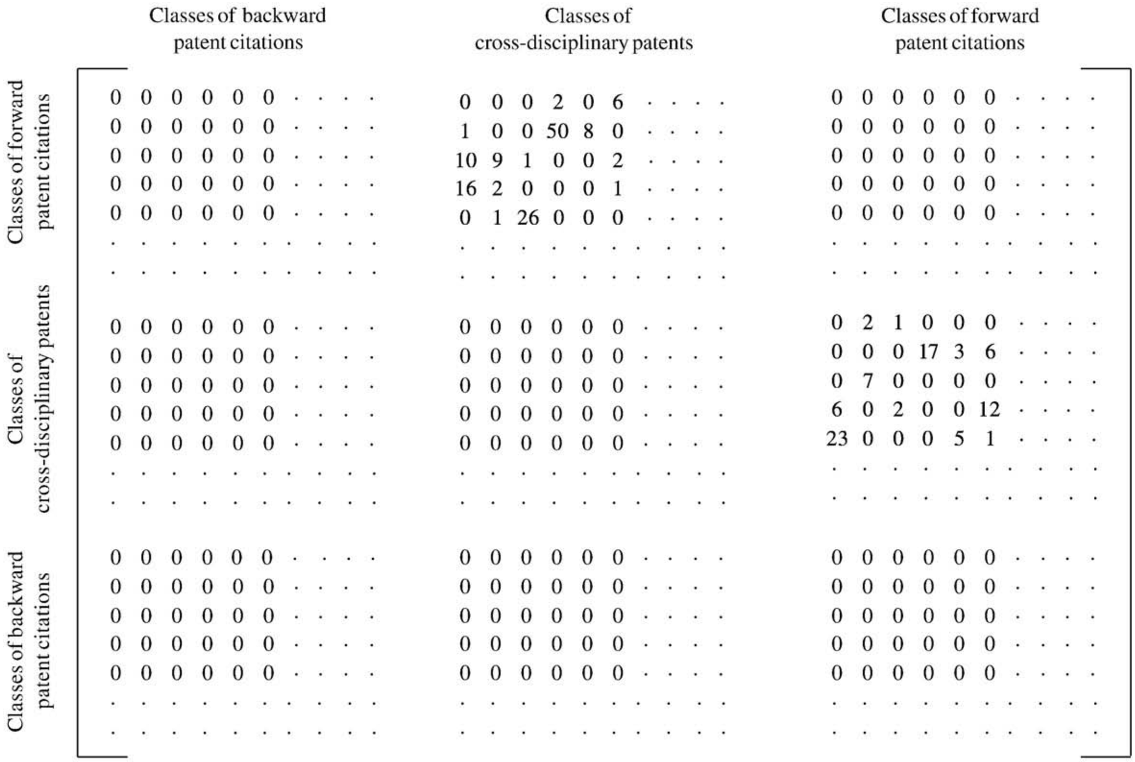
are less numbers of citations in the biochips fields. From this, it can be inferred that fields of technology fusion have more varieties of citation classes than the fields without technology fusion.

3.3. Network generation

The citation network of technology would be a very good relational indicator in tracing trajectories of technologies, including its ascendants and descendants, with an easier display of the complete overview. Backward and forward citation matrices with the weight of fusion degree are combined into one $n \times n$ matrix, as shown in Fig. 3. With combined backward and forward matrix, the 'backward and forward citation' network of cross-disciplinary technology is generated by Ucinet 6.0.

Nodes are defined as a specific technology, at the class level, which belongs to cross-disciplinary technology or as backward/forward patent citation class that would act as a source or nozzle technology of cross-disciplinary technology. The links between the nodes of backward citation and patent, which are the host of technology fusion, become the inflow to the cross-disciplinary technology. The links between the nodes of patent and forward patent citation become the outflow from the cross-disciplinary technology. The thickness of the links indicates the degree of impact of the fusion degree on each source or nozzle technology class. Inflow and outflow is displayed with arrow in order to indicate the directions. The patents are shown as a square while backward and forward patent citations are shown as a circle.

This network visualizes the relationship between technology class and its source and nozzle technology class with respect to the fusion degree and the number of sources or nozzles. Moreover, it provides an easier way of visualizing the patterns of fusion mechanism.



$$
\begin{array}{c|ccccccc|ccccccc|ccccccc}
 & \multicolumn{7}{c|}{\text{Classes of backward patent citations}} & \multicolumn{7}{c|}{\text{Classes of cross-disciplinary patents}} & \multicolumn{7}{c}{\text{Classes of forward patent citations}} \\
\hline
\text{Classes of forward patent citations} & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 2 & 0 & 6 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 0 & 50 & 8 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 10 & 9 & 1 & 0 & 0 & 2 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 16 & 2 & 0 & 0 & 0 & 1 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 26 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & \vdots & & & & & & & \vdots & & & & & & & \vdots & & & & & & \\
\text{Classes of cross-disciplinary patents} & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 2 & 1 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 17 & 3 & 6 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 7 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 6 & 0 & 2 & 0 & 0 & 12 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 23 & 0 & 0 & 0 & 5 & 1 & \cdots \\
 & \vdots & & & & & & & \vdots & & & & & & & \vdots & & & & & & \\
\text{Classes of backward patent citations} & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
 & \vdots & & & & & & & \vdots & & & & & & & \vdots & & & & & & \\
\end{array}
$$

Fig. 3. Combined backward and forward patent citation matrix for mapping.

4. Empirical analysis: The case of nanobiotechnology

4.1. Data: Using patent citation information to trace a nanobiotechnology trajectory

We use the patent citation information for the purpose of tracing technological development trajectory since citations between patents imply the diffusion among technologies. For the empirical analysis, nanobiotechnology patents from a USPTO database are used. The fact that nanotechnology can act as a sensible base technology for cross-disciplinary technology due to its applicable characteristic to almost every technology lends itself to be a strong candidate for the study of cross-disciplinary fields [37]. Moreover, the fact that nanobiotechnology is one of the fastest emerging segments in the cross-disciplinary field [37,38] adds importance to its role. The OECD [39] defined nanobiotechnology as covering the interface among physics, biology, chemistry and engineering sciences.

To mitigate the contention over what is to be considered as cross-disciplinary technology, the nanobiotechnology patent field that incorporates both the nanotechnology and biotechnology classes is classified in terms of both technological classes (IPC) and keywords under the OECD [39] classification and 'NT Patent Analysis Report' by Korean Intellectual Property Office [40]. A total of 517 nanobiotechnology patents were collected which were filed between 1995 and 2005.

Second, to analyze on a patent class level, patent class information was collected on citations totaling 517 patents – published between 1996 and 2005 – which were culled from subsequent patents filed up to August 2008 and all patents cited by the nanobiotechnology patents. The total of 517 nanobiotechnology patents which were published between 1996 and 2005 covered 27 patent classes. Cited patents were 7714 patents covering 152 patent classes and 3034 citing patents covering 111 classes.

4.2. Measuring the fusion degree

In order to indicate the extent of technologies, we use the class citation matrices of each backward and forward patent citation to measure the inflow and outflow degrees of fusion that affect technology fusion to evolve and influence technology fusion, respectively. The higher degree of fusion would indicate that more diverse fields of technologies are involved, and the lower degree of fusion would indicate narrower fields of technologies. For the observation of periodical differences, we divide the nanobiotechnology patent data into two periods, namely, 1996–2000 and 2001–2005, respectively.

Tables 2 and 3 show the value of inflow and outflow degree of fusion and compare the value of inflow and outflow degree of fusion on patent class level that had been published for the two aforementioned periods.

Fig. 4 represents the distribution of patent classes with fusion degree. In the period of 1996–2000, patent classes 252, 422, and 530 had a high value of fusion degree for both inflow and outflow. This implies that these patent classes were developed with the aid of diverse technology fields and influenced the diverse technology fields as well. For 2001–2005, patent class 427 has diverse fields of technologies for its sources and nozzles. By contrast, patent classes 436, 536, 210, 424 and 435, in the period of 1996–2000, and classes 530, 436, 536, 424, 514 and 435, in the period of 2001–2005 are developed from and influence fewer fields of technologies.

Patent classes 560, 702, 210 and 422, in the period of 2001–2005, were developed from diverse technology fields, but they exerted an influence over fewer fields of technologies. This phenomenon seems to indicate converged forms of fusion. The low value of fusion degree of inflow or outflow is interpreted as indicating that a corresponding patent class is developed with the aid

Table 2
Fusion degree of inflow and outflow of nanobiotechnology, 1996–2000.

Fusion degree of inflow	Patent class	Fusion degree of outflow	Flow
0.095239	426	–	only inflow fusion degree
0.070588	252	0.023529	high inflow and outflow fusion degree
0.051829	422	0.0375	high inflow and outflow fusion degree
0.046512	214	–	only inflow fusion degree
0.034483	548	–	only inflow fusion degree
0.023649	530	0.050439	high inflow and outflow fusion degree
0.017241	436	0.01311	low inflow and outflow fusion degree
0.015988	536	0.018044	low inflow and outflow fusion degree
0.011494	210	0.019841	low inflow and outflow fusion degree
0.011364	127	–	only inflow fusion degree
0.011364	205	0.023256	low inflow fusion degree, high outflow fusion degree
0.011236	250	0.061728	low inflow fusion degree, high outflow fusion degree
0.009654	424	0.01503	low inflow and outflow fusion degree
0.009343	435	0.012212	low inflow and outflow fusion degree
0.008235	514	0.021875	low inflow fusion degree, high outflow fusion degree
–	600	0.096386	only outflow fusion degree
–	216	0.0875	only outflow fusion degree
–	359	0.05814	only outflow fusion degree
–	528	0.047059	only outflow fusion degree
–	204	0.041152	only outflow fusion degree
–	382	0.011494	only outflow fusion degree

Table 3
Fusion degree of inflow and outflow of nanobiotechnology, 2001–2005.

Fusion degree of inflow	Patent class	Fusion degree of outflow	Flow
0.190476	560	0.014706	high inflow fusion degree, low outflow fusion degree
0.136364	359	–	only inflow fusion degree
0.08209	427	0.078125	high inflow and outflow fusion degree
0.075758	702	0.014706	high inflow fusion degree, low outflow fusion degree
0.052239	216	–	only inflow fusion degree
0.050725	428	–	only inflow fusion degree
0.043478	205	–	only inflow fusion degree
0.043165	204	–	only inflow fusion degree
0.041045	252	–	only inflow fusion degree
0.029412	250	–	only inflow fusion degree
0.025063	210	0.004902	high inflow fusion degree, low outflow fusion degree
0.025063	422	0.007576	high inflow fusion degree, low outflow fusion degree
0.021898	382	–	only inflow fusion degree
0.021739	600	–	only inflow fusion degree
0.018382	528	0.092308	low inflow fusion degree, high outflow fusion degree
0.014388	504	–	only inflow fusion degree
0.014202	530	0.00764	low inflow and outflow fusion degree
0.01327	436	0.009561	low inflow and outflow fusion degree
0.012478	536	0.012295	low inflow and outflow fusion degree
0.010791	426	0.177966	low inflow fusion degree, high outflow fusion degree
0.010785	424	0.010723	low inflow and outflow fusion degree
0.009569	514	0.005828	low inflow and outflow fusion degree
0.005037	435	0.006061	low inflow and outflow fusion degree
–	523	0.060606	only outflow fusion degree
–	800	0.052239	only outflow fusion degree
–	127	0.044776	only outflow fusion degree
–	548	0.014706	only outflow fusion degree

of fewer fields of technologies or influence over fewer fields of technologies. Patent classes 205 and 514 in the period of 1996–2000 and patent classes 528 and 426 in the period of 2001–2005, which have a low fusion degree for inflow and a high fusion degree for outflow, are evolved with the aid of fewer fields of technologies, but influence the diverse technology fields. It is like diverging into many other different technology fields.

Patent classes, which have only inflow, but has no outflow, are classes 426, 214, 548 and 127 for 1996–2000, and classes 359, 216, 428, 205, 204, 252, 250, 382, 600, and 504 for 2001–2005. Classes 600, 216, 359, 528, 204 and 382 for 1996–2000, and classes 523, 800, 127 and 548 for 2001–2005 are patent classes with only outflow without inflow. In other words, these patent classes have an impact on other fields of technologies only, but have no reference technology fields.

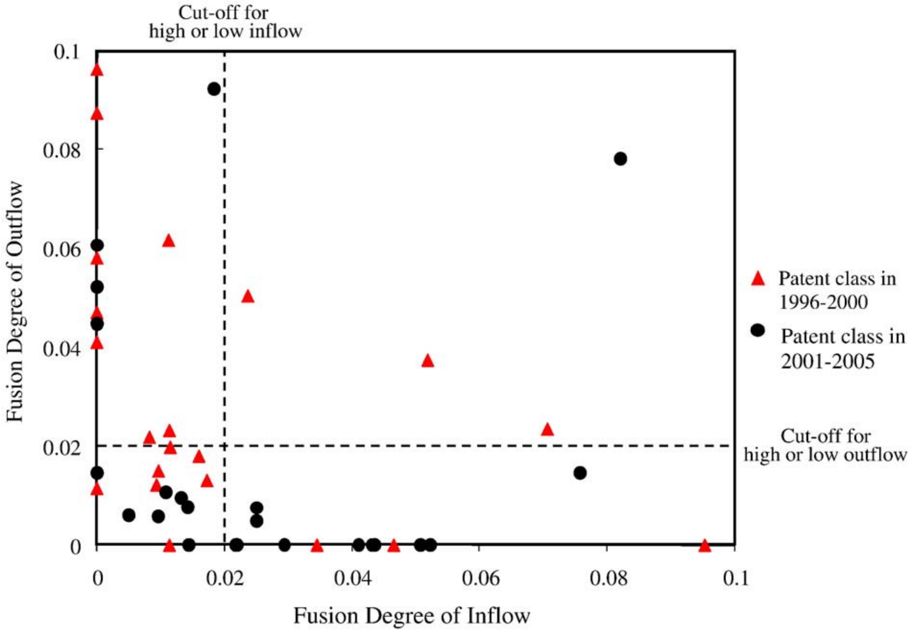


Fig. 4. Distribution of patent classes with fusion degree.

We have been able to ascertain that a patent class with a high degree of fusion source does not necessarily imply a high degree of fusion for nozzle technologies which are able to appear with the help of antecedent technologies. There is no positive relationship between the inflow degree of fusion and the outflow degree of fusion. It can be observed, in 2001–2005 (Fig. 6), that a patent class with diverse source technologies does not necessarily mean that the patent class will influence diverse fields of technologies as well. Classes 560, 702, 210 and 422 are classes that gather knowledge from diverse fields of technologies, but influence rather narrow fields of technologies. In the case of classes 528 and 426, they impact on many more diverse fields of technologies although their source of technology fields is narrow.

4.3. Classifying fusion patterns

We compare the inflow and outflow degree of fusion for each patent class to investigate the fusion patterns along their development paths, from source technologies to nozzle technologies.

The patterns of technology fusion can be classified into a six categories of taxonomy based on patent classes: (i) diverse fields of inflow and outflow technologies, (ii) diverse fields of inflow technologies and narrow fields of outflow technologies, (iii) narrow fields of inflow and diverse fields of outflow, (iv) narrow fields of inflow and outflow technologies, (v) only inflow from other technology fields, and (vi) only outflow to other technology fields. Each category corresponds to (i) high fusion degree of inflow and outflow, (ii) high fusion degree of inflow and low fusion degree of outflow, (iii) low fusion degree of inflow and high fusion degree of outflow, (iv) low fusion degree of inflow and outflow, (v) only inflow fusion degree, and (vi) only outflow fusion degree. They can be explained by the difference in fusion degree between inflow and outflow.

Fusion that advances with the influence of diverse fields of technologies and also affects diverse kinds of technologies is named ‘very heterogeneous-like’ fusion because many heterogeneous classes of source and nozzle technologies are involved. Technology fusion, which is influenced by, and influences, narrow fields of technologies, is named ‘slightly heterogeneous-like’ fusion. We call the phenomenon, which develops with the diverse fields of technologies, but influence rather narrow fields of technologies, ‘converging’ fusion. Fusion with fewer fields of sources and many more fields of nozzles are called ‘diverging’ fusion. Patent class, which has no inflow, but only outflow, is called radiating-only fusion. On the other hand, patent class with only inflow without outflow is called absorbing-only fusion since it does not have any further influence on other technologies, but only absorbs information from other technologies.

Since technology fusion describes a type of innovation that leads to breakthrough function by combining at least two or more existing technologies into hybrid technologies [15], patent classes without either inflow or outflow may not have undergone a complete technology fusion process. Thus, we contend that patent classes having only either inflow or outflow would undergo a partial technology fusion process.

Table 4 summarizes the fusion patterns of technology fusion for nanobiotechnology at patent class level.

4.4. Visualizing the fusion patterns and trajectory of nanobiotechnology

Visualizing the relationships among technologies on a map can be a practical tool for analyzing structures of technological activities [41]. Using backward and forward patent citations in mapping technologies provides visual information to identify its core technologies for merging and emerging. A time series of networks allows the examination of the dynamic changes of technology over time.

We provide a visual map that displays the relationship between technologies and their source or nozzle technology, at patent class level, in relation to the fusion degree of technology class *h* and the number of its sources or nozzles. Figs. 5 and 6 show the trajectories of nanobiotechnology from their sources to nozzles and the examples of visualized fusion patterns during the periods of 1996–2000 and 2001–2005, respectively.

Table 4
Fusion patterns of technology fusion (of nanobiotechnology) on patent class level.

Classification of fusion development	Description	Patent class	Condition (fusion degree)
Very heterogeneous-like fusion	affected by diverse technology fields and influence diverse technology fields	<96-00> 252, 422, 530 <01-05> 427	high fusion degree for both inflow and outflow
Converging fusion	affected by diverse technology fields, but influence narrow fields of technology	<01-05> 560, 702, 210, 422	high fusion degree for inflow, low fusion degree for outflow
Diverging fusion	affected by narrow fields of technology, but influence diverse technology fields	<96-00> 205, 514 <01-05> 528, 426	low fusion degree for inflow, high fusion degree for outflow
Slightly heterogeneous-like fusion	affected by and influence narrow fields of technology	<96-00> 436, 536, 210, 424, 435 <01-05> 530, 436, 536, 424, 514, 435	low fusion degree for both inflow and outflow
Absorbing-only fusion	affected by other technology fields, but not influence any other technology fields	<96-00> 426, 214, 548, 127 <01-05> 359, 216, 428, 205, 204, 252, 250, 382, 600, 504	only inflow fusion degree
Radiating-only fusion	not affected by any other technology fields, but influence other technology fields	<96-00> 600, 216, 359, 528, 204, 382 <01-05> 523, 800, 127, 548	only outflow fusion degree

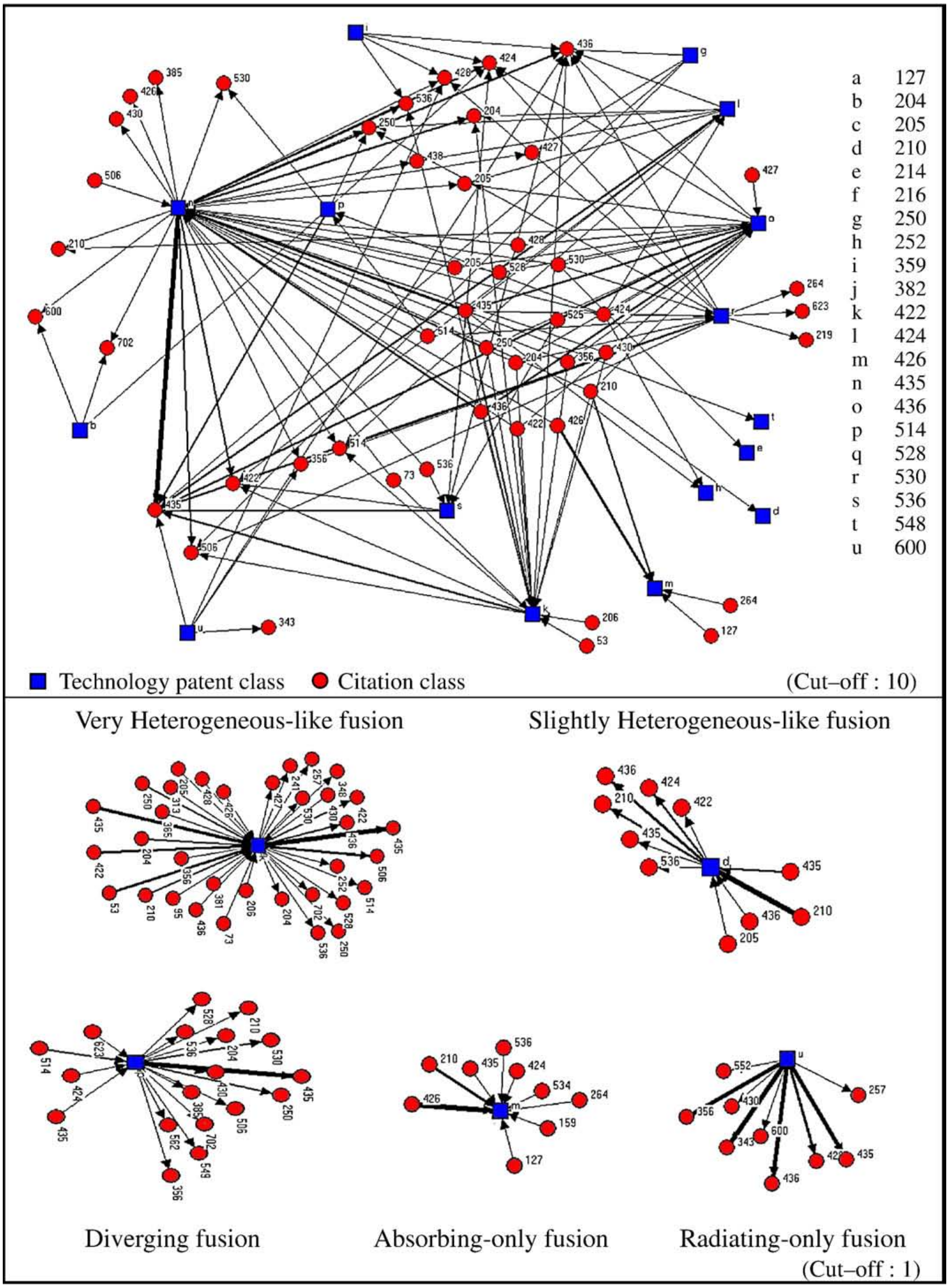
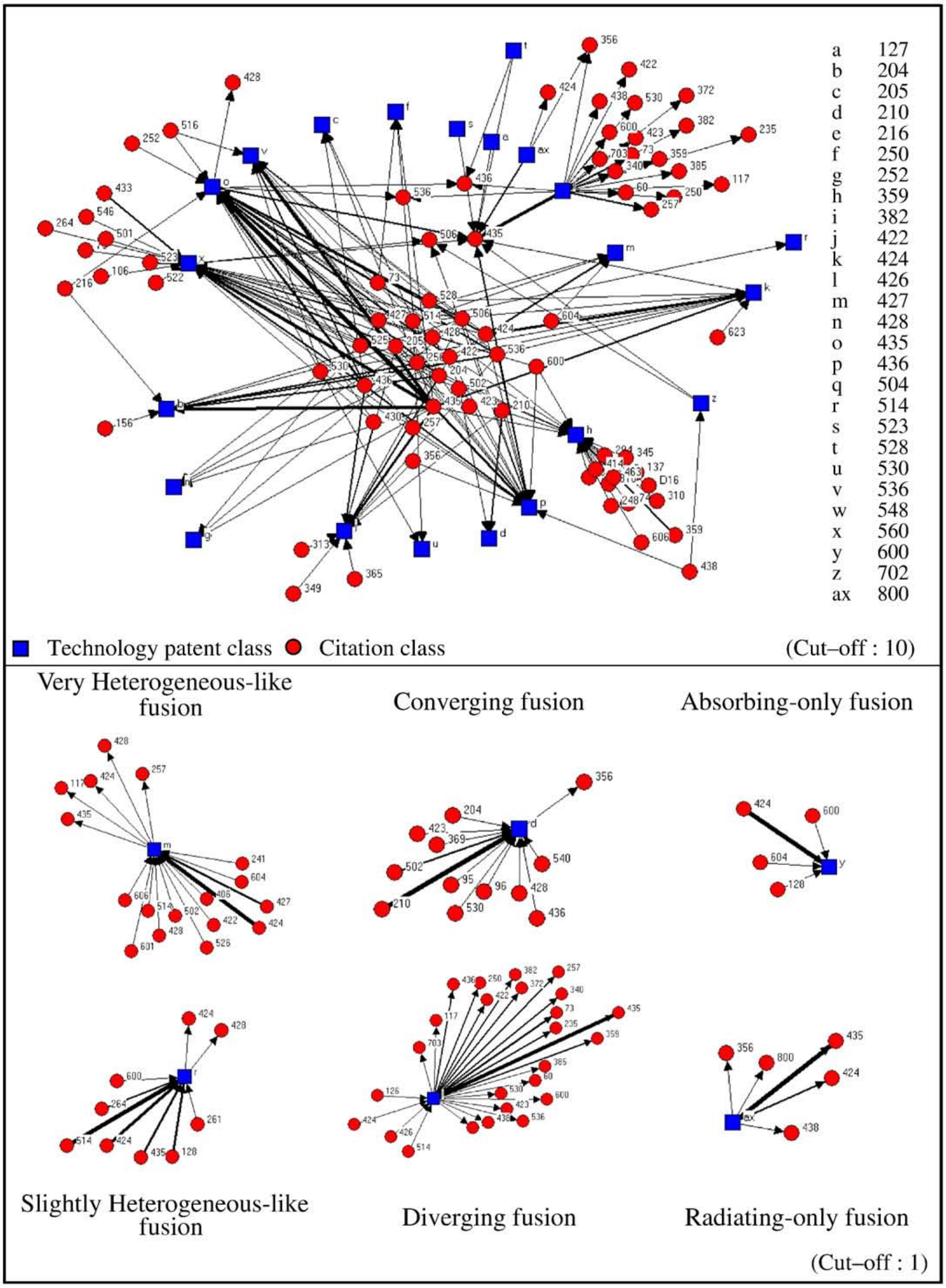


Fig. 5. Citation network for nanobiotechnology at patent class level for 1996–2000.

Very heterogeneous-like fusion is shown with many inflow links and outflow links. This implies that very heterogeneous-like fusion develops with the influence of diverse kinds of technologies while also influencing the diverse technology fields. In contrast, slightly heterogeneous-like fusion has few inflow and outflow links since this fusion is neither influenced by, nor influencing, various technology fields.

We visualized the diverging fusion with less inflow links and many more outflow links. This indicates that diverging fusion affects many more other technology fields than it is affected by other technology fields. Converging fusion shows the opposite phenomenon, in that it has an influence over less technology fields even though it is impacted by myriad technology fields. Thus, this fusion is represented with many more outflow links and less inflow links.



Very Heterogeneous-like fusion

Converging fusion

Absorbing-only fusion

Slightly Heterogeneous-like fusion

Diverging fusion

Radiating-only fusion

Fig. 6. Citation network for nanobiotechnology at patent class level for 2001–2005.

Absorbing-only fusion is described with only inflow links but no outflow links. This fusion took sources from diverse fields of technologies, but did not impact any other technology fields. Opposed to absorbing-only fusion, radiating-only fusion is represented with only outflow links because the technology has impacted other technology fields even though it is not affected by other technology fields.

Fig. 7 shows the positioning movement of fusion patterns from the period of 1996–2000 to the period of 2001–2005. Along the observation of changes of fusion patterns, it is noticed that patent class 422, which belongs to very heterogeneous-like fusion for

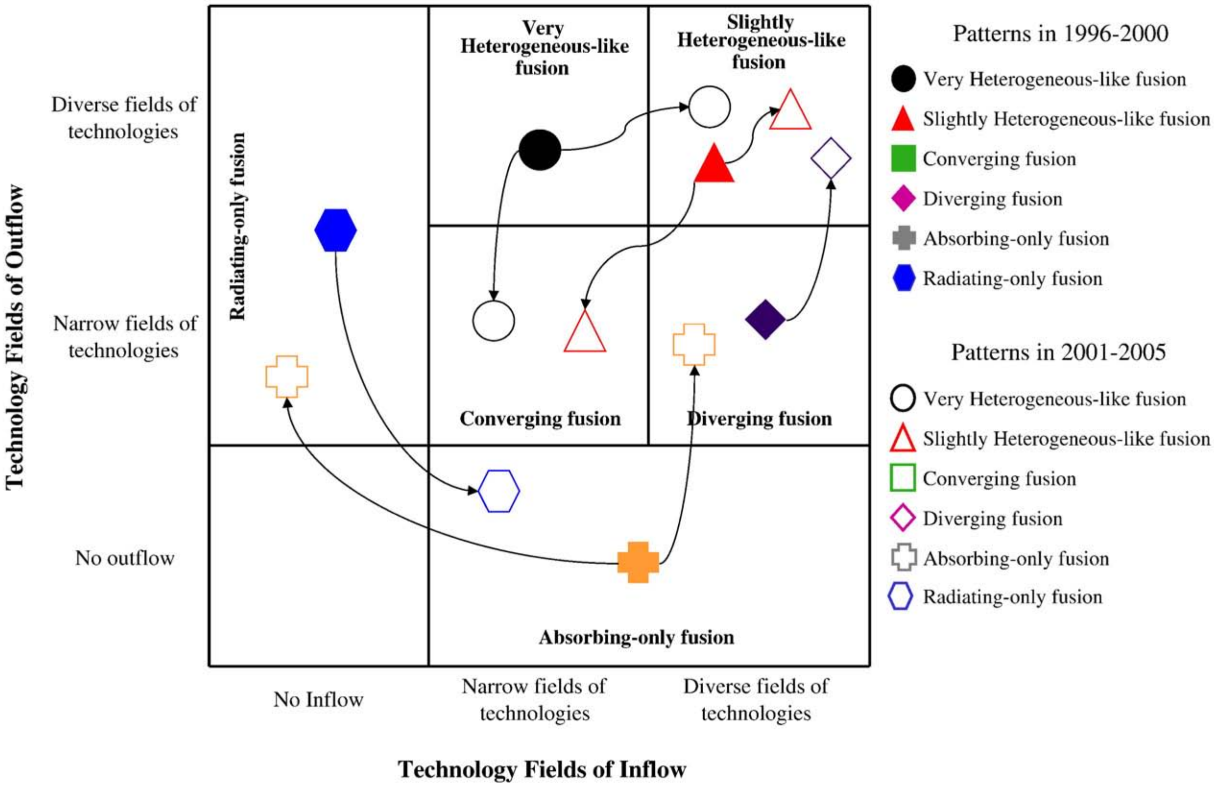


Fig. 7. Changes in fusion patterns from the period of 1996–2000 to 2001–2005.

the period of 1996–2000, changed to converging fusion in the period of 2001–2005. With patent classes 252 and 530 in very heterogeneous-like fusion changing to absorbing-only or slightly heterogeneous-like fusion, we carefully contend very heterogeneous-like fusion develops into the types of fusion that focus on possible technology fields where the technology classes in very heterogeneous-like fusion can have a good influence. The analogy that applies to the advance of slightly heterogeneous-like fusion is similar to the analogy applied to very heterogeneous-like fusion. Class 210 changed to converging fusion and classes 436, 536, 424 and 435 changed to slightly heterogeneous-like fusion. There is a tendency of becoming converging or slightly heterogeneous-like fusion to concentrate on niche technology fields of where they are more capable.

Diverging fusion, class 514, becomes slightly heterogeneous-like fusion from the period of 1996–2000 to 2001–2005. We concluded that with the development of the technology fields of diverging fusion, they came to focus on niche technology fields as well as take sources only from essential technology fields. Class 205 of diverging fusion became absorbing-only fusion during the period of 2001–2005, and we explain this as a dismissing process of not very worthwhile technology. No converging fusion was detected for the period of 1996–2000. We concluded that this period was not mature enough for technology fusion and not capable enough to discover niche technology fields.

Technology fields, such as classes 600, 216, 359 and 382, in radiating-only fusion became absorbing-only fusion, except class 528, which became diverging fusion and we concluded that class 528 is a field with significant potential. From the occurrence that most classes in radiating-only fusion became absorbing-only fusion, it can be conjectured that the ones in radiating-only fusion have no merit in terms of their influencing potential. In the technology fusion, ones without sourcing from ascendant technologies are difficult to evolve as influential technology.

Absorbing-only fusion advanced to diverging fusion or radiating-only fusion. We concluded that the period of 1996–2000 was preparation time for the technology classes 426, 548 and 127 of absorbing-only fusion to become stepping stones for other technologies. Of course, not very effective technology fields became obsolete in any patterns of technology fusion.

Time series observation, as shown in Figs. 5 and 6, exposes the changes in the degree of fusion of each class over time. For 1996–2000, classes 426, 252 and 422 had diverse sources of technology fields while classes 560, 359, 427 and 702 were affected by diverse fields of technologies for 2001–2005. Influential technologies that are widely cited by a variety of technology sectors are patent classes 600, 216, 250, 359 and 530 between 1996 and 2000, and were classes 426, 528, and 427 between 2001 and 2005.

Between 1996 and 2000, technology fusion occurring along with its development affected greater variety of technological fields than what it was influenced by other fields of technologies. However, during the period of 2001–2005, the trajectory of technology fusion showed that there have been more diverse sources of technology fields for its development than nozzles, which are influenced by technology fusion. Comparing the period of 1996–2000 and 2001–2005, technology fusion became more diversified during 2001–2005 in terms of influence it received from and gave to other technology fields.

5. Conclusion

The change in techno-paradigms and the current push for high technology have made ‘collaboration,’ ‘technology fusion,’ ‘technological convergence’ and ‘cross-disciplinarity’ the new descriptors of knowledge. Through technology fusion, key features of technology can be utilized to improve other technologies with less effort and resources than starting from the scratch. Also, technology fusion is often perceived as more successful in achieving breakthroughs and relevant outcomes.

In the case of technology fusion between nanotechnology and biotechnology, biotechnology can be extended to nanobiotechnology by utilizing the ability of nanotechnology which builds and shapes matter one atom at a time. This transfiguration, from biotechnology to nanobiotechnology, advances conventional biotechnology to design and modify the atomic-level details of the objects created [42]. These atomic-level engineering and manufacturing of nanobiotechnology enable to perform in-depth tasks for human health and technology. Technology fusion creates bionanomachines which work best in the environment of a living cell and biomaterials which integrate perfectly with living tissue, for instance.

In attempt to understand the trajectories of technology fusion, we develop an indicator of measuring the degree of fusion in cross-disciplinary technology fields. This measure is derived from the class-level database of backward and forward patent citations, and estimates on to what extent the ascendant and the descendant technologies are spread.

For the optimal degree of technology fusion, unlike setting up the specification for equipments, there cannot be one fixed optimal degree (for technology fusion) since the optimal degree varies according to actors, such as firms, industries, or technology disciplines. Either the diverse inputs or the narrow fields of inputs could be favorable depending on actors and their needs and circumstances. Actors may employ the value of fusion degree as a relative indicator to choose which technology field is suitable for their aim and condition.

According to the degree of fusion, we classify the fusion mechanism into six categories in terms of the diversity of technology fields of inflow and outflow. In opposition to our first hypothesis on the relationship between the degree of source technologies and nozzle technologies, having the diverse fields of technologies as a source is not necessarily positively correlated with the diverse fields of technologies. In some cases, it shows that the narrow fields of reference technologies or no reference technologies tend to produce diverse fields of technologies.

The citation network, which is weighted by fusion degree, is visualized to trace the trajectory and to detect the patterns of technology fusion in order to provide a complete and clear overview at a glance. This map displays the source and the nozzle technologies together as well as flow directions of the sources and nozzles. With the map, the structure of the technology fusion path, including the relations with the source and nozzle technologies, can be examined as a whole. Furthermore, using a time series comparison, we are able to detect conspicuous changes in fusion patterns over time and provide possible explanations. Each fusion pattern has evolved in such a way that they can focus more on their niche technologies, and those technologies that cannot incorporate the technology fusion have been eliminated during the development.

The meso-database of technology, which used the level of patent class, has never been used previously in mapping the trajectory, to the best of the authors' knowledge. This mapping, while not narrowing down alternate choices too strictly, can provide individual firms with more specific technology fields than do the industry-level recommendations. It would help firms to efficiently use their valuable resources as well as help them to avoid risks of diverting to the use of improper technologies. Moreover, information from the changes of fusion patterns can be utilized in setting up firm's strategies, such as identifying their future investing technology fields.

Even with all the efforts to avoid any noise that hampers the accurate evaluation of the measures, there still remain some inherent limitations arising from using patent data as a proxy for technology as was done in the previous research. One of the inevitable limitations is the existence of time lag between patent and its forward citation. Since there is about a 3- to 5-year lag to be cited in the nanobiotechnology field, at least 3 years behind or more should be incorporated. Secondly, information loss during the computation of weight for citation network analysis is another weak limitation in this research. We utilized the data with more than one citation only. This creates a possibility of exclusion of data with only one citation which could have been a source of great potential for disruptive innovation.

Thirdly, our taxonomy cannot be free from criticisms about its limitations. One of main issues is the unit of analysis. While each unit has its pros and cons, the choice can be made among individual technologies, sectors, or industries for taxonomy of technology fusion. In our taxonomy, we use the patent class as the level of analysis and develop a classification system that takes into account some of the problem with taxonomies, such as the size of data. Yet, it has not been verified if the patent class is the most appropriate unit to classify technology fusion.

The final limitation comes from the nature of the cross-disciplinary technology field. While defining the boundary of technology is critical in the field of technology fusion, the definition of boundaries can vary from one researcher to another.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.techfore.2009.06.006.

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