Chapter 7
The Measurement of Synergy

When policy-makers call for "interdisciplinarity," they often mean "synergy." Problem-solving requires crossing boundaries, such as those between disciplines. However, synergy can also be generated in inter-sectorial or geographical collaborations. Synergy is indicated when the whole offers more possibilities than the sum of its parts; "interdisciplinarity" can be an instrument for creating "synergy." Synergy can be measured as an increase of redundancy; that is, the number of options which are available, but not-yet used. Instead of asking for the synergy among pre-defined categories, such as regions, sectors, size-classes, or nations, etc., I propose to let the most synergetic combinations among (potentially heterogenous) variables emerge from the data matrix. A synergy map can be drawn showing (cluster of) available but not-yet-realized options. A computer routine is made available at https://www.leydesdorff.net/software/synergy.triads which compares all possible triads in a data matrix in terms of their contributions to the synergy in a configuration.

In this chapter, I generalize the Triple-Helix indicator for measuring synergy in interactions among three or more helices to an indicator for any data set (e.g., an Excel sheet). As noted, a routine is made available for automating the analysis. I first discuss a toy model that one can follow using pen and paper and then upscale to empirical cases.

In the TH model, synergy is assumed to be generated in interactions among the three TH partners—universities, industries, and governments. Carayannis and Campbell (2009 and 2010), however, proposed to extend the analysis to four and five helices. However, the helices remained defined *ex ante*. In this chapter, I turn the question around and ask for the measurement of synergy among any three variables in a data set. The variables can be permutated so that one can compare among all possible triads. Which combinations of variables (nodes) and relations (links) are most synergetic? Are triplets that generate redundancy sparse and isolated? Or are they connected to a large component?

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L. Leydesdorff, *The Evolutionary Dynamics of Discursive Knowledge*,
Qualitative and Quantitative Analysis of Scientific and Scholarly Communication,
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"Synergy" is an objective different from "interdisciplinarity." The third mission of the university does not necessarily challenge the internal—disciplinary or interdisciplinary—organization of research. In my opinion, the crucial question is whether and how social and scientific relevance can be synergetic so that surplus value for the various stakeholders can be generated (Bunders & Leydesdorff, 1987).

7.1 "Synergy"

The term *synergy* originates from the word $\sigma\upsilon\nu\varepsilon\rho\gamma\acute{\iota}\alpha$ in classical Greek which means "working together." By working together, a whole can be created that is greater than the sum of its parts. In science, for example, synergy may mean that new options have become available because of collaborations across disciplinary, sectorial, or geographic boundaries.

Newly emerging options are vital to innovative systems, more than past performance. A system may run out of steam and be deadlocked if new options are not sufficiently generated. A larger number of *options* adds to the maximum capacity of a system. Unlike biological systems, this maximum capacity of a cultural system—the $H_{\max}$ in information theory—is not a given, but a construct that can further be informed and thus enlarged (see Fig. 4.2). For example, new means of transport can be invented. This adds capacity to (in this case) the transportation system.

The generation of redundancy is based on interactions among selection environments. Whereas interactions among variations generate uncertainty, selections can be expected to reduce uncertainty. The same information can be selected differently by various stakeholders using different criteria. The appreciations from different perspectives ("the meanings of the information") can be shared and thus generate redundancy. Thus, the same or overlapping informations can be involved more than once. Whereas information can be communicated in relations (and measured using Shannon's formulas), meanings are provided and can be shared from different perspectives with reference to horizons of meaning. Sharing can generate an "overlay" among perspectives with a dynamic of redundancy different from that of information processing (Etzkowitz & Leydesdorff, 2000).

For example, when a child asks permission from one of its parents, the other parent is latently present in the response albeit with a potentially different interpretation of the uncertainty in the configuration. Uncertainty can be reduced or increased when a third perspective operates in the background, like in this case of the relation between the parents (Abramson, 1963, pp. 130f.). In a triad, the correlation between each two variables can spuriously be co-determined by a third with a plus or a minus sign.

As discussed in Chapter Five, triads are the building blocks of systems (Bianconi et al., 2014; cf. Krackhart, 1999). All higher-order configurations in networks can be decomposed into triads (Freeman, 1996). The values for uncertainty and redundancy in triads can be aggregated and disaggregated since the Shannon-formulas are based on sigma's (Leydesdorff & Strand, 2013, p. 1895, n. 5). I exploit these possibilities for the development of the indicator of synergy here below.

Table 7.1 Four column vectors and their margin totals in a toy model

v1	v2	v3	v4	Sum
0	0	3	0	3
0	6	0	4	10
9	0	0	3	12
4	4	0	5	13
0	3	4	0	7
13	13	7	12	45

The number of possible triads among n sets or variables is $n * (n - 1) * (n - 2)/(2 * 3)$. This number grows rapidly with an increasing number of n. For $n = 10$, for example, this number of triads is $(10 * 9 * 8)/6) = 120$. (The denominator [2 * 3] corrects for double counting.) Each *node* can partake in $n - 1$ links of which some are parts of triads which generate redundancy and others are not.

Triads contain three nodes and three edges: both links and nodes can be part of more than a single triad.[1] In each of these triads, the nodes and links partake in both the redundancy and uncertainty generated in a triad. How much redundancy is generated at the level of nodes, links, and triads? Let me specify this step-by-step using a toy model; thereafter, I shall upscale to empirical examples.

7.2 A Toy Model

In the "toy" model in Table 7.1, for example, four variables are attributed to five cases like column vectors of a matrix.

One can compute the joint entropy (H_{12}) and mutual information or transmission between the horizontal and vertical dimensions of this matrix (T_{12}) by following the steps explicated in Table 7.2.

Column *e* in Table 7.2 contains the margin totals of the five rows of the data matrix (columns *a* to *d*). Using the grand total of the matrix ($N = 45$) as denominator, relative frequencies are provided in columns *f* to *i*. In column *k* to *n*, the values in this two-dimensional probability distribution (p_{ij}) are transformed into the contributions to the Shannon-type information (by using $H_{ij} = -\Sigma\, p_{ij} * \log_2 p_{ij}$) in bits. It follows from the summation of the cell values that $H_{ij} = 3.23$ bits (at the bottom of column *o*). This is the two-dimensional information content of this matrix.

[1]For example, if the number of nodes $n = 4$, each of the four nodes can participate in $n - 1 = 3$ direct relations [e.g., in the case of node 1 (n1): (1) n1 – n2; (2) n1 – n3; (3) n1 – n4]. The number of unique relations possible in this network is 4 * 3 / 2 = 6, namely: (1) n1 – n2; (2) n1 – n3; (3) n1 – n4; (4) n2 – n3; (5) n2 – n4; (6) n3 – n4. The number of possible triads in this case is (4 * 3 * 2)/(3 * 2) = 4; in this case: (i) n1 – n2 – n3; (ii) n1 – n2 – n4; (iii) n1 – n3 – n 4; and (iv) n2 – n3 – n4.

Table 7.2 Computation of the one- and two-dimensional information in the toy model

Toy model					Probabilities; relative frequencies (n/N)					Two-dimensional $H(12)$ in bits = $-\Sigma\, p_{ij} \log_2(p_{ij})$				
$v1$	$v2$	$v3$	$v4$		$p1$	$p2$	$p3$	$p4$		$i1$	$i2$	$i3$	$i4$	
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*
0	0	3	0	3	0.00	0.00	0.07	0.00	0.07	0.00	0.00	0.26	0.00	0.26
0	6	0	4	10	0.00	0.13	0.00	0.09	0.22	0.00	0.39	0.00	0.31	0.70
9	0	0	3	12	0.20	0.00	0.00	0.07	0.27	0.46	0.00	0.00	0.26	0.72
4	4	0	5	13	0.09	0.09	0.00	0.11	0.29	0.31	0.31	0.00	0.35	0.97
0	3	4	0	7	0.00	0.07	0.09	0.00	0.16	0.00	0.26	0.31	0.00	0.57
13	13	7	12	45	0.29	0.29	0.16	0.27	1.00	0.77	0.96	0.57	0.92	3.23

The margin totals in the vertical and horizontal direction provide us with the one-dimensional probabilities: the information values in column *e* add up to $H_1 = 2.19$ bits. Analogously on the basis of the values in the bottom row of columns *a* to *d*, $H_2 = 1.96$ bits. Using Eq. 4.5 (above):

$$T_{12} = H_1 + H_2 - H_{12} = 2.19 + 1.96 - 3.23 = 0.92\text{bits} \tag{7.1}$$

A matrix contains by definition a two-dimensional distribution $\left(\sum_{ij} p_{ij} = 1\right)$; mutual information in two dimensions is necessarily positive (Theil, 1972). For the representation of a three-dimensional distribution, however, one would need three independent dimensions.

7.3 Vector Coordinates

One can also consider the values in each three columns as vector representations in the *x, y,* and *z* dimensions of a three-dimensional array [*x, y, z*]. The four vectors in Table 7.1 contain four such triplets: {*v*1,*v*2,*v*3}, {*v*1, *v*2,*v*4}, {*v*1,*v*3,*v*4}, {*v*2,*v*3,*v*4}. One can compute for each triplet a three-dimensional H_{123}, the three bidimensional information contents H_{12}, H_{13}, H_{23}, and three one-dimensional information contents H_1, H_3, H_3. I elaborated the computation in the case of the first triplet {*v*1,*v*2,*v*3} in Table 7.3.

Using the bottom line of Table 7.3 and Eq. 4.8, it follows that

$$\begin{aligned} T_{123} &= [H_1 + H_2 + H_3] - [H_{12} + H_{13} + H_{23}] + H_{123} \\ &= (0.89 + 1.53 + 0.99) - (2.21 + 1.86 + 2.27) + 2.69 \\ &= 3.40 - 6.34 + 2.69 = -0.24 \text{ bits} \end{aligned} \tag{7.2}$$

Table 7.3 Exemplary elaboration of the computation of redundancy in the first triplet {$v1$, $v2$,$v3$}

The first triplet {v1, v2, v3}

v1	*v2*	*v3*	*Sum*
0	0	3	3
0	6	0	6
9	0	0	9
4	4	0	8
0	3	4	7
13	13	7	33

Probabilites	One dimension			Two dimensions						Three dimensions		
	*p*1	*p*2	*p*3	*p*12		*p*13		*p*23		*p*123		
	0.00	0.00	0.43	0.00	0.00	0.00	0.15	0.00	0.15	0.00	0.00	0.09
	0.00	0.46	0.00	0.00	0.23	0.00	0.00	0.30	0.00	0.00	0.18	0.00
	0.69	0.00	0.00	0.35	0.00	0.45	0.00	0.00	0.00	0.27	0.00	0.00
	0.31	0.31	0.00	0.15	0.15	0.20	0.00	0.20	0.00	0.12	0.12	0.00
	0.00	0.23	0.57	0.00	0.12	0.00	0.20	0.15	0.20	0.00	0.09	0.12
Sum:	1.00	1.00	1.00	0.50	0.50	0.65	0.35	0.65	0.35	0.39	0.39	0.21

Information in bits	H1	H2	H3	H12		H13		H23		H123		
	0.00	0.00	0.52	0.00	0.00	0.00	0.41	0.00	0.41	0.00	0.00	0.31
	0.00	0.51	0.00	0.00	0.49	0.00	0.00	0.52	0.00	0.00	0.45	0.00
	0.37	0.00	0.00	0.53	0.00	0.52	0.00	0.00	0.00	0.51	0.00	0.00
	0.52	0.52	0.00	0.42	0.42	0.46	0.00	0.46	0.00	0.37	0.37	0.00
	0.00	0.49	0.46	0.00	0.36	0.00	0.46	0.41	0.46	0.00	0.31	0.37
Sum:	0.89	1.53	0.99		2.21		1.86		2.27			2.69

Analogously, the other three possible triplets provide: T_{124} = –0.08; T_{134} = –0.23, and T_{234} = –0.08 bits. The values for the four triplets can be aggregated for the set (because of the sigma's in the Shannon formulas). The sum of the redundancies in the relevant triads can be attributed as a synergy value to the nodes and links participating in the respective triads (Leydesdorff & Strand, 2013, p. 1895, n. 5). As noted, the routine (available at https://www.leydesdorff.net/software/synergy.triads) permutes all column vectors of a data matrix so that all possible combinations of variables are evaluated in terms of their contributions to the synergy.

For example, $v2$ participates in the triads {$v1$, $v2$, $v3$}, {$v1$, $v2$, $v4$}, and {$v2$, $v3$, $v4$}, but not in {$v1$, $v3$, $v4$}. Among the triads in which a vector participates some will generate information ($T_{123} > 0$) and others redundancy ($T_{123} < 0$). One can define the synergy value of $v2$ in this matrix as the sum of the negative values of the triplets in which $v2$ participates. For $v2$, this is [–0.24 – 0.08 – 0.08] = –0.40 bit of information.

Both $v1$ and $v2$ participate in the triads {$v1$, $v2$, $v3$} and {$v1$, $v2$, $v4$} which generate –0.24 and –0.08 bits of redundancy, respectively. The link between $v1$ and $v2$ can analogously be attributed with this redundancy shared between $v1$ and $v2$. This is – 0.24 for {$v1$, $v2$, $v3$} plus – 0.08 for {$v1$, $v2$, $v4$}, and thus –0.32 bits. One can visualize the resulting retentions of synergy in this toy network as in Fig. 7.1. It happens that all links and nodes participate in the generation of redundancy in this specific "toy" model.

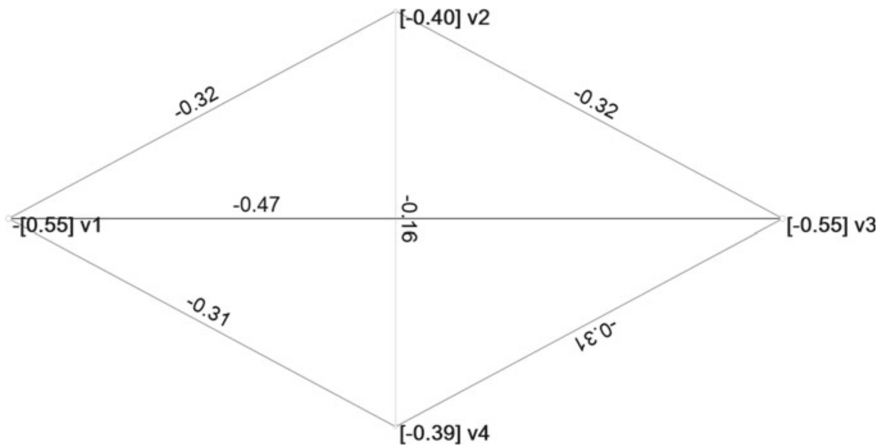

Fig. 7.1 Synergy retention network of the toy model (in bits of information)

7.4 Empirical Applications

7.4.1 Synergy in International Co-Authorship Relations

In addition to interactions among the disciplines, synergy can also be generated in extra-scientific contexts, such as university-industry relations or in geographical co-locations. Using data collected from the Web-of-Science on 28 June 2020 (Leydesdorff et al., 2013),[2] Table 7.4 shows the numbers of internationally co-authored papers among six western-Mediterranean countries in 2009: France, Italy, Spain, Morocco, Tunisia, and Algeria.

Figure 7.2a shows the affiliations network of internationally co-authored papers among these six nations. France has relations with Italy and Spain (within the EU),

Table 7.4 International co-authorship relations among six western-Mediterranean countries in 2009

	France	Italy	Spain	Morocco	Algeria	Tunisia
France	0	3970	3065	383	681	765
Italy	3970	0	2834	68	35	85
Spain	3065	2834	0	118	45	70
Morocco	383	68	118	0	33	53
Algeria	681	35	45	33	0	29
Tunisia	765	85	70	53	29	0

[2] I repeated the data analysis on June 26, 2008.

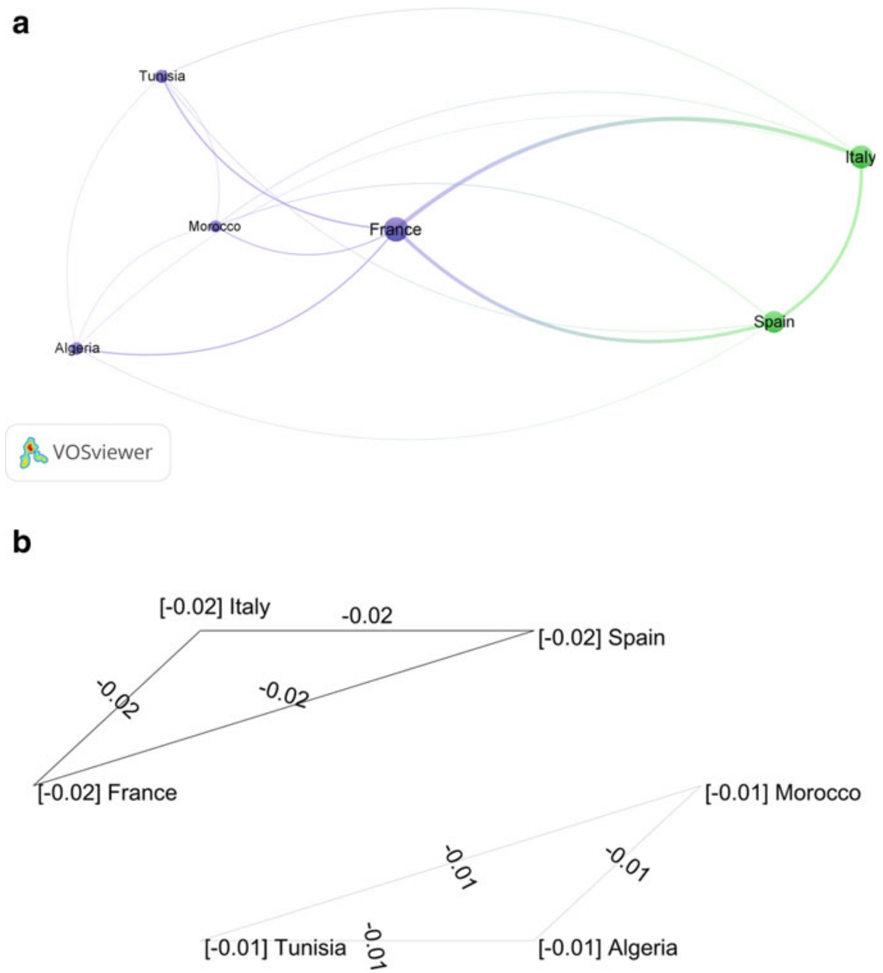

Fig. 7.2 **a** Affiliations network among six western-Mediterranean countries, **b** synergy network among six western-Mediterranean countries

but one can expect co-authorship relations with scholars in the former colonies of France in northern Africa. Scholars in these countries are often francophone.

Figure 7.2b shows the synergy network among these six nations: the three European nations generate synergy from their collaborations as do the three northern-African nations among them. However, the values for the European countries are twice those for the African ones. However, there is no synergy indicated between France and the northern-African countries in 2009, although there was synergy in previous years. One thus can conclude that scholars in France have more options in relations to EU partners than with the northern-African nations.

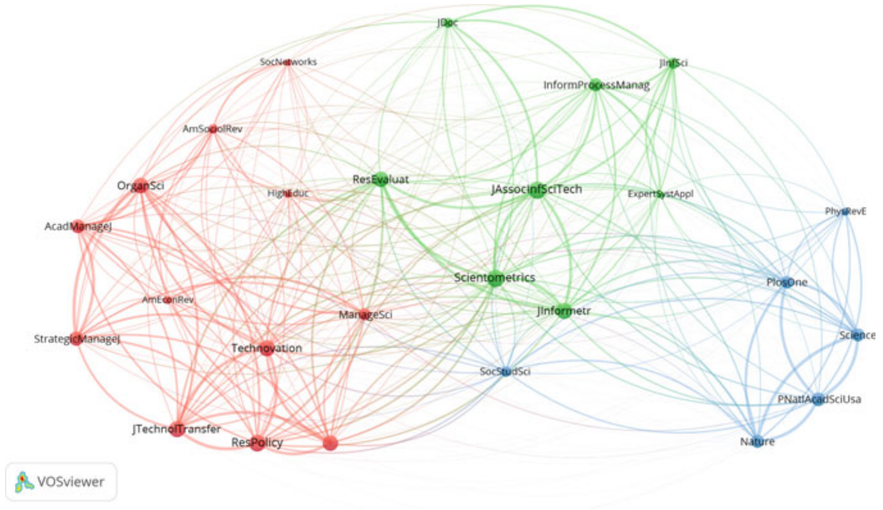

Fig. 7.3 Map based on cosine-normalized citing patterns among 26 journals cited in *Scientometrics* during 2017. Clustering based on the Louvain algorithm (Blondel et al., 2008); VOSviewer was used for the layout and visualization

7.4.2 Synergy in Aggregated Citation Relations Among Journals

As a second example, I use the aggregated journal-journal citation matrix of 26 journals cited in reference lists of publications in *Scientometrics* during 2017 more than a threshold value of 43 times.[3] I chose this example because the disciplinary and interdisciplinary classification of journals is often intuitive.

Figure 7.3 provides a map of this network of journal-journal relations on the basis of the cosine-normalized ("citing") vectors in the citation matrix. The structure induced by Blondel et al.'s (2008) algorithm for decomposition shows three groups of journals: information-science journals in the direct environment of *Scientometrics*, multidisciplinary ones (e.g., *PNAS, PLOS One*, and *Nature*) on the right side, and policy and management journals on the left side of the map (e.g., *Research Policy* and *Technovation*).

For $n = 26$ (as in this case), the number of possible triads among the vectors is (26 * 25 * 24)/(2 * 3) = 2,600. Of these triads, 38 (1.4%) contribute to the redundancy. Consequently, the vast majority of triplets (98.6%) does not generate redundancy. However, 18 of the 26 (69.2%) journals participate in triplets which generate redundancy.

[3]This threshold is based on using 1% of the total number of references summed over the papers in this journal (6464) after subtraction of the 2161 within-journal self-citations; one percent of (6464 – 2161 =) 4303 references. One-percent of this is 43, the threshold value in this study.

Table 7.5 Rank-ordering of synergy contributions of 26 journals and journal-journal relations

Journal (Nodes)	Synergy in bits	Journal-journal relation (Links)		Synergy in bits
Am Econ Rev	-4.27	*Expert Syst Appl*	*Am Econ Rev*	-3.08
Expert Syst Appl	-3.08	*Manage Sci*	*Am Econ Rev*	-0.79
Manage Sci	-0.79	*Strategic Manage J*	*Am Econ Rev*	-0.75
Strategic Manage J	-0.75	*Acad Manage J*	*Am Econ Rev*	-0.65
Acad Manage J	-0.65	*Science*	*Am Econ Rev*	-0.56
Science	-0.56	*Soc Networks*	*Am Econ Rev*	-0.50
Soc Networks	-0.50	*Nature*	*Am Econ Rev*	-0.48
Nature	-0.48	*Expert Syst Appl*	*Strategic Manage J*	-0.33
Technol Forecast Soc	-0.32	*Technol Forecast Soc*	*Am Econ Rev*	-0.32
Phys Rev E	-0.26	*Expert Syst Appl*	*Science*	-0.31
Res Policy	-0.23	*Nature*	*Expert Syst Appl*	-0.29
P Natl Acad Sci USA	-0.22	*Manage Sci*	*Expert Syst Appl*	-0.28
Scientometrics	-0.22	*Expert Syst Appl*	*Acad Manage J*	-0.28
Plos One	-0.21	*Phys Rev E*	*Am Econ Rev*	-0.26
Organ Sci	-0.15	*Expert Syst Appl*	*Technol Forecast Soc*	-0.25
High Educ	-0.08	*Expert Syst Appl*	*Phys Rev E*	-0.25
J Technol Transfer	-0.03	*Res Policy*	*Am Econ Rev*	-0.23
Am Sociol Rev	0.00	*P Natl Acad Sci USA*	*Expert Syst Appl*	-0.22
J Inf Sci	0.00	*P Natl Acad Sci USA*	*Am Econ Rev*	-0.22
Inform Process Manag	0.00	*Scientometrics*	*Am Econ Rev*	-0.22
Technovation	0.00	*Scientometrics*	*Expert Syst Appl*	-0.22
J Informetr	0.00	*Expert Syst Appl*	*Plos One*	-0.21
J Assoc Inf Sci Tech	0.00	*Plos One*	*Am Econ Rev*	-0.21
Soc Stud Sci	0.00	*Expert Syst Appl*	*Res Policy*	-0.19
J Doc	0.00	*Organ Sci*	*Am Econ Rev*	-0.15
Res Evaluat	0.00	*Expert Syst Appl*	*Soc Networks*	-0.13
		… (55 – 25 =) 30 other link		…

Furthermore, each *link* can be part of $n * (n - 1)/2$ triads. For $n = 26$, this amounts to 325 possible values; 55 of them (16.9%) have a negative value. In Table 7.5 the links are listed in terms of most synergy. Combining the redundancy values for nodes and links, one can generate a network; VOSviewer was used to visualize this network in Fig. 7.3.[4] Table 7.5 lists the 26 journals in terms of synergy values in the left-most column, and in terms of decreasing redundancy in links between these journals in the next two columns.

Science ranks on the synergy indicator on the 6th position, and *Nature* follows on the 8th rank. However, large journals with a pronouncedly disciplinary identity such as the *Am Econ Rev* and a number of journals in the management sciences generate more synergy than *Science* and *Nature.* Among the library and information-science journals, the journal *Scientometrics* scores highest on synergy (with rank number 13 and −0.22 bits of redundancy). However, the journal *Social Networks* occupies the

[4]The noted computer routine provides among other things the files "minus.net" and "minus.vec" in the Pajek format so that one can proceed to the visualization and further analysis of the synergy network.

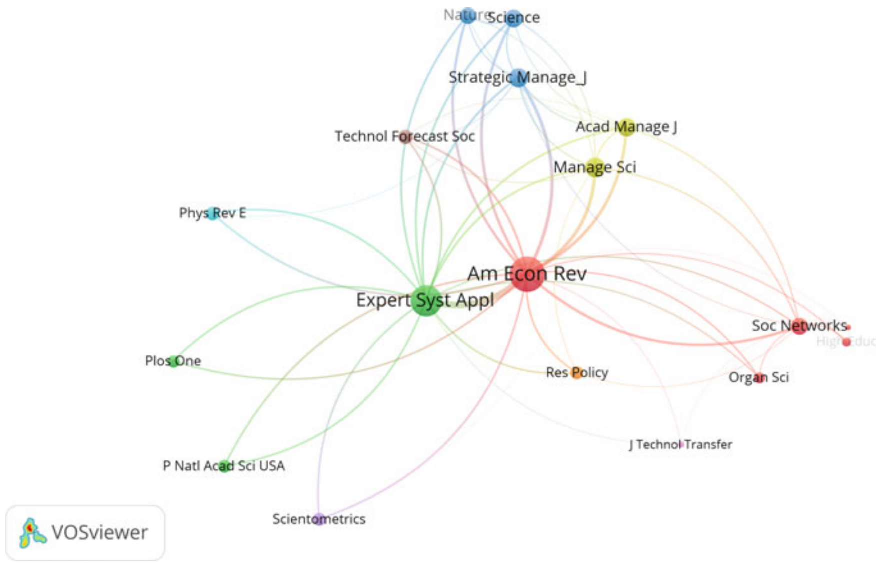

Fig. 7.4 Synergy network among the citing patterns of 26 journals in the citation environment of *Scientometrics* in 2017

7th position on the ranking of synergy values with −0.50 bits of redundancy. This is more than twice as high as the value of −0.22 for *Scientometrics*.

The synergy map in Fig. 7.4 is very different from the affiliations map in Fig. 7.3. The interpretation of this figure raises all kinds of questions. For example, *Scientometrics* is not central to its synergy map. However, one should keep in mind that this is a single case; the purpose of this exercise was a proof of concept. More cases and further refinement of parameter choices are needed before one can draw empirical conclusions; for example, about the significance of differences. Note that the synergy indicator allows to combine, for example, authorship and disciplinary-specific variables (e.g., title-words). The indicator can be used for the evaluation of any set of three or more variables, including disciplinary affiliations, geographical address, or demographic characteristics.

7.5 Discussion and Concluding Remarks

Unlike most performance indicators, the synergy indictor was not generated in a research evaluation practice, but is theory-based (McGill, 1954; Ulanowicz, 1997; Yeung, 2008; cf. Krippendorff, 2009a and b). Bridging the gap from theory to practice will require more empirical work and examples. For example, in a next project, it may be interesting to study synergy in translation research because the generation of synergy is a stated objective of this research program. In translation research, the objective is to accelerate the application of new knowledge from basic (e.g., molecular) biology in the clinic ("from bench to bed") or vice versa to articulate demand at the bedside in terms which can be made relevant for research agendas in pre-clinical specialisms.

In my opinion, "synergy" is more important for the evaluation of the social functions of science than performance indicators which usually are intended to serve the management of research. However, university-industry relations can be conceptualized as non-linear processes of transfer, application, and incubation. The mediation between supply and demand may require managerial or governmental interventions. In university-industry-government ("Triple Helix") relations, feedbacks can be more important than linear transfer.

Wu et al. (2019) developed an indicator of disruptiveness using the differences between citing and cited patterns over generations of papers as an indicator of change. The comparison of disruptiveness with synergy can be a subject for further research. Using Medical Subject Headings (MeSH) of MEDLINE/PubMed, Petersen et al. (2016) showed a relation between synergy-development and innovativeness during technology-specific periods of time.

In sum: by appreciating redundancies, one shifts the focus from the measurement of past performance to the question of the number of options. The measurement of synergy can also be relevant for the coupling to other areas of policy making (cf. Rotolo et al., 2017). Synergy refers to options which are possible, but not yet fulfilled, whereas most bibliometric indicators hitherto evaluate past performance; that is, options that have already been realized. More generally, the measurement of redundancy may provide methodologies opening a range of future-oriented indicators.

References

Abramson, N. (1963). *Information theory and coding*. New York, etc.: McGraw-Hill.

Bianconi, G., Darst, R. K., Iacovacci, J., & Fortunato, S. (2014). Triadic closure as a basic generating mechanism of communities in complex networks. *Physical Review E, 90*(4), 042806.

Blondel, V. D., Guillaume, J. L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment, 8*(10), 10008. https://doi.org/10.1088/1742-5468/2008/10/P10008

Bunders, J., & Leydesdorff, L. (1987). The causes and consequences of collaborations between scientists and non-scientific groups. In S. S. Blume, J. Bunders, L. Leydesdorff & R. D. Whitley (Eds.), *The social direction of the public sciences: Causes and consequences of cooperation between scientists and nonscientific groups. Sociology of the Sciences Yearbooks* (Vol. 11, pp. 331–347). Dordrecht/Boston: Reidel.

Carayannis, E. G., & Campbell, D. F. J. (2009). 'Mode 3' and 'Quadruple Helix': Toward a 21st century fractal innovation ecosystem. *International Journal of Technology Management, 46*(3), 201–234.

Carayannis, E. G., & Campbell, D. F. J. (2010). Triple Helix, quadruple Helix and quintuple Helix and how do knowledge, innovation, and environment relate to each other? *International Journal of Social Ecology and Sustainable Development, 1*(1), 41–69.

Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: From national systems and 'Mode 2' to a Triple Helix of university-industry-government relations. *Research Policy, 29*(2), 109–123.
Freeman, L. C. (1996). Cliques, Galois lattices, and the structure of human social groups. *Social Networks, 18*(3), 173–187.
Krackhardt, D. (1999). The ties that torture: Simmelian tie analysis in organizations. *Research in the Sociology of Organizations, 16*(1), 183–210.
Krippendorff, K. (2009a). W. Ross Ashby's information theory: a bit of history, some solutions to problems, and what we face today. *International Journal of General Systems, 38*(2), 189–212.
Krippendorff, K. (2009). Information of Interactions in complex systems. *International Journal of General Systems, 38*(6), 669–680.
Leydesdorff, L., Wagner, C. S., Park, H. W., & Adams, J. (2013). International collaboration in science: The global map and the network. *El Profesional de la Información*, *22*(1), 87–94.
Leydesdorff, L., & Strand, O. (2013). The Swedish system of innovation: Regional synergies in a knowledge-based economy. *Journal of the American Society for Information Science and Technology, 64*(9), 1890–1902. https://doi.org/10.1002/asi.22895
Leydesdorff, L., & Ivanova, I. A. (2021; early view). The Measurement of "Interdisciplinarity" and "Synergy" in Scientific and Extra-Scientific Collaborations. *Journal of the Association for Information Science and Technology*. https://doi.org/10.1002/asi.24416
McGill, W. J. (1954). Multivariate information transmission. *Psychometrika, 19*(2), 97–116.
Petersen, A., Rotolo, D., & Leydesdorff, L. (2016). A Triple Helix model of medical innovations: *Supply*, *demand*, and *technological capabilities* in terms of medical subject headings. *Research Policy, 45*(3), 666–681. https://doi.org/10.1016/j.respol.2015.12.004
Rotolo, D., Rafols, I., Hopkins, M. M., & Leydesdorff, L. (2017). Strategic intelligence on emerging technologies: Scientometric overlay mapping. *Journal of the Association for Information Science and Technology, 68*(1), 214–233. https://doi.org/10.1002/asi.23631
Ulanowicz, R. E. (1997). *Ecology, the ascendent perspective.* New York: Columbia University Press.
Wu, L., Wang, D., & Evans, J. A. (2019). Large teams develop and small teams disrupt science and technology. *Nature, 566*(7744), 378–382.
Yeung, R. W. (2008). *Information theory and network coding*. New York, NY: Springer.