Journal of Informetrics 9 (2015) 488–498

Contents lists available at ScienceDirect

Journal of Informetrics

journal homepage: www.elsevier.com/locate/joi

Measuring science-based science linkage and non-science-based linkage of patents through non-patent references

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 28 April 2015
Accepted 28 April 2015

Keywords:
Science linkage
Patent citations
Non-patent references

ABSTRACT

This paper analysed the citations of patents to science- and non-science-based references as an agency of the linkage between technology and science. A review of the literature identified a variety of techniques of measuring science linkage (SL) with various results. Therefore, this study aimed to compare the differences between science-based SL and non-science-based linkage (NSL). Patent data were collected from the United States Patent and Trademark Office database for the past two decades. Results showed a phenomenon of rapidly growing NSL of patents at different levels of technological fields and firms. In addition, field- and firm-specific differences in the linkages between science and technology were identified. This study analysed various types of SL performances of the top 20 firms in the Computers and Communications field and found that science–technology linkages were stronger in Lucent, Mitsubishi and Microsoft. It is worth noting that Texas Instruments (TI) was ranked thirteenth in science-based SL but third in Relative SL Ratio. Based on the Relative SL Ratio, TI's science-based SL was much higher than its NSL.

1. Introduction

Research has shown that invention and innovation originate in basic and applied research, progressing into technological and economic growth (Rosenberg & Birdzel, 1990; Narin & Olivastro, 1992; Narin, Hamilton, & Olivastro, 1995; Narin, 2000; Acosta & Coronado, 2003; Klitkou & Gulbrandsen, 2010). This positive relationship between important technological advances and economic outcomes has been statistically measured by high citations between science (using papers as a proxy) and technology (using patents as a proxy).

Science linkage (SL) was first proposed and defined by Narin in 1991 as 'the average number of "other references cited" on the front pages of U.S. patents'. However, the SL formula and meaning were not clarified in detail until the publication of the Tech-Line® Background Paper in 2000. While its importance and popularity are evidenced in the literature, there is no common agreement as to what counts as a "science-based reference" for the purpose of SL calculations. In Narin's (2000) definition of the SL indicator, he excluded non-science-based references from non-patent references (NPRs). Similarly,

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http://dx.doi.org/10.1016/j.joi.2015.04.004

Meyer (2000a, 2000b), who explored the different motivations for citing non-patent literature, found that only some are science-related. In other words, not all NPRs are science-based references.

It is argued that counting all NPRs as science-based references cannot reflect real linkages between science and technology. It is also observed that science-based references include more than Thomson Reuters Science Citation Index (SCI) papers. Only considering SCI papers for SL calculations arguably cannot reflect real science–technology linkages either. The past two decades have seen an increasing growth of citations to non-science-based references, with the number of such citations overtaking the number of citations to science-based references. To this end, this study aims to compare the differences between science-based SL and non-science-based linkage (NSL).

This paper begins with a review of the literature on characteristics of SL, comparisons between science-based NPRs and non-science-based NPRs, and SL as an indicator of technological innovation. It goes on to explain the methodology employed in the empirical study. The patent data analysed are presented in diagrams and tables with textual explanations. Finally, implications, based on field- and firm-specific differences in the linkages between science and technology, are discussed in Section 4.

1.1. Characteristics of science linkages

While substantial research has studied the links between science and technology, a review of the literature observed various methods of statistically measuring such links. A common quantitative method used to measure the relationship between science and technology is citation analysis (Coward & Franklin, 1989; Hicks, Breitzman, Hamilton, & Narin, 2000; Tijssen, 2001; Acosta & Coronado, 2003; Bhattacharya & Meyer, 2003; Chen & Hicks, 2004; Gupta, 2006; Lo, 2010). Other methods used include: inventor-author name matches (Coward & Franklin, 1989; Boyack & Klavans, 2008), author–inventor co-publications (Breschi & Catalini, 2009; Klitkou & Gulbrandsen, 2010) and peer opinions through interviews and surveys (Fagerberg, 1987; Tijssen, 2002).

Among the various citation analysis techniques, SL has been widely adopted, to a varying extent, in the literature to measure the links between science and technology. The central idea of the indicator of SL is to use the "other references cited" (Narin & Olivastro, 1992) or "non-patent references" (Narin, 2000) cited on the front page of granted U.S. patents to directly measure the link. According to CHI Research, Inc. (Narin, 2000), SL was defined as "the average number of science papers referenced on the front page of the company's patents" to indicate "how leading edge [the] company's technology [is]".

When Narin (2000) first proposed the SL indicator, he included only science-based references and excluded other non-patent literature references from the SL calculations. A complicated issue resides in what counts as science-based references, as not all NPRs cited on the front page of granted U.S. patents belong to science-based references. Although complicated, this distinction is considered to be essential, because linkage to science is the driving force behind many important areas of technology.

1.2. Comparisons between science-based science linkage and non-science-based linkage

As mentioned in the previous section, the SL definition (Narin, 2000) clearly pointed out the necessity of distinguishing science-based references from non-science-based references among the NPRs. For example, science-based NPRs include scientific journal papers, meetings and books, whereas non-science-based NPRs include industrial standards, technical disclosures, engineering manuals and every other conceivable kind of published material (Narin, Hamilton, & Olivastro, 1997).

However, the application of SL in the following publications varied, with two distinctive approaches observed in the literature. When selecting science-based references for the SL calculations, one approach included all NPRs (e.g. Gupta, 2006; Lo, 2010) and the other used only papers listed in the SCI database (e.g. Tijssen, Buter, & van Leeuwen, 2000; Tijssen, 2001; Verbeek et al., 2002; Hullmann & Meyer, 2003; Han, 2007). Somewhere between the two approaches are, for example, Park and Kang (2009), including academic journals and conference proceedings as science-based references.

It is clear that the indicator of SL has been widely applied in the literature after Narin (2000). Different from Narin's (2000) approach, many authors did not exclude non-science-based references from NPRs when calculating SL. However, it is observed that Narin (2000) included patent reports as science-based references. In order to reflect real linkages between science and technology, this study adopts Narin's definition of SL but argues that a more rigid criterion to distinguish science-based SL and NSL is needed.

1.3. Science linkage as an indicator of technological innovation

Generally speaking, a lot of research employed the SL indicator and concluded that there is a positive relationship between technology and research (Narin et al., 1997; Sorenson & Fleming, 2004; Klitkou & Gulbrandsen, 2010). It was identified in the literature that the SL indicator was widely applied at different levels, e.g. at the firm level (Narin, 2000), at the country level (Narin, 1991, 1994; Narin & Olivastro, 1992; Narin et al., 1997; Narin, Albert, Kroll, & Hicks, 2000; Gupta, 2006; Klitkou & Gulbrandsen, 2010; Park & Kang, 2009) and at the level of technological fields (Narin & Olivastro, 1992; Anderson, Williams, Seemungal, Narin, & Olivastro, 1996; Hullmann & Meyer, 2003; Chen & Hicks, 2004; Lo, 2010). This study builds upon the work of Narin and other scholars and further explores the SL comparisons between firms, countries and technological fields.

Despite its popularity in the literature, some debates in the literature concern whether the science–technology relationship is causal. For example, Sirilli (1998) stated that "we have no explicit model capable of determining causal relations between science, technology, economy and society in a single synthesis." In line with this, Meyer (1998) also argued that "it is necessary to corroborate these measures more carefully first and investigate the question whether a citation linkage really equals a causal link." Such authors saw a need for a balanced analysis between quantitative and qualitative measurement of science–technology linkages.

Furthermore, SL was developed as a quantitative indicator to measure science–technology linkages. However, to what extent does it really reflect the linkages between science and technology? As discussed in the previous section, a key issue resides in the distinction between science-based SL and NSL.

2. Methodology

2.1. Patent data and technological fields

In this study, patent data were collected solely from the United States Patent and Trademark Office (USPTO) database, which is generally accepted and is accessible to the researchers. While there exist different categories of patents (e.g. plant patents, design patents, reissues and continuations), this study, based on the recommendation by Narin (2000), collected the number of regular U.S. utility patents to keep the focus of the database on the key category of patents which contributes to corporate technological strengths. In order to observe the recent development of patent performance, this study covered the past two decades, divided into four periods, that is, 1993–1997, 1998–2002, 2003–2007 and 2008–2012. In total, 3145,890 patents granted during these periods were gathered for analysis.

Data collected from the USPTO database were divided into four periods in order to observe the long-term development of SLs. The analysis then focused on the third period (i.e. 2003–2007) and the fourth period (i.e. 2008–2012) in order to observe the recent SL performance change of technological fields and countries. Finally, the SL performance in the fourth period (i.e. 2008–2012) was observed in order to analyse firms' latest SL performance positions.

According to the U.S. National Bureau of Economic Research (NBER) – as in Hall, Jaffe, and Trajtenberg (2001) – there are six main technological fields: Chemical; Computers and Communications (C&C); Drugs and Medical (D&M); Electrical and Electronics (E&E); Mechanical; and Others. This study conducted a variance analysis of SL in these six main technological fields.

2.2. Classification of non-patent references

A computer algorithm was developed in this study to classify the utility patents using keyword matching. The remaining unclassified patents were then manually reviewed by the researchers. In order to avoid the situation where an NPR matched the keywords for different categories, all NPRs were logged into the computer and automatically matched following a defined procedure: Patent Documents, Journal Papers, Conference Papers, Books, Reports/Manuals and Webpages. At each step, only the NPRs that were unclassified by the matching process in previous categories would be processed. All NPRs were initially processed to decide whether they belonged to the Journal Paper type. If an NPR met the requirements for both the Journal Paper type and the Web Page type, it would be classified as the Journal Paper type.

The 'references cited' in the U.S. patents include 'U.S. Patent Documents', 'Foreign Patent Documents' and 'Other References'. SL calculations focused on the NPRs that belonged to 'Other References'. Therefore, this study excluded all the patent documents in 'Other References' and regarded the rest as NPRs. In terms of patent documents, 'Other References' were checked against the string consisting of 2 digits from the country code list (United States Patent and Trademark Office, 2014a) with at least four digits and the string of 'U.S. Appl. No.'. The list of NPRs that met the requirements were then manually reviewed and classified as the Patent type. The remaining 'Other References' were filtered by 'patent' and the researchers then decided whether they belonged to the Patent Document type. 'Other References' that belonged to the Patent Document type were excluded in this study for science-based SL and NSL calculations.

Journal keyword matching was processed based on the full names and abbreviations, as well as volume (vol) and number (no) of the journal lists indexed by the Science Citation Index (SCI), Social Sciences Citation Index (SSCI), Arts and Humanities Citation Index (A&HCI) and Engineering Index (EI). If an NPR met the requirements, it was classified as the Journal Paper type. The remaining NPRs were then filtered by 'journal', and the researchers decided whether they belonged to the Journal Paper type.

Conference keyword matching was processed based on the conference title lists indexed by the Conference Publications in IEEE Xplore. If an NPR met the requirements, it was classified as the Conference Paper type. The remaining NPRs were then filtered by 'conference', 'symposium', 'meeting' or 'proceeding', and the researchers decided whether they belonged to the Conference Paper Type.

In terms of books, NPRs were checked against the complex condition 'chap (chapter) + [0–9]' or '[0–9] + Ed. (Edit., Edition)' or 'book'. The list of NPRs that met the requirements were then manually reviewed and classified as the Book type.

Table 1
Examples of each NPR category.

Other references category	Example
Science-based NPRs	
Journal papers	• Glover, S. "Automatic Switching at the Edmonton Television Studios," SMPTE Journal, Nov. 1966, vol. 75, pp. 1089–1092. (*In US8621547*) • Article entitled "Spam!" by Cranor et al. in Communications of the ACM, vol. 41, No. 8, Aug. 1998, pp. 74–83. (*In US8621559*) • Hyoka, Japanese Journal of Telemedicine and Telecare, Oct. 1, 2008, vol. 4, No. 2, pp. 273–274. (*In US8621588*)
Conference papers	• International Conference, Proceedings (Lecture Notes in Computer Science, vol. 3983), pp. 1098–1106. (*In US8613103*) • Saul, J. M. Hardware/Software Codesign for FPGA-Based Systems. Proceedings of the 32nd Hawaii International Conference on System Sciences (1999). (*In US8613080*) • Wu et al., Hybrid Cache Architecture with Disparate Memory Technologies, ISCA' 09 Proceedings of the 36th Annual International Symposium on Computer Architecture, pp. 34–45. (*In US8613074*)
Books	• Peal, David, "America Online Official Internet Guide," 2nd ed., Osborne/McGraw-Hill, 1998. (*In US8612515*) • Hennessy et al., "Computer Architecture—A Quantitative Approach", 2nd ed., 1996, pp. 246–250. (*In US8612394*) • Bernard, Ryan, "The Corporate Intranet," 2nd ed., 1996. (*In US8612515*)
Non-science-based NPRs	
Reports/manuals	• Symantec Antivirus Corporate Edition User Manual Version 5.1; Oct. 25, 2001; Symantec Corporation; pp. 29–35. (*In US8613091*) • HP Storage Essentials SRM 6.0 Installation Guide. Jan. 2008. HP. 1st ed. Part No. T4283-96113. pp. 1–5, 97–136, 219–228. (*In US8612968*) • FLEXIm End Users Guide, Version 9.2. Jul. 2003. Published by Macrovision. 166 pages. (*In US8620819*)
Web pages	• "Symantec Glossary"; Symantec.com; printed on Jun. 6, 2006; pp. 1–3; located at ⟨http://securityresponse.symantec.com/avcenter/refa.html⟩ #worm (*In US8613095*) • Haley Enterprise, "The Rete Algorithm," 2002, [online] [Retrieved on Oct. 29, 2002] Retrieved from the Internet ⟨http://www.haley.com/0072567836705810/ReteAlgorithm.html⟩. (*In US8613083*) • ⟨http://www.entrust.com/pki.htm⟩ What is a PKI? Dec. 8, 2006, 5 pages. (*In US8613067*)
Excluded from SL calculation in this study	
Patent documents	• PCT/US2009/064767, International Preliminary Report on Patentability, Mailed May 26, 2011, 7 pages. (*In US8621642*) • Official Communication for U.S. Appl. No. 11/532,855 mailed Jan. 27, 2011. (*In US8621631*) • Non-Final Office Action for U.S. Appl. No. 11/539,202 dated Dec. 14, 2009. (*In US8621587*)
N/A	• Osmonds Teat Seal, 4 pgs. (*In US 7828765*) • John Hedger, Oracle (TCA), U.K. (1980). (*In US 7734251*) • Visa U.S.S., "VisaSmart". (*In US 7828208*)

In terms of reports and manuals, NPRs were checked against the keywords 'report', 'manual', 'times', 'news', 'magazine', 'handbook', 'catalogue', 'guide' and 'article'. The list of NPRs that met the requirements were then manually reviewed and classified as the Report/Manual type.

In terms of web pages, NPRs were checked against the URL string consisting of 'http', '://', 'www.', 'org', '.net', '.com' and '.gov'. The list of NPRs that met the requirements were then manually reviewed and classified as the Web Page type. All NPRs were matched in the order of the Journal, Conference, Book, Patent Document and Report/Manual types. If they met the requirements, they were classified as one of the five types. For those NPRs left unclassified, if they contained the URL string, then they were classified as the Web Page type. It was noticed that some Open Access papers failed to meet the journal keyword matching and therefore were classified as non-science-based NPRs, which is recognized as a limitation of this study.

After the aforementioned keyword matching and classification process, the remaining NPRs were manually reviewed and classified by the researchers. In the end, approximately five percent of the NPRs remained unclassified, which were regarded as N/A and were not investigated in this study.

This study excluded patent documents from 'Other References' and divided the remaining references into five categories of NPRs, which were then classified into two broad groups. Specifically, books, conference papers and journal papers were regarded as science-based NPRs; reports/manuals and web pages were regarded as non-science-based NPRs. Additionally, a category of N/A was created to accommodate those NPRs that could not be recognised. Examples of these categories can be found in Table 1. Due to the low percentage of N/A in all NPRs, NPRs in the category of N/A was neglected when distinguishing science-based SL and NSL.

2.3. Science linkage indicators

According to CHI Research, Inc. (Narin, 2000), SL was defined as “the average number of science papers referenced on the front page of the company’s patents”, to indicate “how leading edge [the] company’s technology [is]”. In accordance with the definition, a formula for SL was developed (Narin, 2000), as below:

$$\text{Science linkage (SL)} = \frac{\text{The number of research papers cited in granted patents}}{\text{Number of patents granted}}, \tag{1}$$

A review of the literature showed various criteria for distinguishing science-based NPRs and non-science-based NPRs. Different from Narin’s (2000) criteria, the criteria used to distinguish science-based NPRs and non-science-based NPRs in this study showed more rigour. For example, patent reports were not regarded as science-based NPRs in this study. Hence, the formulas for science-based SL and NSL were developed in this study, as below:

$$\text{Science-based SL} = \frac{\text{Science-based NPRs citations in granted patents}}{\text{Number of patents granted}}, \tag{2}$$

where science-based NPRs include: books, conference papers and journal papers.

$$\text{NSL} = \frac{\text{Non-science-based NPRs citations in granted patents}}{\text{Number of patents granted}}, \tag{3}$$

where non-science-based NPRs include: reports/manuals and web pages.

$$\text{Relative SL Ratio} = \frac{\text{Science-based SL of a firm/Non-science-based linkage of a firm}}{\text{Science-based SL of total firm/Non-science-based linkage of total firm}} \tag{4}$$

When the Relative SL Ratio is close to 1, it indicates that the ratio of science-based SL to NSL of a firm is close to the ratio of science-based SL to NSL for all firms. When the Relative SL Ratio is close to 0, it indicates that the non-science-based NPRs account for the majority of a firm’s NPRs.

3. Results

This section starts with the citation trend of various types of NPRs, and proceeds to compare differences between science-based SL and NSL. It then examines the SL changes and growth rates of the top 20 patent assignees in the C&C field.

3.1. Citation trends of various types of NPRs

As mentioned in Section 2, ‘Other References’ were divided into two broad groups: one was science-based NPRs, and the other was non-science-based NPRs. Science-based NPRs included journal papers, conference papers and books and science-based SL indicated their average citations per category. Non-science-based NPRs included reports/manuals and web pages, and NSL indicated their average citations per category. An examination of the statistics in Table 2 clearly demonstrates that while journal papers (belonging to science-based NPRs) and reports/manuals (belonging to non-science-based NPRs) accounted for the highest percentage of NPRs, both showed a decreasing trend over the past 20 years. In contrast, the percentage of the citations to web pages steadily increased.

3.2. Comparisons between science-based science linkage and non-science-based linkage

To take the analysis a step further, Fig. 1 shows a curve diagram indicating trends in total NPR SL, science-based SL and NSL over the past 20 years. Generally, NSL has increasingly grown in the last two decades, overtaking science-based SL. It is also noted that NSL has rapidly increased since 2008.

Table 2
Citation trends of various types of other references.

	1993–1997 (%)	1998–2002 (%)	2003–2007 (%)	2008–2012 (%)
Science-based NPRs	40.15	42.07	40.59	34.40
Journal papers	32.12	34.10	31.94	26.75
Conference papers	5.04	5.40	6.33	5.82
Books	2.99	2.57	2.32	1.83
Non-science-based NPRs	51.55	50.28	49.41	51.75
Reports/manuals	51.54	49.05	44.54	44.85
Web pages	0.01	1.23	4.87	6.90
Patent documents	3.17	3.20	5.46	9.83
N/A	5.13	4.45	4.54	4.02

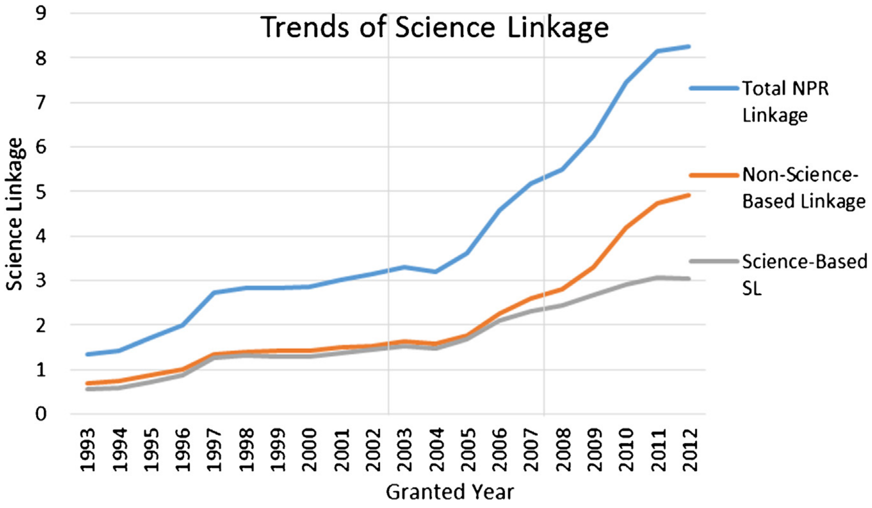

Fig. 1. Trends of science linkage.

Fig. 2 shows the science-based SL and NSL of the six technological fields over the four periods. The coordinate axes were used to show all patents' SLs, with science-based SL on the *x* axis and NSL on the *y* axis. The SLs of the D&M and Chemical fields were located in the upper right quadrant in the coordinate axes, indicating that their science–technology linkages, both science-based and non-science-based, were higher than those of other fields in the fourth period. It can therefore be inferred that the number of citations to both science-based and non-science-based NPRs were high in the D&M and Chemical fields.

Fig. 2 also considers the SL performance of all fields as a whole, labelled as All Fields. It is clear that C&C, Mechanical and Others had a higher slope (i.e. containing a higher proportion of NSL) than All Fields. It indicates that their citations to non-science-based NPRs grew quicker than All Fields over the third and fourth periods. On the contrary, Chemical, E&E and D&M had a lower slope (i.e. containing a higher proportion of science-based SL) than All Fields. It is inferred that the number of citations to science-based NPRs in these fields was higher than All Fields over the third and fourth periods. Therefore, it is concluded that Chemical, E&E and D&M belong to fields whose growth in citations to non-science-based NPRs was slower than All Fields.

Fig. 3 shows the SL performance of the top ten countries by patent counts, with science-based SL on the *x* axis and NSL on the *y* axis. The coordinate axes were used to show the total patents' average SL in the fourth period. Based on the number of granted patents, the top ten countries were: Taiwan (TW), South Korea (KR), Japan (JP), Denmark (DE), France (FR), the

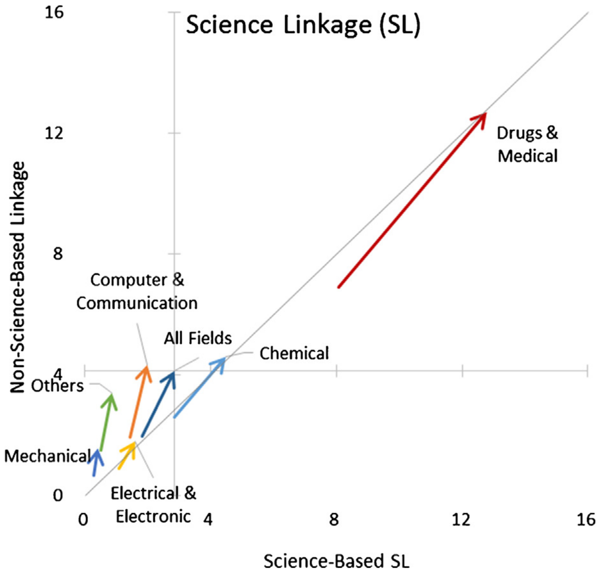

Fig. 2. Science linkage of the six technological fields.

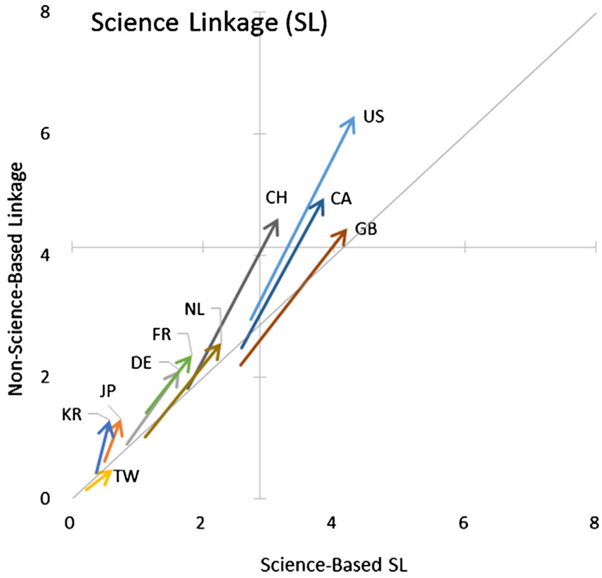

Fig. 3. Science linkage of the top ten countries.

Netherlands (NL), China (CH), Canada (CA), the United Kingdom (GB) and the United States (US). It is clear that the top ten countries' science-based SL increased, but their NSL increased even more. The top ten countries can be divided into four groups, depending on their science-based SL and the highest NSL performance. The U.S. performed best, followed by a group consisting of CA, GB and CH, and then a group of NL, FR and DE, and the final group of KR and JP. The group of CA, GB and CH was located in the first quadrant, suggesting that both their science-based SL and NSL were higher than the average SL of total patents. Countries of the last group were located in the third quadrant, suggesting that both their science-based SL and NSL were lower than the average SL of total patents.

3.3. *Science linkage changes of the top 20 assignees in computers and communications field*

Table 3 shows the Total NPR SL, science-based SL, NSL and Relative SL Ratio of the top 20 patent assignees in the C&C field between 2008 and 2012. It was observed that some firms performed very differently in different SLs rankings. For example, Texas Instruments (TI) was not ranked in the top 10 in Total NPR SL and science-based SLs, but it was ranked third in Relative SL Ratio. It is inferred that although TI did not have a large number of citations to Total NPRs and science-based NPRs, its number of citations to non-science-based NPRs was even lower (i.e. the lowest one among the top 20 firms) and its Relative SL Ratio reached 6.93, which in turn contributed to its third position in Relative SL Ratio. Lucent and Mitsubishi were ranked

Table 3
The SLs (ranks) of the top 20 assignees in C&C field in 2008–2012.

Assignee	Total NPR SL	Science-Based SL	Non-Science-Based linkage	Relative SL Ratio
Microsoft	**12.57** (**1**)	**3.80** (**1**)	**4.59** (**1**)	1.79 (12)
Cisco	**5.99** (**2**)	0.76 (9)	**2.67** (**2**)	0.62 (20)
AT&T	**5.38** (**3**)	0.80 (8)	1.15 (7)	1.51 (16)
Intel	4.39 (4)	**1.32** (**2**)	**1.69** (**3**)	1.68 (13)
IBM	3.93 (5)	1.08 (4)	1.28 (4)	1.83 (10)
Nokia	3.27 (6)	0.86 (6)	1.18 (6)	1.57 (15)
HP	2.84 (7)	0.81 (7)	0.95 (8)	1.83 (10)
Fujitsu	2.83 (8)	0.55 (12)	1.19 (5)	1.00 (19)
Mitsubishi	2.35 (9)	1.01 (5)	0.23 (19)	**9.47** (**2**)
Lucent	2.22 (10)	**1.13** (**3**)	0.24 (18)	**10.19** (**1**)
Sony	2.03 (11)	0.57 (11)	0.57 (11)	2.16 (6)
Motorola	1.88 (12)	0.45 (15)	0.67 (9)	1.46 (17)
Toshiba	1.86 (13)	0.49 (13)	0.40 (15)	2.61 (4)
Panasonic	1.85 (14)	0.40 (16)	0.43 (13)	1.97 (8)
Samsung	1.78 (15)	0.37 (17)	0.63 (10)	1.28 (18)
Seiko Epson	1.67 (16)	0.37 (17)	0.40 (15)	2.03 (7)
NEC	1.62 (17)	0.59 (10)	0.54 (12)	2.35 (5)
Hitachi	1.33 (18)	0.37 (17)	0.41 (14)	1.96 (9)
TI	0.99 (19)	0.49 (13)	0.15 (20)	**6.93** (**3**)
Canon	0.94 (20)	0.26 (20)	0.34 (17)	1.68 (13)

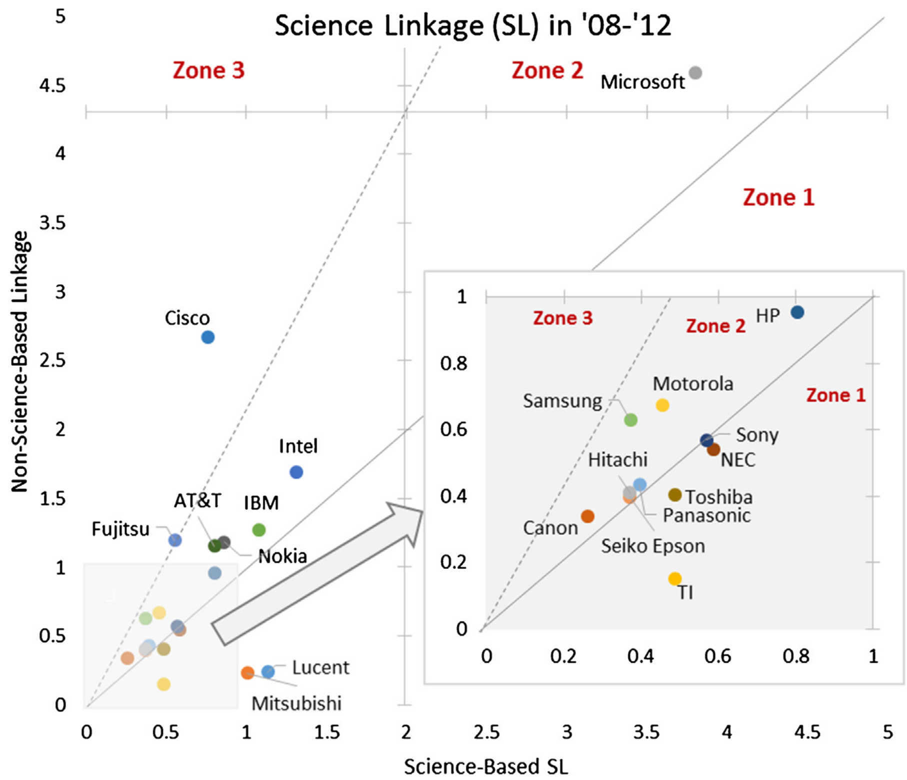

Fig. 4. SL performances of the top 20 firms in the C&C field.

third and fifth respectively in science-based SL, but they were the top two firms in Relative SL Ratio, which indicated that their average number of citations to science-based NPRs (absolute performance) and Relative SL Ratio (relative performance) were high.

Cisco ranked second in Total NPR SL and ninth in science-based SL, but its Relative SL Ratio was the lowest. Despite the fact that Cisco had more citations to Total NPRs and science-based NPRs, because it cited more non-science-based NPRs than other firms, its Relative SL Ratio was the worst.

Both firms' absolute performance of patent citations to science-based NPRs (i.e. science-based SL) and relative patent performance (i.e. Relative SL Ratio) are showed in Table 3. It shows that simply calculating science-based SL would overestimate the science linkage of Microsoft, Intel, IBM, HP, Nokia, AT&T, Motorola, Fujitsu, Samsung and Cisco (being ranked higher in Relative SL Ratio). It means that those firms cited relatively more non-science-based NPRs. Simply calculating science-based SL would underestimate the science linkage of Lucent, Mitsubishi, TI, NEC, Toshiba, Sony, Panasonic, Seiko Epson, Hitachi and Canon (being ranked lower in Relative SL Ratio). This means that those firms cited relatively fewer non-science-based NPRs.

Fig. 4 shows the SL performance of the top 20 assignees between 2008 and 2012 in the C&C field using a quadrant diagram. In the figure, three zones were identified, divided by the two lines, i.e. the solid diagonal and the dotted line that went through the origin. For firms located on the right-hand side of the solid line (Zone 1), their science-based SL values were higher than their NSL, and their Relative SL Ratios were higher than other patent performance. For firms located between the solid and dotted lines (Zone 2), their science-based SL values were lower than their NSL, but their Relative SL Ratios were higher than other patent performance. For firms located on the left-hand side of the dotted line (Zone 3), not only were their science-based SL values lower than their NSL, but their Relative SL Ratios were also lower than all other patent performance.

Furthermore, the four quadrants were divided according to the SLs of total patents, and firms' positions in different quadrants represent different SL performances. Only Microsoft was located in the first quadrant, where both science-based SL and NSL were higher than the total patents' SL. The other nineteen firms – Lucent, Mitsubishi, TI, Intel, IBM, HP, NEC, Nokia, Toshiba, Sony, AT&T, Panasonic, Seiko Epson, Hitachi, Motorola, Fujitsu, Samsung, Cisco and Canon – were located in the third quadrant, where both science-based SL and NSL were lower than the total patents' SL. It is reasonable to note that the firm located in the first quadrant performed better than those located in the third quadrant based on their science-based SL and NSL values.

Observations were made through firms' positions in the three zones divided by the solid and dotted lines. It was found that if a firm was closer to the *x* axis and had a higher *x* coordinate (i.e. with higher science-based SL), its Relative SL Ratio value was higher. The variances of firms' Relative SL Ratio values were even clearer in a vector space.

In Zone 1, the values of science-based SL/NSL of the six firms tended to be low; among them, Lucent, Mitsubishi and TI were ranked in the top three in Relative SL Ratio, which could be seen as firms having the highest science linkage. Purely from the perspective of science-based SL, which was close to Narin's (2000) original SL calculation, the performance of these three firms would be underestimated. Arguably, this could not reflect the fact that their Relative SL Ratios were higher than the field's average performance. The positions of Sony, NEC and Toshiba were closer to the diagonal, showing that they had similar science-based SL/NSL values. Although their values for science-based SL/NSL were lower than those of AT&T, their Relative SL Ratios were higher (see Table 3).

In Zone 2, Microsoft was the only firm located in the first quadrant and its science-based SL/NSL values were higher than the overall performance of the field. In other words, Microsoft ranked top in science-based SL. Although it cited a large number of science-based/non-science-based NPRs, it was observed that it cited more non-science-based NPRs than science-based NPRs. Therefore, its Relative SL Ratio was ranked twelfth. In Zone 3, Cisco and Fujitsu had lower Relative SL Ratios than the overall performance of the field.

Overall, compared with other approaches that only calculate SL values, the Relative SL Ratio arguably is more likely to genuinely reflect science linkage. Furthermore, observing the positions in a vector space helps clearly observe firms' science-based SL/NSL values and Relative SL Ratios.

4. Conclusion and discussion

This study has met the aims set at the outset of this paper. Specifically, this study divided NPRs into five categories and classified books, conference papers and journal papers into the group of science-based NPRs. It further considered not only science-based SL but also the ratio of science-based SL to NSL compared to the overall performance in the field. Interesting observations were also made regarding rapidly growing NSL of patents and differences of science-based SL and NSL at the levels of technological fields and firms respectively, which are discussed below. Research limitations are also acknowledged.

4.1. Rapidly growing non-science-based linkage during 2003–2007 and 2008–2012

This study examined both science-based SL and NSL. It was observed that NSL was higher than science-based SL in general and at the levels of technological fields, countries and firms, particularly over the periods of 2003–2007 and 2008–2012. Such a phenomenon suggested a trend of patent application moving from basic patents to applied patents. Nevertheless, variances between science-based SL and NSL were observed at different levels of technological fields, countries and firms. NSL was higher than science-based SL in all technological fields, countries and firms examined in the fourth period (i.e. 2008–2012). It was also clear that patents in the D&M field had the highest level of linkage to science among all fields examined; U.S. patents had the highest level of linkage to science among all countries examined; and patents of Microsoft, Micron and Intel had the highest level of linkage to science among all firms examined.

A deeper analysis revealed more detailed variances. For instance, NSL in the C&C field was higher than that in All Fields, but science-based SL in the C&C field (located in the second quadrant in Fig. 2) was lower than that in All Fields in the fourth period. It suggested that the C&C field emphasised citations to non-science-based NPRs, which could be related to the attributes of this specific field. For the majority of firms studied, their NSL increased in the fourth period. On the contrary, both the science-based SLs and NSL of TI and GE decreased, which indicated that their patents clearly had less linkage to science. However, Eastman Kodak's science-based SL increased, whereas its NSL decreased. The reasons for such a phenomenon remain unknown, and call for further investigation.

4.2. Field-specific differences in science linkage performance

Although the SL indicator was widely used to indicate technological innovation, the findings of this study indicate that there are field-specific differences in the interface between science and technology, with SL performance varying according to different technological fields. This finding resonated with Coward and Franklin (1989) and Klitkou and Gulbrandsen (2010). SL performance has also been discussed within specific technological fields, for instance, nanotechnology (Hullmann & Meyer, 2003), tissue engineering (Chen & Hicks, 2004) and genetic engineering technology (Lo, 2010). It is therefore argued that comparisons of SL performance between different technological fields do not provide meaningful implications due to the diversity of their nature. For example, comparing SL performance between the fields of pharmacy, semi-conductors and computers is not meaningful.

Furthermore, three criteria need to be satisfied for a U.S. patent to be issued: usefulness, novelty and not being obvious from prior art (United States Patent and Trademark Office, 2014b). Emphasised in patent law is that an issued patent must be applicable in real life. A patent with high SL means that it highly cites science-based references, which in turn implies that it cannot be directly applied to the development of inventions. Here lies a contradiction. The purpose of a patent application is to protect the right of an inventor to not have his or her invention infringed upon, and an essential criterion for an issued patent resides in its usefulness. However, high SL indicates that a patent highly cites basic research (e.g. physics and chemistry). It is therefore argued that a patent with high SL cannot be instantly and directly applied to the development of an invention which is supposed to be useful in real life.

4.3. Firm-specific differences in the science linkage performance

Narin (2000) argued that "a company with a portfolio of highly cited, highly science linked patents is more likely to be technologically successful than one that does not have such portfolio." This study re-examined the SL calculation and classified NPRs into two groups, one science-based and the other non-science-based. In addition to journal papers (see Narin, 2000), this study also regarded conference papers and books as science-based NPRs while calculating science-based SL. Furthermore, this study argued that a firm's science–technology linkage should calculate both science-based SLs and Relative SL Ratio in order to consider its ratio of citations to science-based NPRs to non-science-based NPRs and its difference from the overall performance of the field. If the variance is obvious (i.e. the Relative SL Ratio is either extremely high or low), it means that the percentage of a firm's citations to different types of NPRs is different from those of other firms. If the Relative SL Ratio is higher, it means that the percentage of a firm's citations to science-based NPRs is higher, and vice versa.

This study analysed various types of SL performances of the top 20 firms in the C&C field and found that Lucent, Mitsubishi, TI and Microsoft performed best in science-based SL or Relative SL Ratio, indicating their strong science–technology linkages. It is worth noting that TI was ranked thirteenth in science-based SL but third in Relative SL Ratio. This shows that based on the SL calculation, the science-based SL performance of TI was not strong; however, based on the Relative SL Ratio, TI was 6.93 times as good as the overall performance of the field, which indicated that TI's science-based SL was much higher than its NSL. This study regarded this phenomenon as a strong science–technology linkage. Furthermore, the fact that Microsoft had high SL values in the C&C field may be attributed to the high SL performance of its software patents, which calls for further investigation in the future.

Findings of this study also suggest that differences in the characteristics of firms have an impact on firms' SL performances. Take the field of semi-conductors as an example: The SL performance of leading factories (e.g. design houses) differs from that of sub-manufacturers. The latter, by nature, focus on practical application. As a result, they would have low SL performance, but this does not mean that they have low competitiveness.

As mentioned earlier, SL has been employed as an indicator of technological innovation. However, it is argued that a firm with low SL values is not necessarily one that lacks competitiveness. For example, Samsung was listed as one of the top 20 patent assignees, with relatively lower SL values than other patent assignees (see Table 3). From a practical perspective, however, Samsung is a rather competitive firm, taking into account its high revenue.

4.4. Research limitations

Whilst 'Other References' may be scholarly knowledge or relevant from a scientific perspective, they are not visible in patent applications. In fact, an applicant for a patent has an information disclosure statement in compliance with Patent Rules. Any information disclosure statement must include a list of all patents, publications, applications, or other information submitted for consideration by the Office (37 C.F.R. 1.97 & 1.98). The information contained in statements which comply with the content requirements of both 37 CFR 1.98 & 1.97 will be considered by the examiner (Manual of Patent Examining Procedure 609.05(b)). Therefore, 'Other references' may not be fully presented in the patent applications, which however would not cause obvious bias in SL analysis.

Another research limitation resided in country biases. The primary focus of this study was on the SL indicator, drawing upon NPRs in patent citations. However, the NPRs in the Japan Patent Office or European Patent Office were not available to the researchers, and therefore this study collected patent data solely from the USPTO database, which was accessible to the researchers. As a result, there might be a country bias towards US-originating patents and therefore the U.S. 'performed best'. It was also acknowledged that 'domestic' U.S. patents were included and patents from firms outside the U.S. were only used if a patent was interesting enough to apply for in the U.S., which might impose a bias on the results.

Furthermore, this study classified a large number of 'Other References' in the U.S. patents through comparing strings and then manually reviewing the results. Misjudgement might occur during this kind of process, especially when it came to the Web Page and N/A types. As for the NPRs in the Web Page type, if their titles matched the requirements of the other five types of NPRs, they were first classified into one of the those types in the order of Journal Paper, Conference Paper, Book, Patent Document and Report/Manual. However, if the web page NPRs missed titles or remained unrecognized, this study was unable to review all URLs and accurately classify them into appropriate types. The researchers randomly selected 100 web page NPRs and entered the websites, and found that only eight NPRs were classified as the Journal, Conference or Report/Manual types. Such a small percentage of misjudgments did not have a significant impact on the reliability and validity of the results derived from this study. Plus, approximately five percent of NPRs were unclassified and therefore regarded as N/A, excluding them from the SL analysis in this study. This is also acknowledged as one of the limitations of this study.

References

Acosta, M., & Coronado, D. (2003). Science–technology flows in Spanish regions: An analysis of scientific citations in patents. *Research Policy*, *32*(10), 1783–1803.

Anderson, J., Williams, K., Seemungal, D., Narin, F., & Olivastro, D. (1996). Human genetic technology: Exploring the links between science and innovation. *Technology Analysis & Strategic Management*, *8*(2), 135–156.

Bhattacharya, S., & Meyer, M. (2003). Large firms and the science–technology interface: Patents, patent citations, and scientific output of multinational corporations in thin films. *Scientometrics*, *58*(2), 265–279.

Boyack, K. W., & Klavans, R. (2008). Measuring science–technology interaction using rare inventor–author names. *Journal of Informetrics*, *2*(3), 173–182.

Breschi, S., & Catalini, C. (2009). Tracing the links between science and technology: An exploratory analysis of scientists' and inventors' networks. In *Networks, power and relations: First NPR workshop* 16–17 September 2009, Milan,

Chen, C., & Hicks, D. (2004). Tracing knowledge diffusion. *Scientometrics*, *59*(2), 199–211.

Coward, H. R., & Franklin, J. J. (1989). Identifying the science–technology interface: Matching patent data to a bibliometric model. *Science, Technology, & Human Values*, *14*(1), 50–77.

Fagerberg, J. (1987). A technology gap approach to why growth rates differ. *Research Policy*, *16*(2–4), 87–99.

Gupta, V. K. (2006). References to literature in patent documents: A case study of CSIR in India. *Scientometrics*, *68*(1), 29–40.

Hall, B. H., Jaffe, A. B., & Trajtenberg, M. (2001). *The NBER patent citation data file: Lessons, insights and methodological tools*. Cambridge: National Bureau of Economic Research.

Han, Y. (2007). Measuring industrial knowledge stocks with patents and papers. *Journal of Informetrics*, *1*(4), 269–276.

Hicks, D., Breitzman, A., Hamilton, K., & Narin, F. (2000). Research excellence and patented innovation. *Science and Public Policy*, *27*(5), 310–320.

Hullmann, A., & Meyer, M. (2003). Publications and patents in nanotechnology. *Scientometrics*, *58*(3), 507–527.

Klitkou, A., & Gulbrandsen, M. (2010). The relationship between academic patenting and scientific publishing in Norway. *Scientometrics*, *82*(1), 93–108.

Lo, S. S. (2010). Scientific linkage of science research and technology development: A case of genetic engineering research. *Scientometrics*, *82*(1), 109–120.

Meyer, M. (1998). Patents citing scientific literature: Is the relationship causal or casual? In *IPTS report, No. 28*.

Meyer, M. (2000a). Does science push technology? Patents citing scientific literature. *Research Policy*, *29*(3), 409–434.

Meyer, M. (2000b). What is special about patent citations? Differences between scientific and patent citations. *Scientometrics*, *49*(1), 93–123.

Narin, F. (1991). Globalization of research, scholarly information, and patents—ten year trends. *The Serials Librarian*, *21*(2–3), 33–44.

Narin, F. (1994). Patent bibliometrics. *Scientometrics*, *30*(1), 147–155.

Narin, F. (2000). Tech-line® background paper. In J. Tidd (Ed.), *From knowledge management to strategic competence* (pp. 155–195). London: Imperial College Press.

Narin, F., Albert, M., Kroll, P., & Hicks, D. (2000). *Inventing our future: The link between Australian patenting and basic science*. Retrieved from ⟨http://www.arc.gov.au/pdf/00_02.pdf⟩ (accessed 01.02.14).

Narin, F., Hamilton, K. S., & Olivastro, D. (1995). Linkage between agency supported research and patented industrial technology. *Research Evaluation*, *5*(3), 183–187.

Narin, F., Hamilton, K. S., & Olivastro, D. (1997). The increasing linkage between US technology and public science. *Research Policy*, *26*(3), 317–330.

Narin, F., & Olivastro, D. (1992). Status report: Linkage between technology and science. *Research Policy*, *21*(3), 237–249.

United States Patent and Trademark Office. (2014a). *Country codes*. Retrieved from ⟨http://patft.uspto.gov/netahtml/PTO/help/helpctry.htm⟩ (accessed 01.12.14).

United States Patent and Trademark Office. (2014b). *Manual of patent examining procedures*. Retrieved from ⟨http://www.uspto.gov/web/offices/pac/mpep/⟩ (accessed 13.08.14).

Park, H., & Kang, J. (2009). Patterns of scientific and technological knowledge flows based on scientific papers and patents. *Scientometrics*, *81*(3), 811–820.

Rosenberg, N., & Birdzel, L. E., Jr. (1990). Science, technology and the Western miracle. *Scientific American*, *263*(5), 42–54.

Sirilli, G. (1998). Conceptualising and measuring technological innovation. In *IDEA report, 1, 3*. IDEA.

Sorenson, O., & Fleming, L. (2004). Science and the diffusion of knowledge. *Research Policy*, *33*(10), 1615–1634.

Tijssen, R. J. W. (2001). Global and domestic utilization of industrial relevant science: Patent citation analysis of science–technology interactions and knowledge flows. *Research Policy*, *30*(1), 35–54.

Tijssen, R. J. W. (2002). Science dependence of technologies: Evidence from inventions and their inventors. *Research Policy*, *31*(4), 509–526.

Tijssen, R., Buter, R., & van Leeuwen, T. (2000). Technological relevance of science: An assessment of citation linkages between patents and research papers. *Scientometrics*, *47*(2), 389–412.

Verbeek, A., Debackere, K., Luwel, M., Andries, P., Zimmermann, E., & Deleus, F. (2002). Linking science to technology: Using bibliographic references in patents to build linkage schemes. *Scientometrics*, *54*(3), 399–420.