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Evolutionary convergence of the patterns of international research collaborations across scientific fields

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EVOLUTIONARY CONVERGENCE OF THE PATTERNS OF INTERNATIONAL RESEARCH COLLABORATIONS ACROSS SCIENTIFIC FIELDS[1]

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Abstract

Frame and Carpenter (1979) analysed the pattern of international research collaboration among scientific fields in 1970s. Starting from this pioneering work, this paper investigates international collaborations over 1997-2012 and compares the critical results with earlier studies to detect the evolution of collaboration patterns in different scientific fields. Empirical analysis supports two vital findings, given by: *a*) a relatively stable structure of international research collaborations over time across different scientific fields; *b*) a convergent process of collaboration patterns between theoretical and applied research fields. One important determinant of the latter result might be due to the increasing interdisciplinary nature of research fields that supports the convergence between basic and applied sciences.

Keywords: Scientific Fields, Research Collaboration, Science Evolution, Co-authorship, Co-publishing, Interdisciplinary, Convergence.

JEL classification: O31; O39; O10; N00; N31; N33.

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1. Introduction

International scientific collaboration has received much attention by scholars since it is a main feature of scientific communities across different research fields[2]. Research collaboration can take place at different levels: individual researchers, research teams/labs, departments, universities, sectors and nations (Katz and Martin, 1997). In general, by sharing knowledge and data, research collaboration improves labour efficiency in the scientific production process. Katz and Martin (1997, p. 15) claim that research collaboration is: "a cross-fertilization of ideas which may . . . generate new insights or perspectives that individuals, working on their own, would not have grasped (or grasped as quickly)". Research collaborations are a rational division of scientific labour to increase the efficiency of subjects/organisations in order to achieve fruitful results in shorter time (Coccia, 2014a).

De Solla Price (1963) was a pioneer in measuring collaborations via multi-authored articles. These have been widely recognised as forming the most useful and apt scientific indicator for measuring and evaluating research collaborations (*cf.* de Solla Price and Beaver, 1966; van Raan, 1988; 1998; Egghe, 1991; Luukkonen *et al.,* 1993; Stokes and Hartley, 1989; Glänzel and De Lange, 1997).

In economics of science, it is crucial to analyse patterns of international collaboration across different scientific disciplines in order to detect evolutionary trends of scientific fields[3]. Frame and Carpenter (1979) have analysed, considering 1973 data, the patterns of international research collaborations of some scientific fields. Starting from this pioneering work, the purpose of this paper is to investigate the recent international co-authorships of research institutions and to compare the results with earlier studies in order to detect vital characteristics concerning the basic *structure* and *evolutionary dynamics* of different scientific fields over time.

[2] Cf. Zitt *et al.,* 2000; Schubert and Braun, 1990; Peters and Van Raan, 1989; Beaver, 2001; Cummings and Kiesler, 2005; *cf.* Hackett, 2005; Lee and Bozeman, 2005; Presser, 1980.
[3] Cf. de Solla Price, 1963; 1986; Kuhn, 1970; Beaver and Rosen, 1978; Luukkonen *et al.*, 1992; Frame, 1979; Frame et al., 1977; Inhaber, 1977; Stephan, 1996.

2. Theoretical background and related studies

Beaver and Rosen (1978) argue that scientific collaboration is not a modern feature of scientific fields, since the early collaborations appeared during the scientific revolution of the 17th and 18th centuries. In fact, Beaver and Rosen (1978, pp. 73-74) consider a historical bibliography of papers before 1800 and show that the earliest collaborative papers were from 1665 by joint researches among Hooke, Cassini and Boyle. According to these scholars, the beginning of scientific collaboration represents a response to the "professionalization of science" (Beaver and Rosen, 1978, p. 65).

Puuska *et al.* (2014) argue that in current economies both international and domestic co-publishing have increased during the last decades in all scientific fields. Georghiou (1998, pp. 613-616) shows a huge increase in the number and share of collaborative papers between the European Union and other industrialised countries (*e.g.* Australia, Canada, Japan, New Zealand, Korea and USA) over 1985-1995. Modern society endows international collaboration with a new feature of scientific vitality.

Various motives for performing collaborative research have been discussed, including access to high-tech equipment or facilities, sharing skills and specific materials, as well as enhancing scientific visibility and recognition (Beaver and Rosen, 1978, p. 70). In recent decades, scientific collaboration has also increased due to the complexity and high cost of scientific research concerning 'big science' (Hand, 2010; Katz and Martin, 1997; De Solla Price, 1986) as well as to the growing importance of new multidisciplinary fields (Jeong *et al.,* 2011; Van Leeuwen and Tijssen, 1993). In addition, the rapid growth of Information and Communication Technologies (ICTs), the improvement of transportation technology together with the reduction of cost have also greatly facilitated scientific communication and "the rise of research network" (Adams, 2012; *cf.* Katz and Martin, 1997). Laudel (2001) argues that most research collaborations start with a face-to-face meeting in fruitful environments such as conferences, congresses, symposium, research labs, etc. (*cf.* Bozeman, 2004: Latour and Woolgar, 1979).

International collaboration intensity tends to vary greatly among different scientific disciplines, with the highest frequency of co-authored scientific research in astronomy. In fact, joint research in astronomy seems to be driven by the necessity of sharing equipment and data in observatories (Beaver and Rosen, 1978). Frame and Carpenter (1979), using data from the 1973 Science Citation Index concerning journals in all scientific fields and a sample of key countries, show the highest international collaboration intensity in earth & space sciences and physics, but the lowest intensity is in engineering. Luukkonen *et al.* (1992), considering data of the year 1983, show similar results: higher collaborations are also in earth and space science, mathematics and physics.

In general, the analysis of the patterns of international research collaboration is of great scientific interest to understand the nature and evolution of different scientific fields. This study tackles this issue and aims to pinpoint vital characteristics of scientific collaboration that support the structure and evolutionary patterns of research fields.

3. Data and study design

3.1 Data collection

This study focuses on international research collaborations in scientific fields based on article counts from the set of journals covered by the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) in the dataset by National Science Foundation (2014)-National Center for Science and Engineering Statistics, special tabulations from Thomson Reuters (2013). In particular, this study considers published articles in all scientific fields classified by co-authorship attribute (total articles with domestic institutions only; Total articles with international institutions), in the period 1997–2012. Articles with international institutions are counts of articles with one or more institutional addresses outside the country.

The research fields of the study are listed in Appendix A, whereas the international co-authored papers across scientific fields are analysed considering a sample of forty countries (listed in Appendix B). Scientific publications produced by these forty countries accounted for 97% of the worldwide total output in the studied period. This study also considers a subset of 11 Western countries and 9 research fields in order to provide results comparable with the study by Frame and Carpenter (1979). The 11 countries yielded in the 1996 about 65% of the worldwide production of scientific articles, and this share declined to 51% in 2011 likely due to the fast growth of scientific production by China.

3.2 Methodology

First of all, this study computes per scientific field *i* the total intensity of internationally co-authored papers (ICP $_{it)}$ during the period 1997 - 2012. The formula is given by:

$$ICP_{it} = \frac{\text{Co−authored articles with international institutions}_{it}}{Total\ article_{it}} \qquad (1)$$

Where *i*= scientific field (*cf.* Appendix A); *t* =1997, …, 2012.

- ☐ *Dynamics of collaboration patterns*. The temporal evolution of collaboration patterns across scientific fields is examined by regression analysis. Ordinary Least Squares (OLS) is applied to capture the vital relationships between dependent variable – Intensity of international collaborations per research field (ICP_{it}) – and explanatory variable time *t* . Coefficients of regression of estimated relationships assess how international research collaborations change over time in scientific fields.

- ☐ *Structure of collaboration patterns*. The structure of scientific fields is analysed by the hierarchical clustering, by means of squared Euclidean distance and the method of Ward. This technique detects the groups of scientific fields that have similar intensities of international co-authored papers over 1997-2012.

- ☐ *Comparison of collaboration patterns with previous studies.* The results of this study are compared with earlier studies by Frame and Carpenter (1979) and Luukkonen *et al.* (1992). To put all the ICP_{it} values from different studies in a comparable framework, we standardise the intensities as follows:

$$Z_{it} = \frac{ICP_{it} - \mu_t}{\sigma_t} \qquad (2)$$

where

Z_{it} = Standardised value of ICP_{it}

ICP_{it} = Intensity of internationally co-authored papers per research field *i* at year *t*

μ_t = the arithmetic mean of the ICP in all fields at year *t*
σ_t = the standard deviation of the ICP in all fields at year *t*

The absolute value of Z_{it} represents the distance between the raw score ICP_{it} and the mean in unit of the standard deviation. Z_{it} is negative when the raw score is below the mean, positive when it is above. A zero value of Z_{it} indicates that the raw intensity is equal to the arithmetic mean.

In addition, this study applies a non-parametric measure of association (Spearman's *rho* ρ) and Pearson's coefficients of correlation to analyse the ranking and distribution of the intensity of internationally co-authored papers among scientific disciplines over time (ICP_{it} per research field *i* at *t*).
Spearman's *rho* ρ for a sample of size *n* is:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{3}$$

where $d_i = x_i - y_i$ *is* the difference between ranks, and *n* is the size of sample.

The Pearson's correlation coefficient is *r:*

$$r = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{4}$$

σ_{xy} is covariance between X and Y, σ_x and σ_y are standard deviation.

- *Dynamics of collaboration patterns.* To examine the relative variability of collaboration intensity in different fields over time, this study also applies the Coefficient of Variation (CV_t) given by:

$$CV_t = \frac{\mu_t}{\sigma_t} \tag{5}$$

where:
CV_t is the coefficient of variation at year *t*
μ_t is the arithmetic mean of the collaboration intensities in all research fields at year *t*
σ_t is the standard deviation of collaboration intensities in all research fields at year *t*

The comparison of coefficient variation values in different time periods reveals the dynamics of the degree of variation. An increasing CV indicates that the collaboration performance across all fields is divergent, whereas a decreasing CV shows a convergence trend.

Statistical analyses are performed by Statistics Software SPSS® version 15.0.

4. Empirical analyses

4.1 Trends of international research collaboration intensity

Figure 1 shows the growing trend of international collaboration intensities in different scientific disciplines during the period 1997 - 2012. Astronomy is on the top; its international collaboration intensity increased from 68 per cent in 1997 to 83 per cent in 2012. In spite of their steadily rising values, Medicine, Chemistry and Engineering have relatively lower intensities. The collaboration patterns are analysed by a regression analysis to measure the rate of growth over time per research field.

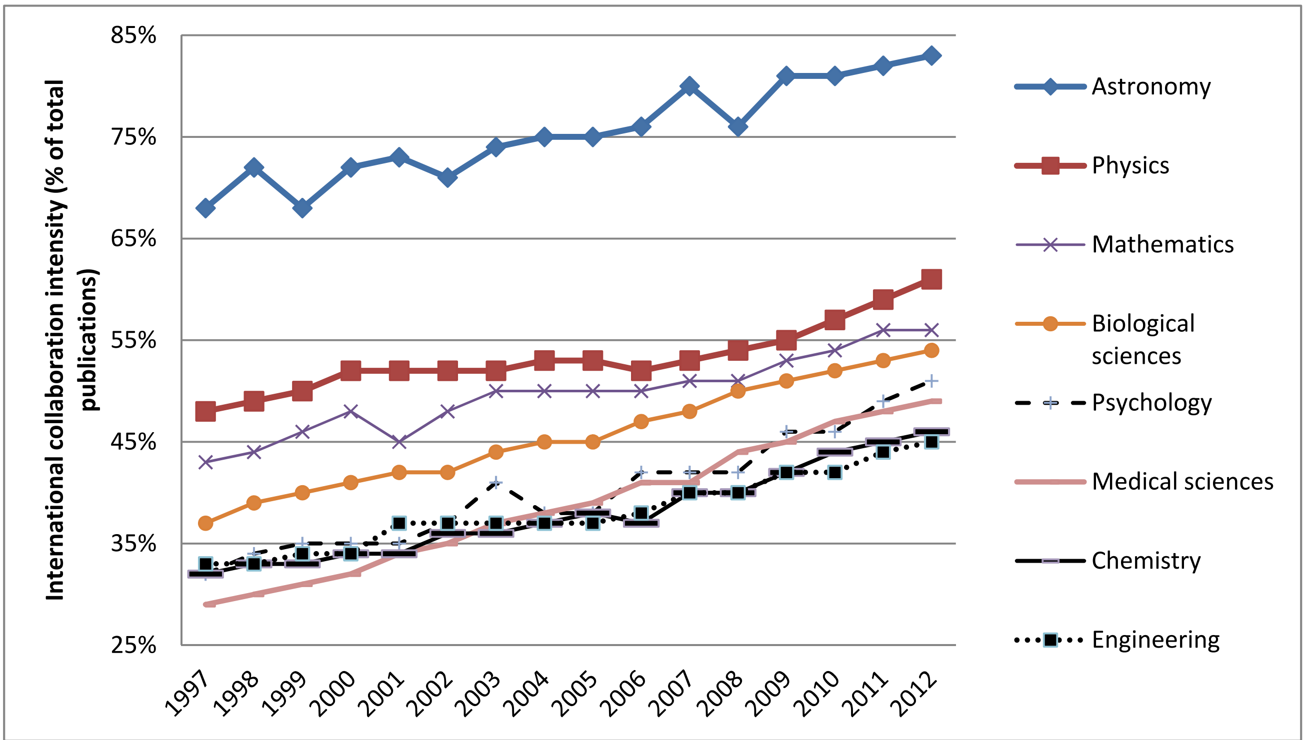

Figure 1: Trend of the intensity of international collaborations by scientific field

Note: This figure is plotted based on the absolute value of intensity

Table 1 shows the estimated relationships by linear regression analysis over 1997-2012. The results also show a strong (*probabilistic*) explanatory power of linear models: significance of β coefficients is $p \leq 0.001$ and R^2 has high values.

Table 1: OLS regressions in scientific fields

Research Fields	*Constant* α *(St. Err.)*	*Coefficient* β *(St. Err.)*	R^2 *(St. Err. of the Estimate)*	*F* *(sign.)*
Astronomy	−18.436	0.010***	0.894	127.12
	(1.702	(0.001)	(0.016)	(0.00)
Physics	−12.674	0.007***	0.832	75.339
	(1.521)	(0.001)	(0.014)	(0.00)
Geosciences	−21.719	0.011***	0.982	839.226
	(0.767)	(0.000)	(0.007)	(0.00)
Mathematics	−15.451	0.008***	0.925	185.627
	(1.171)	(0.001)	(0.011)	(0.00)
Computer Sciences	−14.386	0.007***	0.649	28.743
	(2.771)	(0.001)	(0.025)	(0.00)
Biological Sciences	−21.770	0.011***	0.991	1571.727
	(0.561)	(0.000)	(0.005)	(0.00)
Psychology	−22.502	0.011***	0.923	180.041
	(1.707)	(0.001)	(0.016)	(0.00)
Medical Sciences	−27.322	0.014***	0.995	2761.25
	(0.527)	(0.000)	(0.005)	(0.00)
Other Life Sciences	−20.295	0.010***	0.773	52.087
	(2.867)	(0.001)	(0.026)	(0.00)
Chemistry	−18.044	0.009***	0.951	293.231
	(1.076)	(0.001)	(0.010)	(0.00)
Engineering	−15.006	0.008***	0.942	246.176
	(0.981)	(0.000)	(0.009)	(0.00)
Agricultural Sciences	−20.102	0.01***	0.957	336.603
	(1.117)	(0.001)	(0.010)	(0.00)
Social Sciences	−17.167	0.009***	0.846	83.379
	(1.918)	(0.001)	(0.018)	(0.00)

Note: 1) Dependent variable: Intensity of internationally co-authored papers; Explanatory variable *t;* 2) ***Coefficients β are all significant at $p \leq 0.001$; Explanatory variable is the time *T*= 1997-2012.

4.2 Structure of international research collaborations across scientific fields

The structure of collaboration pattern across scientific disciplines is examined by hierarchical clustering. Figure 2 shows three basic groups of the under studied 13 scientific fields:

Group 1: Astronomy

Group 2: Physics, Mathematics, Computer, Biological and Geo Sciences

Group 3: Engineering, Chemistry, Medicine, Psychology, Social sciences, Agricultural Science and other Life Sciences

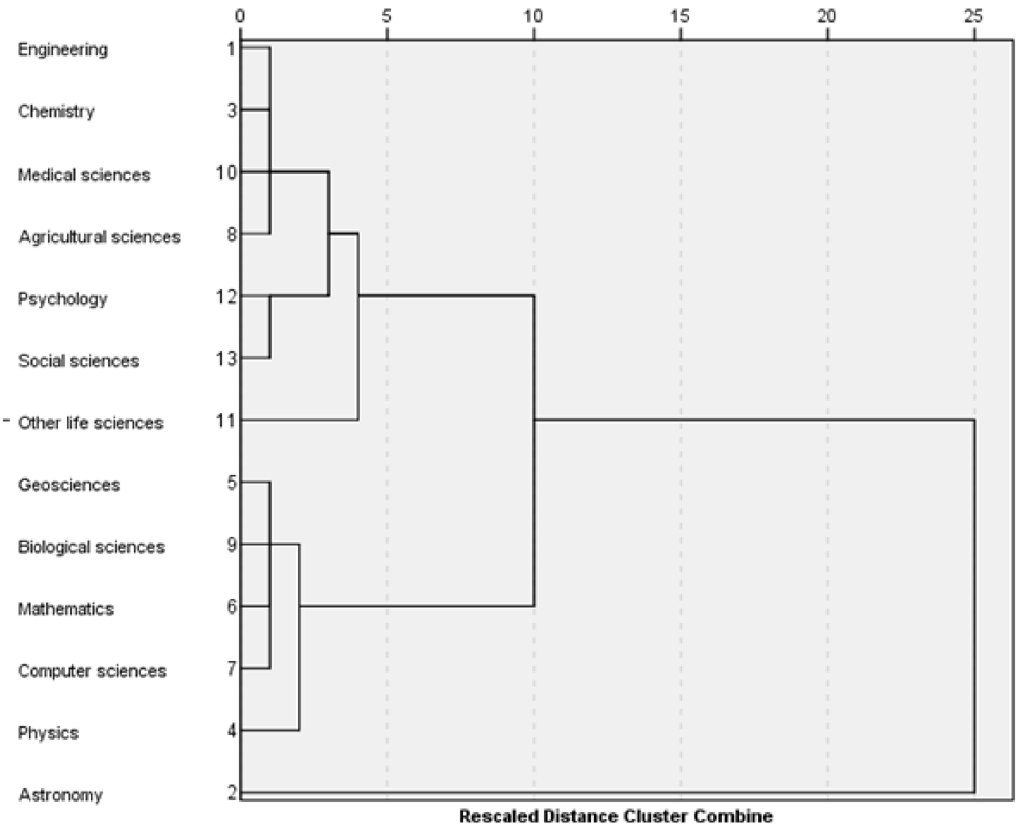

Figure 2: Similarity clusters of the intensity of international collaborations

Note: 1) Hierarchical clusters are performed using Ward's method and applying squared Euclidean distance.
2) Period: 1997-2012.

The main characteristics of these three groups are as follows.

First, theoretical fields (group 1 and 2) have a higher intensity of international collaborations over time (*see also* in Fig. 1). Research in these fields focuses mainly on general scientific and technological problems.

Second, contrary to theoretical fields, applied sciences (in particular engineering, human and social sciences, *i.e.* group 3), which focus on local and specific technical problems (context-dependent issues), have lower international collaboration intensity. This result is in line with the argument by Allen *et al.* (1979, p. 695): "Science may be said universal. . . . Technology [applied sciences], on the other hand, is not universal".

Third, astronomy seems to be an outlier, with the largest distance from other research fields in terms of collaboration pathway.

4.3 Comparison of results (with studies by Frame and Carpenter, 1979 and Luukkonen et al., 1992)

Despite the general acceleration in scientific collaboration intensity of all research fields, as shown in Figure 1, an interesting observation is that Astronomy, Physics and Mathematics tend to have *higher* intensity throughout the period 1997-2012; *vice versa* Chemistry, Engineering and Psychology have *lower* intensity. In order to further investigate the long-run evolution of international collaboration patterns among research fields, this study combines its results with those by Frame and Carpenter (1979) and Luukkonen *et al.* (1992). Standardisation *Z* is applied to all collaboration intensities in order to make them comparable (*see* Methodology section for details). Results of the standardisation are reported in Table 2 and Table C1 in Appendix.

Table 2: Intensity of international collaborations per key scientific fields (comparison of results from different studies)

	Frame and Carpenter (1978, p. 484)	Luukkonen *et al.* (1992, p. 118)		THIS STUDY	
Subject	*1973*	*1973*	*1983*	*1997-2012 (40 countries)*	*1997-2012 (11 countries)*
	%	%	%	%	%
Astronomy	4.45	5.38	11.8	77.1	78.8
Physics	4.23	4.39	9.45	54.0	56.6
Mathematics	3.75	5.47	10.78	50.5	52.0
Biomedical Research	2.63	3.51	6.93	n.a.	n.a.
Chemistry	2.03	2.42	5.37	47.9	40.6
Biology	1.68	3.01	5.84	46.4	46.1
Psychology	1.66	n.a.	n.a.	41.7	34.9
Clinical Medicine	1.61	2.47	4.77	39.8	38.7
Engineering	1.46	2.04	5.16	38.9	39.4

Standardisation of results by *Z* per year

	Frame and Carpenter (1978, p. 484)	Luukkonen *et al.* (1992, p. 118)		THIS STUDY	
Subject	*1973*	*1973*	*1983*	*1997-2012 (40 countries)*	*1997-2012 (11 countries)*
	%	%	%	%	%
Astronomy	1.52	1.33	1.55	2.24	2.13
Physics	1.34	0.60	0.70	0.36	0.58
Mathematics	0.94	1.40	1.18	0.08	0.25
Biomedical Research	0.02	–0.06	–0.21	n.a.	n.a.
Chemistry	–0.48	–0.86	–0.77	–0.13	–0.54
Biology	–0.77	–0.43	–0.60	–0.26	–0.16
Psychology	–0.79	–2.66	–2.71	–0.64	–0.94
Clinical Medicine	–0.83	–0.83	–0.99	–0.79	–0.68
Engineering	–0.95	–1.15	–0.85	–0.86	–0.63

Note: 1) Detailed description of Z standardisation is provided in the methodology section. Data are standardised within the set of year (or period), *i.e.* t=1973, 1983, etc.; "n.a." means no data available.
2) Refer to Appendix C for more details.

Table 2 shows the comparison of the results of this study with those by Frame and Carpenter (1979) and Luukkonen *et al.* (1992). Although these studies were performed in periods with different socio-economic and technological contexts (*i.e.* in 1973, 1983 and 1997-2012 period), the results have a great degree of similarity. *Patterns of international research collaboration concerning scientific fields seem to have a rather stable structure in their evolutionary pathways.* In other words, some disciplines persist with a higher intensity of international research collaboration over time (*e.g.* Physics), *vice versa* Engineering and Clinical medicine. Figure 3 synthetises this similarity of results over a time span of about 40 years.

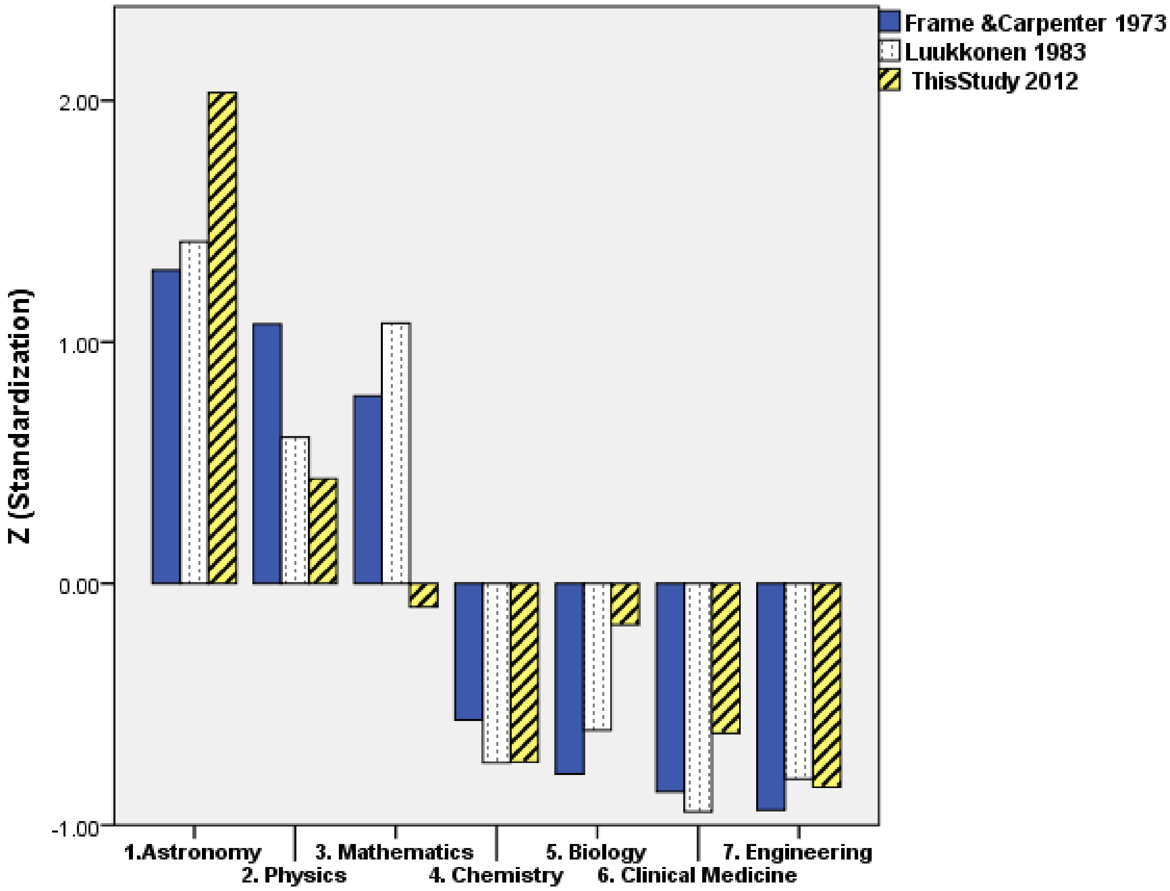

Figure 3: Intensity of collaboration (standardised Z) among three studies performed in different time period.

Spearman' rho ρ and Pearson's coefficients of correlation r between results of this paper and previous studies rigorously show that both have high positive significant values (Table 3). This confirms that evolutionary pathways of international collaboration in different scientific fields remained unchanged in their temporal trajectories. In particular, Astronomy and Physics (representatives of theoretical research fields) had high intensity of international collaborations in 1973, 1983 and this tendency continued over 1997-2012, whereas Engineering (a field of applied research to develop technology) had lower international collaborations in 1973, 1983 and this continued over 1997-2012 as well.

Table 3: Correlation between this study and previous ones

	Frame & Carpenter Data 1973	Luukkonen *et al.* Data 1973	Luukkonen *et al.* Data 1983
Spearman's rho ρ			
Correlation Coefficient	1.000***	0.786**	0.893***
Sig. (2-tailed)	0.0	0.036	0.007
N	8	7	7
Pearson's Correlation r	0.827**	0.763**	0.826**
Sig. (2-tailed)	0.011	0.046	0.022
N	8	7	7

Note: 1) ***Correlation is significant at the 0.01 level (2-tailed);** Correlation is significant at the 0.05 level (2-tailed). 2) This study covers data over 1997 – 2012 period.

These findings reveal that, despite the fast growth of international co-authorships in different disciplines, the structure of collaborative research across scientific fields in their evolutionary pathways tends to be unchanged (*stability of scientific structure*). That is, *the rank of the intensity of collaboration patterns across research fields in 2012 is similar to that of 40 years ago*.

4.4 Evolutionary convergent process of international research collaboration patterns between theoretical and applied sciences

This study has standardised the collaboration intensity across disciplines to put various results in a comparative analytical framework (*see* Table 2 and Table C1 in Appendix C). Figure 4 displays the evolutionary dynamics of collaboration patterns across research fields. Although the structure of collaborative science is unchanged (Astronomy and Physics were the research fields with the highest intensity of international collaborations in 1973, 1983 and they continued this tendency also during 1997-2012, whereas the Engineering and Clinical medicine had lower intensity in 1973, 1983 as well as over 1997-2012 period), results in Fig. 4 show that, except the outlier of Astronomy pathway, the gap between all other fields has been reducing, tremendously. This indicates a critical convergent process of international collaboration pathways across different research fields. This result demonstrates that external factors are affecting pathways of scientific collaboration performance in various fields, despite they do not dramatically change the intrinsic nature and basic collaboration structure of science.

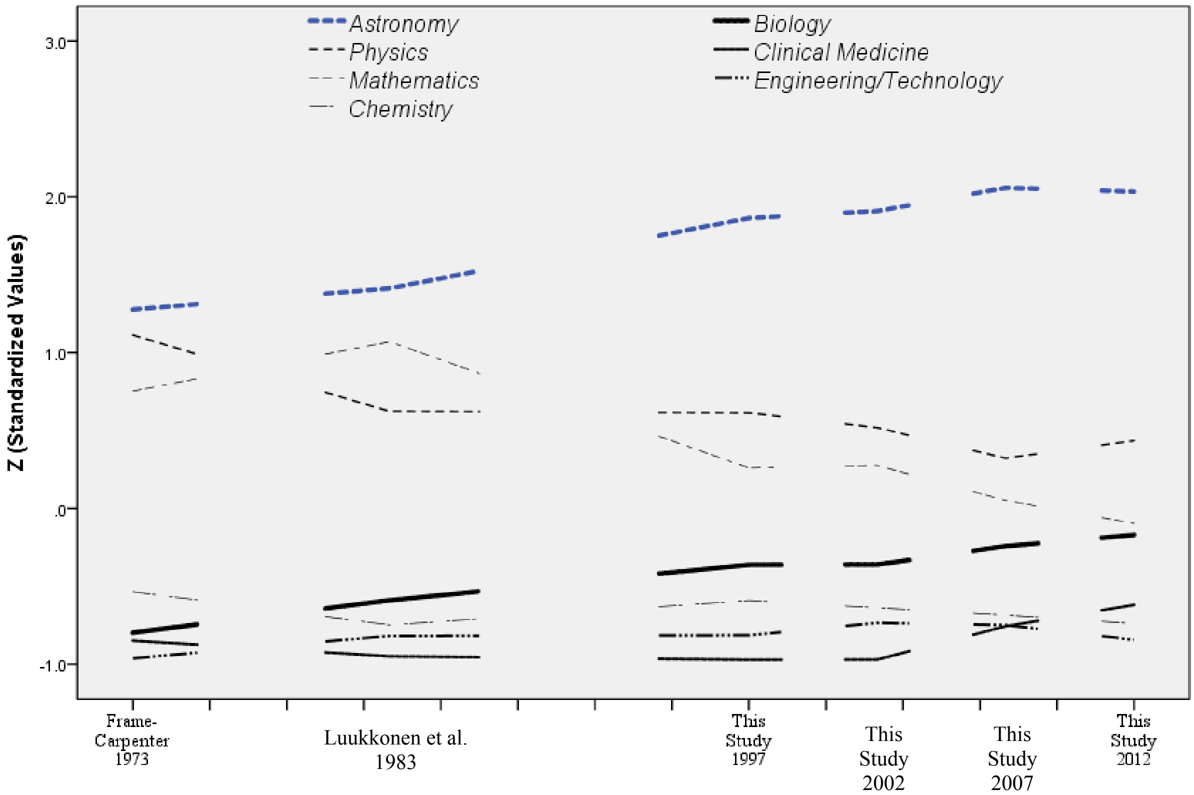

Figure 4: Patterns of international research collaboration across scientific fields

Note: Standardised Z values are obtained based on collaboration intensity. See more information in Table 2 and Table C1 in Appendix C.

By classifying all fields into two major groups, *i.e.* theoretical and applied sciences, Figure 5 presents the evolutionary dynamics of these binomial macro-collaboration patterns. A vital observation is the clear evolutionary convergence between pathways of theoretical and applied sciences. This convergence is even more pronounced if the outlier field of Astronomy is excluded (*cf.* Fig. 4). *The coefficients of estimated relationships confirm a clear convergent process of collaboration patterns, with both theoretical and applied research fields approaching towards the line of zero –Z standardised value*[4]. The convergence can be further analysed by the coefficient of variation (CV), which declines constantly, both in the first case with all fields and in the second case without Astronomy (Table C2 in Appendix). The continuously decreasing variance of international research collaborations confirms the strong long-run convergent process in collaboration patterns across scientific fields.

[4] As indicated in the Methodology section, a zero-Z standardised value indicates that the collaboration intensity is equal to the arithmetic mean.

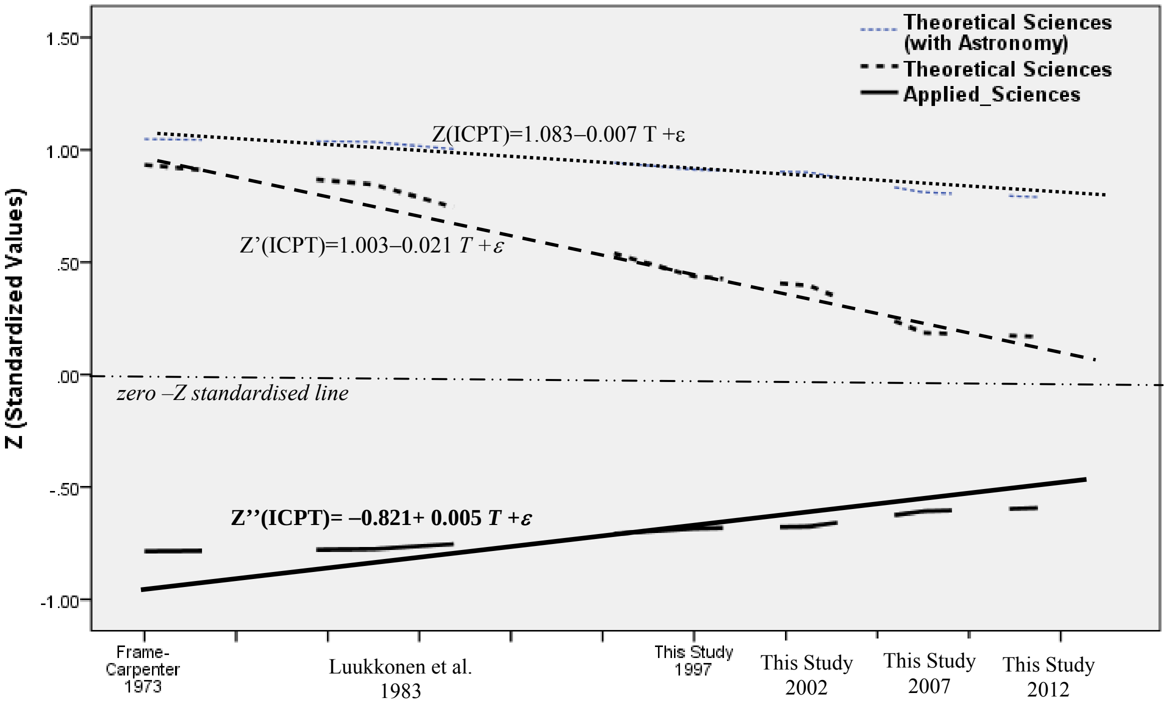

Figure 5: Convergent process of the intensity of international research collaborations between theoretical and applied sciences

Note: 1) Based on Z standardised values indicated in Table 2 and Table C1 in Appendix C.
2) *Theoretical Sciences* include Astronomy, Physics and Mathematics; *Applied Sciences* include Chemistry, Biology, Clinical Medicine and Engineering;
3) The intermittent lines of theoretical and applied sciences are based on observed data; the linear lines are estimated relationships by OLS Method.
4) Z(ICP)=Standardisation of intensity of internationally co-authored papers; T=*time;* ε=Error term; significant coefficients of regression $p \leq 0.001$; R^2 adj.≥90%. 0.001

In short, evolutionary pathways of collaborative research in different fields have a stability of structure: high collaboration intensity in theoretical research fields and lower intensity in applied ones persist over time (*cf.* Tijssen, 2010). However, in the long run, the gap is diminishing by an on-going process of evolutionary convergence of collaboration pattern between theoretical and applied sciences.

4.5 Explanation of convergence process and possible determinants

The convergent process of collaboration pathways across scientific fields is due to the underlying dynamics of high growth rates in applied research fields (*e.g.* Medical sciences and Psychology) and lower growth rates in theoretical ones (*e.g.* Mathematics and Physics).

Potential determinants of this convergence of collaboration pattern, with diminishing gap between applied and theoretical sciences, can be due to: a) the increasing interdisciplinarity of current research fields, and b) very strong impact of emerging transversal disciplines (*e.g.*

nanoscience and molecular biology-*cf.* Coccia, 2014). These two factors are closely connected. In particular, the evolution of science and technology has supported the emergence of new disciplines by either from one specific discipline or through the combination of multiple scientific fields (*cf. also* Jamali and Nicholas, 2010; Riesch, 2014). US National Research Council (2014) states that interdisciplinarity is a key element to spur breakthroughs by research teams with both theoretical and applied scientists. In recent decades, some new scientific fields have been established with an intrinsically interdisciplinary nature, such as nanoscience, nanotechnology, biotechnology, cognitive science, computational biology, bimolecular physics, bioengineering, etc. (*cf.* Jeffrey, 2003; Wang *et al.,* 2013; Roco and Bainbridge, 2002; Van Raan, 2000; Wagner *et al.,* 2011). Battard (2012) argues that emerging scientific fields, such as nanotechnology, involve several disciplines around the same complex problem: " laboratories are technological hubs through which scientists converge from multiple scientific backgrounds" (Battard, 2012, p. 235). In addition, traditional disciplines, such as Chemistry and Physics and Biology have been shown to be highly interdisciplinary as well (Silva *et al.* 2013; Boyack *et al.,*2005; Carley and Porter, 2012). The characteristic of interdisciplinarity in both emerging and traditional scientific fields, in the light of "big science" challenge, tends to induce converging pathways of research patterns between different scientific fields – including their patterns of international collaborations – for the solution of complex problems necessary to the modern societies and economies (*cf.* Coccia, 2014; Tijssen, 2010).

5. Lessons learned and concluding observations

The collaboration pattern of global scientific research is a topic of great interest for scholars in different disciplines (Frame and Carpenter, 1979; Beaver, 2001; Newman, 2001; Barabási *et al.,* 2002; Tomassini and Luthi, 2007). This study provides insights on the main characteristics of the evolutionary process in international research collaborations across research fields. Some vital observed facts of this study can be summarised as follows:

1. *Growing trend of international research collaboration is observed in all fields.* Modern facilities such as fast transportation technology and better ICTs have boosted international research collaborations greatly.
2. *General structure of international collaboration across fields has remained stable due to the nature of disciplines.* Basic research fields such as Astronomy and Physics have an in-

trinsic nature oriented to high international collaborations since they have to solve theoretical problems of universal interests for human development (*cf.* Storer, 1970; Beaver and Rosen, 1978; Frame and Carpenter, 1979; Luukkonen *et al.,* 1992). In addition, the high intensity of collaborations in basic science is also due to the need of sharing main scientific equipment, infrastructures and facilities to advance theoretical knowledge (*cf.* Latour, 1987; Latour and Woolgar, 1979). Instead, some applied research fields, such as social sciences or engineering, tend to have a low intensity of international research collaboration due to their nature of aiming at local issues, which are mainly context-dependent problems (Crane, 1972; Frame and Carpenter, 1979; Luukkonen *et al.,* 1992; Coccia, 2014).

3. *Converging trajectories of collaboration patterns.* This study shows a clear evolutionary convergence of international research collaborations between theoretical and applied sciences.
4. *Interdisciplinarity and emerging research fields as possible determinants underlying the convergent process.* The emergence of new interdisciplinary scientific fields (such as nanotechnology, biotechnology, computational biology, bimolecular physics, and bioengineering) and the high interdisciplinarity character of some traditional fields reduce the gaps of research collaboration patterns between different scientific fields. International collaboration, as one typology of research pattern, has become similar across disciplines.

In sum, despite the fast growing intensity of international collaborations in different scientific disciplines, the general collaboration structure has remained unchanged. The nature of academic disciplines is the primary factor in determining the patterns of international research collaborations. In the evolutionary process of science, however, the gap of research genres between theoretical and applied sciences has been significantly narrowed down over time.

Appendix A: Fields and subfields of publications data

Engineering
- Aerospace engineering
- Chemical engineering
- Civil engineering
- Electrical engineering
- Mechanical engineering
- Metals and metallurgy
- Materials engineering
- Industrial engineering
- Operations research and management
- Biomedical engineering
- Nuclear technology
- General engineering
- Miscellaneous engineering and technology

Astronomy

Chemistry
- Analytical chemistry
- Organic chemistry
- Physical chemistry
- Polymers
- General chemistry
- Applied chemistry
- Inorganic and nuclear chemistry

Physics
- Acoustics
- Chemical physics
- Nuclear and particle physics
- Optics
- Solid state physics
- Applied physics
- Fluids and plasmas
- General physics
- Miscellaneous physics

Geosciences
- Meteorology and atmospheric sciences
- Geology
- Earth and planetary sciences
- Oceanography and limnology
- Marine biology and hydrobiology
- Environmental sciences

Mathematics
- Applied mathematics
- Probability and statistics
- General mathematics
- Miscellaneous mathematics

Computer sciences

Agricultural sciences
- Dairy and animal sciences
- Agricultural and food sciences

Biological sciences
- General biomedical research
- Miscellaneous biomedical research
- Biophysics
- Botany
- Anatomy and morphology
- Cell biology, cytology, and histology
- Ecology
- Entomology
- Immunology
- Microbiology
- Nutrition and dietetics
- Parasitology
- Genetics and heredity
- Pathology
- Pharmacology
- Physiology
- General zoology
- Miscellaneous zoology
- General biology
- Miscellaneous biology
- Biochemistry and molecular biology
- Virology

Medical sciences
- Endocrinology
- Neurology and neurosurgery
- Dentistry
- Environmental and occupational health
- Public health
- Surgery
- General and internal medicine
- Ophthalmology
- Pharmacy
- Veterinary medicine
- Miscellaneous clinical medicine
- Anaesthesiology
- Cardiovascular system
- Cancer
- Gastroenterology
- Haematology
- Obstetrics and gynaecology
- Otorhinolaryngology
- Paediatrics
- Psychiatry
- Radiology and nuclear medicine
- Dermatology and venereal disease
- Orthopaedics
- Arthritis and rheumatism
- Respiratory system

Medical sciences (continued)
- Urology
- Nephrology
- Allergy
- Fertility
- Geriatrics
- Embryology
- Tropical medicine
- Addictive diseases
- Microscopy

Other life sciences
- Speech/language pathology and audiology
- Nursing
- Rehabilitation
- Health policy and services

Psychology
- Clinical psychology
- Behavioural and comparative psychology
- Developmental and child psychology
- Experimental psychology
- Human factors
- Social psychology
- General psychology
- Miscellaneous psychology
- Psychoanalysis

Social sciences
- Economics
- International relations
- Political science and public administration
- Demography
- Sociology
- Anthropology and archaeology
- Area studies
- Criminology
- Geography and regional sciences
- Planning and urban studies
- General social sciences
- Miscellaneous social sciences
- Science studies
- Gerontology and aging
- Social studies of medicine

Appendix B: Country/economy of the sample

Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, Hungary, India, Iran, Ireland, Italy, Israel, Japan, Mexico, New Zealand, Norway, Poland, Portugal, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, The Netherlands, Turkey, United Kingdom, United States of America.

Appendix C:

Table C1: Intensity of international collaborations considering data 1997-2012

	Intensity of internationally co-authored papers							
Subject	**1997** 40 countries	**1997** 11 countries	**2002** 40 countries	**2002** 11 countries	**2007** 40 countries	**2007** 11 countries	**2012** 40 countries	**2012** 11 countries
Astronomy	0.68	0.69	0.71	0.75	0.80	0.81	0.83	0.86
Physics	0.48	0.50	0.52	0.55	0.53	0.57	0.62	0.64
Mathematics	0.43	0.44	0.48	0.51	0.51	0.53	0.56	0.57
Chemistry	0.32	0.31	0.36	0.38	0.40	0.43	0.46	0.49
Biology	0.37	0.35	0.42	0.42	0.48	0.49	0.54	0.56
Psychology	0.32	0.24	0.37	0.30	0.42	0.35	0.51	0.43
Clinical Medicine	0.29	0.26	0.35	0.33	0.41	0.42	0.49	0.50
Engineering	0.33	0.28	0.37	0.36	0.40	0.42	0.45	0.47
AVERAGE	0.40	0.38	0.45	0.45	0.49	0.50	0.56	0.57
	Standardisation Z							
Subject	**1997** 40 countries	**1997** 11 countries	**2002** 40 countries	**2002** 11 countries	**2007** 40 countries	**2007** 11 countries	**2012** 40 countries	**2012** 11 countries
Astronomy	2.14	1.99	2.15	2.03	2.28	2.16	2.23	2.16
Physics	0.63	0.75	0.56	0.65	0.30	0.47	0.48	0.57
Mathematics	0.20	0.40	0.27	0.42	0.09	0.20	0.00	0.04
Chemistry	-0.66	-0.45	-0.73	-0.49	-0.73	-0.52	-0.79	-0.59
Biology	-0.22	-0.22	-0.19	-0.22	-0.07	-0.09	-0.12	-0.03
Psychology	-0.64	-0.96	-0.63	-1.00	-0.55	-1.06	-0.42	-0.97
Clinical Medicine	-0.85	-0.83	-0.81	-0.82	-0.60	-0.59	-0.52	-0.48
Engineering	-0.60	-0.67	-0.62	-0.58	-0.71	-0.58	-0.85	-0.70

Note: Astronomy in some studies is called Earth/Space.

Table C2: Coefficient of Variation

Period of data	1973	1983	1997	2002	2007	2012
	Frame and Carpenter	Luukkonen *et al.*	This Study	This Study	This Study	This Study
Coefficient of Variation *(all fields)*	0.49	0.39	0.38	0.31	0.27	0.23
Coefficient of Variation *(without Astronomy)*	0.49	0.37	0.27	0.20	0.13	0.12

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