RUCH FILOZOFICZNY
LXXV 2019 2

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The Science of Science – Some Recent Advances

DOI: http://dx.doi.org/10.12775/RF.2019.019

1. The Historical Background

The present paper is a corollary to a diagnosis concerning the directions of development of the science of science by Professor Urszula Żegleń, the President of the Science of Science Committee of the Polish Academy of Science in 2007–2015, which she expounded in her recent paper *Necessity and perspectives of studies on science in the light of dynamic development of science and technology* that builds upon her former writings,[1] preceded by a longstanding tradition of such overviews inspired by the original paper of Tadeusz Kotarbiński.[2] Before I proceed to outline the recent advances in the science of science (2010 onwards), a short historical introduction is in order.

[1] Paweł Kawalec, Urszula Żegleń, "Stan badań w zakresie naukoznawstwa w Polsce", in: *Refleksje nad stanem wybranych obszarów nauki w Polsce w ocenie Zespołów Integracyjnych i Integracyjno-Eksperckich PAN* (Warszawa: PAN, 2010), 27–49; Urszula Żegleń, "O etosie badacza w świetle wyzwań współczesnej nauki i techniki (śladami polskich naukoznawców)", *Zagadnienia Naukoznawstwa* 52, no. 1(207) (2016): 45–62; idem, "Metodologia nauk w Polsce. (Tradycja – stan aktualny – prognozy)", *Zagadnienia Naukoznawstwa* 36, no. 4 (2000): 499–506.

[2] Tadeusz Kotarbiński, "Przegląd problemów nauk o nauce", *Zagadnienia Naukoznawstwa* 1, no. 2–3 (1965): 5–25; Wojciech Gasparski, "Przegląd problemów nauk o nauce po latach", *Zagadnienia Naukoznawstwa* 36, no. 4 (2000): 443–460.

The modern idea to systematically investigate science itself was first introduced by Stanisław Michalski,[3] who in the 1920's launched Koło Naukoznawcze ("the Science of Science Circle").[4] Its members included Florian Znaniecki,[5] as well as Maria and Stanisław Ossowskis,[6] who are now recognized as the founders of the science of science movement in Poland. Maria and Stanisław Ossowskis extended Znaniecki's former argumentation and identified three core disciplines that constitute scientific study of science: epistemology and philosophy of science, psychology of scientific creativity and anthropology or sociology of science. They claimed the necessity to recognize science as a social practice, which cannot be fully grasped on the basis of its "immanent factors" alone.[7] The overall argument presented by Ossowskis was taken by Michalski as the rationale for his idea of launching an autonomous discipline of "the science of science" and a dedicated journal (*Organon* published since 1936) as well as a projected research institute. These plans, however, did not come to fruition because of the outbreak of WWII and premature death of Michalski in 1949.

An alternative proposal[8] was later advanced by John Bernal in his book *The Social Function of Science*.[9] It was, at least partly, motivated by "disillusion" by negative effects of science development, such as unemployment, inequality or new weapons threatening "personal security". Moreover, as Bernal observed, there was "a strange coincidence, the disturbing events of the Great War, the Russian revolution, the economic crises, the rise of Fascism, and the preparation for newer and more terrible wars have been paralleled inside the field of science by the greatest changes in theory", such as emergence of mathematical logic, relativity and quantum mechanics, biochemistry and genetics.[10] So, he set out to elaborate on "the fact that science is both affecting and being affected by the social changes of our time", emphasizing that "this is a social and

[3] Urszula Żegleń, "Potrzeba i perspektywy badań naukoznawczych w świetle dynamicznego rozwoju nauki i technologii", *Zagadnienia Naukoznawstwa* 53, no. 2(212) (2017): 158.

[4] Paweł Kawalec, "Philosophical Perspectives: The Science of Science – From Inception to Maturity", in: *A New Organon: Science Studies in Interwar Poland*, ed. Friedrich Cain, Bernhard Kleeberg (Tübingen: Mohr Siebeck, 2018), 521–535.

[5] Florian Znaniecki, "Przedmiot i zadania nauki o wiedzy", *Nauka Polska* 5 (1925): 1–78.

[6] Maria Ossowska, Stanisław Ossowski, "Nauka o nauce", *Nauka Polska* 20 (1935): 1–12; idem, "The science of science", *Minerva* 3, no. 1 (1964): 72–82.

[7] Ibidem, 75.

[8] Bernal was well aware of the preceding Polish tradition: Marta Skalska-Zlat, "Nalimov and the Polish Way Towards Science of Science", *Scientometrics* 52, no. 2 (2001): 211.

[9] John D. Bernal, *The Social Function of Science* (London: Routledge, 1939).

[10] Ibidem, 2.

economic rather than a philosophical inquiry". For Bernal, then, overall "Scientific research and teaching are in fact small but critically important sections of industrial production".[11]

Admittedly, he was first to provide ample, but necessarily incomplete, evidence establishing the link between the economic growth and intensity of R&D. In fact, he significantly contributed to the UK almost doubled increase in R&D public expenditure of the post-war period. Bernal's unwillingness to pursue the underlying mechanism of the effectiveness of economic regularities related to R&D spending was inherited by the post-war mainstream economists like Paul Samuelson, Kenneth Arrow, Richard Nelson and Robert Solow.[12]

Slightly later, in the early 1950's, Derek de Solla Price initiated the turn of "the tools of science on science itself".[13] He explicitly motivated it by an analogy with physics: "The method to be used is similar to that of thermodynamics, in which is discussed the behavior of a gas under various conditions of temperature and pressure. One [...] considers only an average of the total assemblage in which some molecules are faster than others, and in which they are spaced out randomly and moving in different directions. On the basis of such an impersonal average, useful things can be said about the behavior of the gas as a whole, and it is in this way that I want to discuss the analysis of science as a whole".[14] The first publications of de Solla Price predate the major advancements in the science of science[15] that are presented in the remainder of this paper.

2. The Computational Turn in the Science of Science

However, it was only in the middle 1960's that de Solla Price's ideas really took off.[16] Although the main perspectives, such as philosophy and history, economics, scientometrics and sociology significantly differed,

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[11] Ibidem, 9–10.

[12] Ewa Okoń-Horodyńska, "Ewaluacja polityki innowacji", in: *Ewaluacja w procesie tworzenia polityki naukowej i innowacyjnej*, ed Grażyna Prawelska-Skrzypek (Warszawa: PAN, 2017), 237.

[13] Derek J. de Solla Price, "Quantitative measures of the development of science", *Archives Internationale d'Histoire des Sciences* 14 (1951): 85–93.

[14] Idem, *Little science, big science – and beyond* (New York: Columbia University Press, 1986), xiv.

[15] Ignacy Malecki, "Ewolucja koncepcji naukoznawstwa w ostatnim półwieczu", *Zagadnienia Naukoznawstwa*36, no. 4 (2000): 438.

[16] Grażyna Prawelska-Skrzypek, J. Maciąg, "Główne nurty krytyki ewaluacji polityki naukowej i innowacyjnej oraz sposoby jej doskonalenia na przykładzie wybranych krajów", in: *Ewaluacja w procesie tworzenia polityki naukowej i innowacyjnej*, ed. Grażyna Prawelska-Skrzypek (Warszawa: PAN, 2017), 304.

they seem to have converged then on a common topic of the growth of knowledge.[17] Apparently, OECD was instrumental in creating a shock impulse for "the science of science" development as evidenced, for instance, by the rapid increase of the average degree within "the science of science" keyword network (Fig 1).[18] The average degree indicates the average number of connections of each node in the network, as given by:

$$< k > = \frac{2E}{N}$$

where E is the number of edges and N – the number of nodes in a given network.

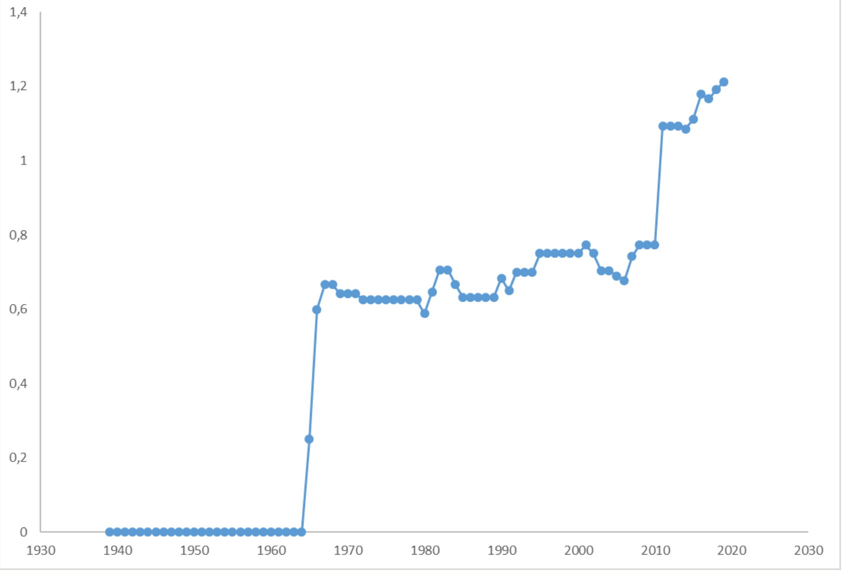

Figure 1. Average degree of keyword network. Analysis of Web of Science (WoS) dataset for "science of science" as subject.

[17] Examined in more detail in: Paweł Kawalec, *Metodologia integralna: studium dynamiki wiedzy naukowej* (Lublin: Wydawnictwo KUL, 2018).

[18] Other arguments are presented in: Jan Kozłowski, "Ewaluacja nauki", in: *Ewaluacja w procesie tworzenia polityki naukowej i innowacyjnej*, ed. Grażyna Prawelska-Skrzypek (Warszawa: PAN, 2017), 98.

The first institutionalized form for the systematic science of science research appeared as late as 1966 with the establishment of Science Policy Research Unit at the newly established University of Sussex. Richard Outhwaite examined its historical background.[19] Asa Briggs, who was appointed as pro-vice-chancellor and the Dean of the School of Social Studies, was highly influenced by the then hotly debated *The Two Cultures* of C. P. Snow.[20] One of Snow's arguments concerned the educational policy in the UK, which he contrasted with the one in Germany and the USA. He objected that the UK system strongly favors the classical humanistic education at the expense of the science and engineering one, while it was the latter that mostly contributed to the military success during WWII. In consequence, the policy makers lacked the necessary knowledge to make adequate decisions regarding research funding and economic growth. Briggs invited his colleague from the Leeds University, the then famous philosopher of science, Stephen Toulmin to help him conceptualize science policy research unit to be established since the beginning of 1966. The SPRU center was headed till 1982 by a famous economist Chris Freeman, who was largely interested in policy-related issues and therefore focused on economic studies, which were published in *Research Policy*, a newly established journal in 1971. However, one of the SPRU members, Roy MacLeod, was instrumental in establishing a complimentary journal *Science Studies* (renamed later as *Social Studies of Science*) focused on "conceptual structures of modern science", "the evolution of the scientific community, and the normative assumptions implicit in different scientific roles".[21] In 1975 the journal published a "country report" concerning the Polish "science of science", which was written by Bohdan Walentynowicz, the editor of *Zagadnienia Naukoznawstwa*. MacLeod in 1970 set up a complimentary academic unit at Sussex "History and Social Studies of Science", which pursued historical and qualitative research, while SPRU proceeded with quantitative econometric analyses of spending on research and development. The pitfalls of the idea of "finalization in science", which was elaborated in Germany and supposed to append Thomas Kuhn's philosophy of science, well epitomizes the tensions that existed then between the three research areas on science: history and philosophy of science, economics of science and social studies of science.[22] Apparently, they were overcome at the international level with setting up the International Commission

[19] William Outhwaite, "Science of science at Sussex University", *Zagadnienia Naukoznawstwa* 53, no. 2(212) (2017): 149–156.

[20] Charles P. Snow, Stefan Collini, *The Two Cultures* (Cambridge University Press: 2012).

[21] Outhwaite, *Science of science at Sussex University*, 151.

[22] Ibidem, 154–155.

for Science Policy Studies, renamed later as the International Council for Science Policy Studies, during the XIVth International Congress for the History of Science held in Tokyo/Kyoto in August 1974.[23] It was headed by Jacques J. Salomon and Derek de Solla Price as Vice-President and its 21 members from 15 countries included, among others, Ignacy Malecki and Bohdan Walentynowicz as well as Gennady Dobrov and Semion Mikulinsky.

Apparently, the clustering of authors, based on citation analysis within the science of science publications (1939–2018), reveals some distinct areas of activity that emerged during this period (Fig. 2). Panel (a) in Figure 2 depicts a compact structure of the major clusters, with a numerous (over thirty) disconnected authors. The historical adequacy of this clustering may be debatable,[24] nevertheless I shortly discuss some rationale by zooming-in the major clusters. The cluster presented by panel (b) captures some of the main contributors to the early phase of the Russian tradition of "Науковедение" (*Naukovedenie*),[25] such as Gennady Dobrov and Semion Mikulinsky.[26] Panel (c) presents contributors to more recent use of network science analyses in the science of science, such as Mark E. Newman and his collaborators. Scientometrics and information science contributions are presented in panel (d) with the leading role of Loet Leydesdorff and Eugene Garfield – undoubtedly two classics of the field, who intensely used computational methods in their own research. Panel (e) reflects the early contributions of Alvin M. Weinberg, and later authors, such as Julia Lane, to decision-making in science policy. The three remaining panels (e), (g) and (h) are discussed in more detail in the next section, considering their role in more recent trends in the science of science (2010 onwards).

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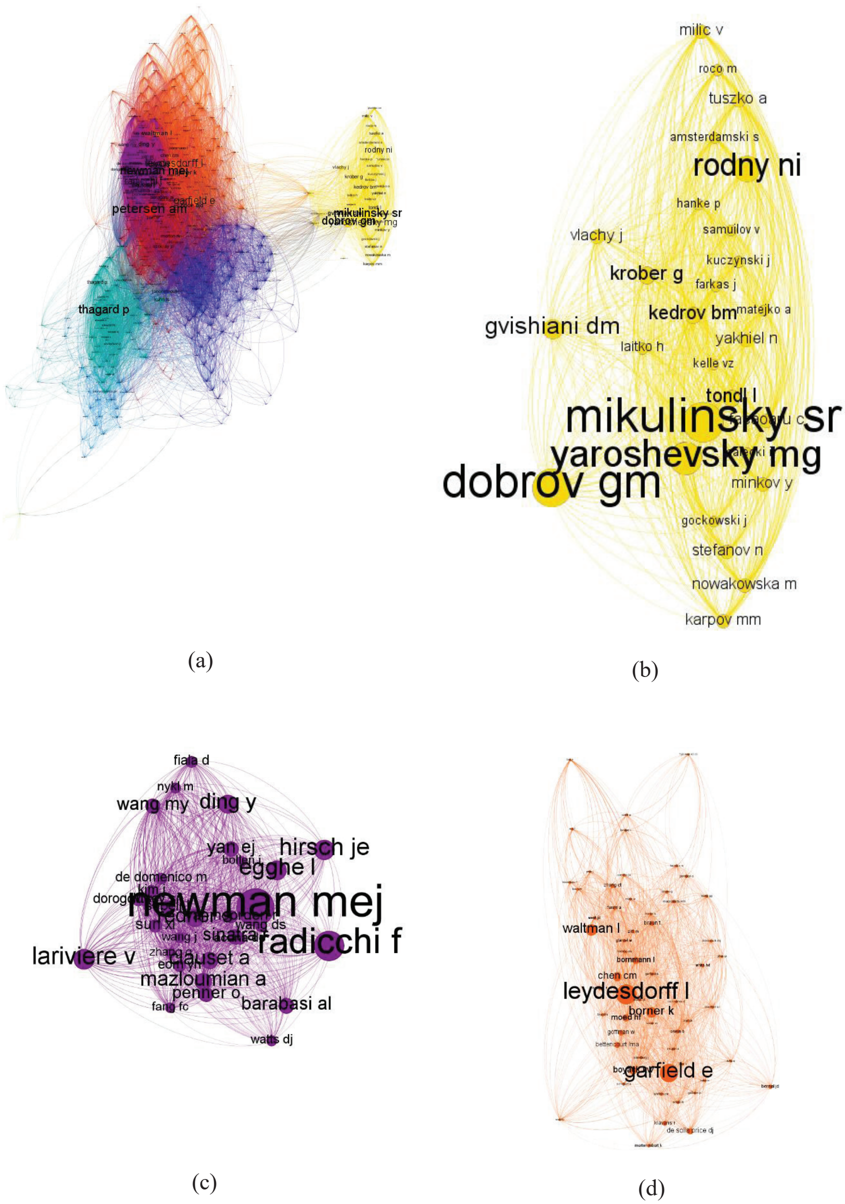
[23] Ina Spiegel-Rösing, Roy MacLeod, "The International Council for Science Policy Studies", *Social Studies of Science* 6, no. 1 (1976): 133.

[24] *Models of Science Dynamics*, ed. Andrea Scharnhorst, Katy Börner, Peter van den Besselaar (Berlin– Heidelberg: Springer, 2012).

[25] Other terms used in different European countries are succinctly discussed in: Malecki, *Ewolucja koncepcji naukoznawstwa w ostatnim półwieczu*, 437.

[26] Michał Kokowski, "The Science of Science (Naukoznawstwo) in Poland: The Changing Theoretical Perspectives and Political Contexts – A Historical Sketch from the 1910s to 1993", *Organon* 47 (2015): 147.



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kuczynski j
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matejko a
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laitko h
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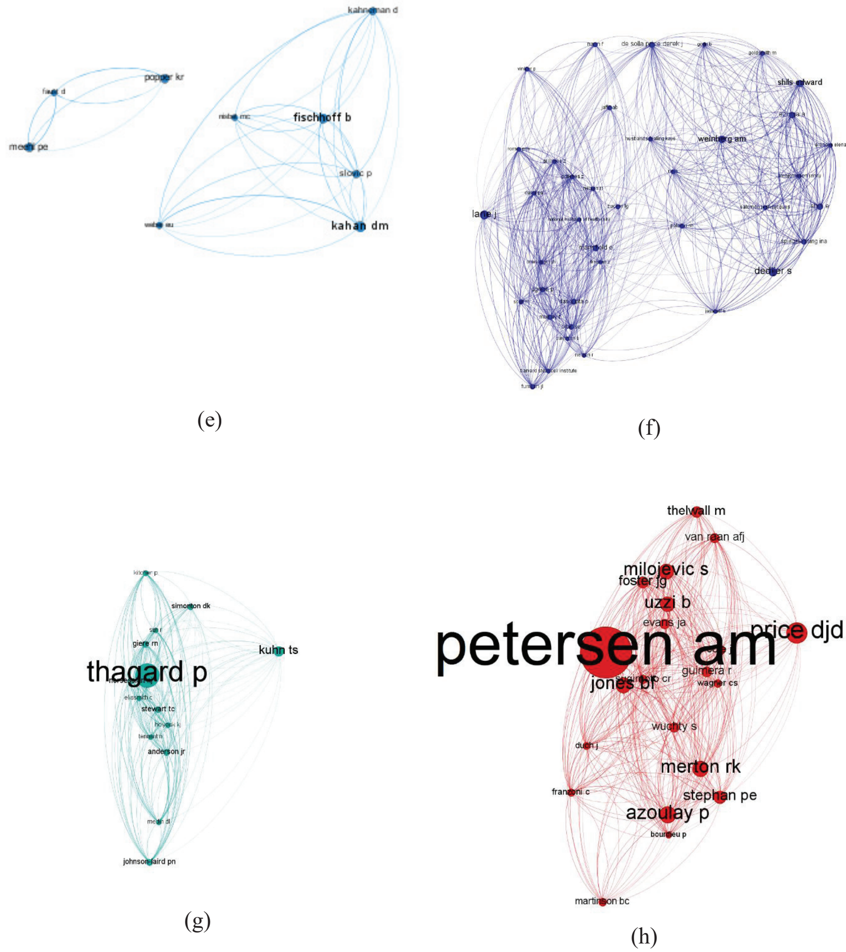

Figure 2. The main contributors and areas of science of science research (the size of node corresponds to the number of occurrences in the dataset). Analysis of WoS dataset on "science of science" as subject.

Although the analyses of the dynamics of the science of science over time, which are based on scientometric data alone, are inherently limited,[27] still they inspire some interesting conjectures. Thus, Figure 3 clearly illustrates the fact that the critical change in the science of science studies was around 1980's.[28] Until that time science of science studies

[27] Paweł Kawalec, "Cognitive Dynamics of Research Routines: Case Study of MicroRNA", in: *The Logic of Social Practices*, ed. Raffaela Giovagnoli (Cham: Springer International Publishing, 2019), forthcoming.

[28] Prawelska-Skrzypek, Maciąg, "Główne nurty krytyki", 304.

were predominantly a humanistic and qualitative area of research. The main focus was on history and philosophy of science as well as educational studies, including the STEM and "Nature of Science" programs. However, with a growing dominance of computational approaches and research on science funding, the corresponding shift resulted in dominance of the respective areas, including also strongly computationally-oriented research in information science.

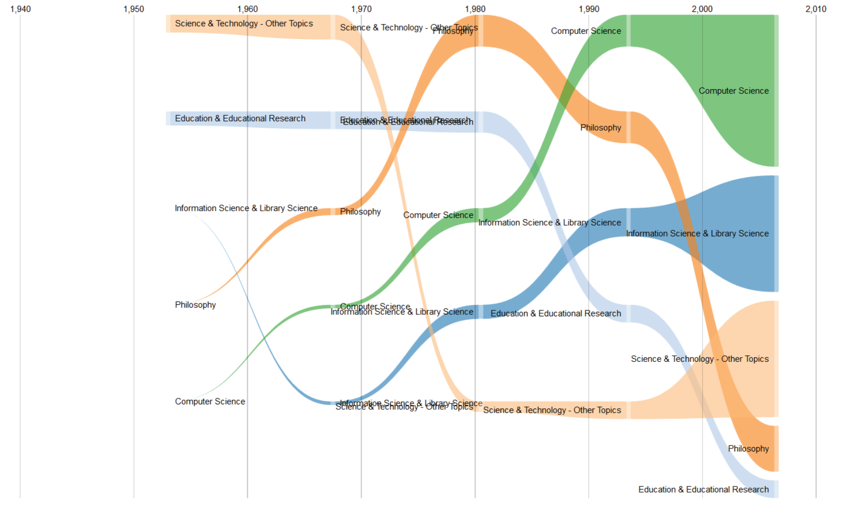

Figure 3. Changes in dominant areas of research in science of science studies. Analysis of the WoS dataset using WoS research areas.

A similar trend is also reflected in Figure 4 concerning the main cited authors. In the early phase in 1950's and 1960's the names of Francis Bacon and Stephen Toulmin well epitomize the two core areas of the humanistic approach, namely history and philosophy of science.[29] Apparently, both authors had also important contributions to the relevant institutionalization processes – Bacon with his vision of the organization of scientific collaboration and Toulmin, who was instrumental in establishing the SPRU unit in Sussex in 1960's. Two decades to follow seem to have been dominated by the Russian scholars (Dobrov, Mikulinsky) with their central role in ideologized policy making under the commu-

[29] In overview of the science of science in Poland Wojciech Gasparski identifies history and philosophy of science as still the dominant trend as of late 1980's: Wojciech Gasparski, "O aktualnym stanie badań naukoznawczych w Polsce", *Zagadnienia Naukoznawstwa* 25, no. 3–4 (1989): 377–380. The rationale for the epistemic primacy of epistemological research on science is discussed by Tadeusz Kotarbiński in his early contribution to the science of science in Poland (Kotarbiński, "Przegląd problemów nauk o nauce").

nist regime.[30] Next, follows the socio-economic phase as manifested by the names of notable social scientists Paul E. Meehl and Pierre Bourdieu.[31] They brought measurement techniques from the mathematized parts of social sciences and also strong emphasis on the economic analyses.[32] And, finally, the computational turn as reflected by the names of two significant contributions, namely Alexander Petersen and Eugene Garfield.

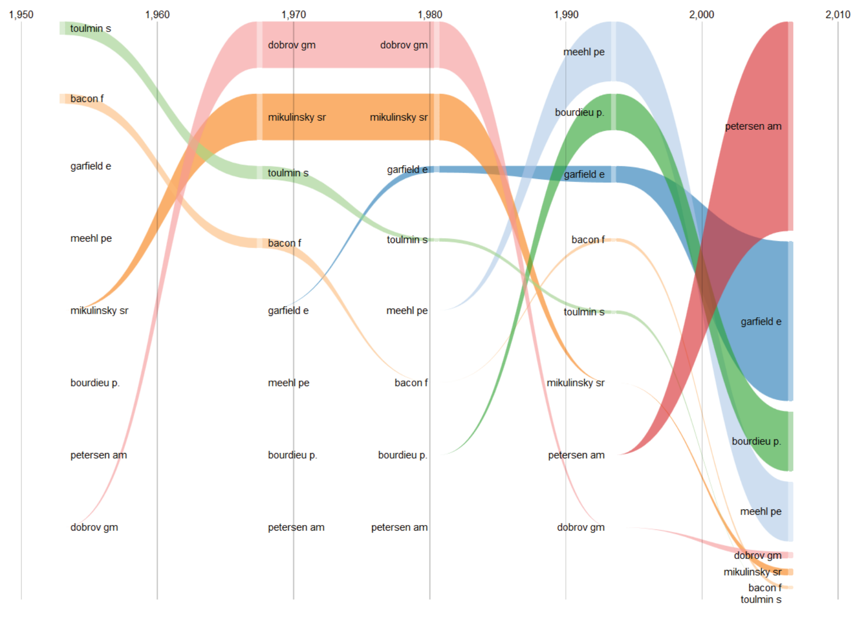

Figure 4. The main cited authors timeline for science of science. Analysis of the WoS dataset.

Of course, it would require a much more detailed examination of historical evidence to test the above conjectures. Nevertheless, the cita-

[30] Interestingly, Poland was exceptional in not having an institutionalized form for the science of science to have this ideological effect: W. A. Werner, "Rozwój naukoznawstwa do roku 2000", *Zagadnienia Naukoznawstwa* 21, no. 3 (1985): 323. Moreover, such an institution was created by autonomous and bottom-up initiative of scientific community: Wojciech Gasparski, "Naukoznawstwo: ocena stanu dyscypliny", *Zagadnienia Naukoznawstwa* 30, no. 1–4 (1994): 8.

[31] In the literature it is more common to recognize this phase with the elaboration of "Mode 2" of scientific knowledge production: Michael Gibbons et al., *The new production of knowledge: the dynamics of science and research in contemporary societies* (London: SAGE, 1994); Helga Nowotny, Peter B. Scott, Michael T. Gibbons, *Re-thinking science: knowledge and the public in an age of uncertainty* (Cambridge, UK: Polity, 2001). For a succinct account of this model see: Kawalec, *Metodologia integralna*, ch. 7.

[32] Ibidem, 84.

tion analysis clearly suggests the following phases in the course of the science of science development as exhibited in Table 1.

Phase	Focus	Period	Cited Authors
Humanistic	History and philosophy of science, educational studies	1939–1970	F. Bacon S. Toulmin
Ideological-political	Science policy, central planning	1970–1990	G. M. Dobrov S. R. Mikulsky
Socio-economic	Statistics, econometrics, sociology	1990–2010	P. Bourdieu P. E. Meehl
Computational	Scientometrics, newtork science, simulations	2010–present	E. Garfield A. Petersen

Table 1. The phases in the science of science development.
Based on the aforementioned analyses of the WoS dataset.

The above indicated phases may require substantial revisions in the course of a more detailed historical study. Nonetheless, there is ample evidence that the last phase – dubbed here "computational" – is marked by a radical and robust change of publication and citation patterns. Figure 5 illustrates it with a remarkable change in citations pattern that occurs 2010 onwards.

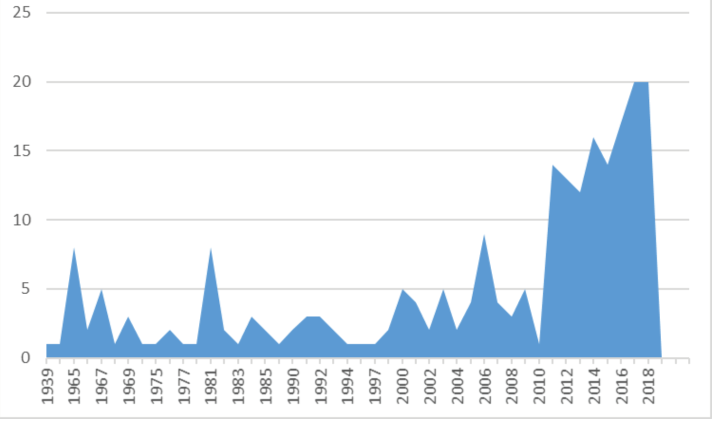

Figure 5. Science of science annual citations timeline.
Analysis of the WoS dataset.

This change is accompanied by other noteworthy transformations. For instance, nearly 60% of all publications after 2010 have been contributed by authors with US affiliation. Worth mentioning is also a steadily growing share of Chinese authors (Fig. 6).

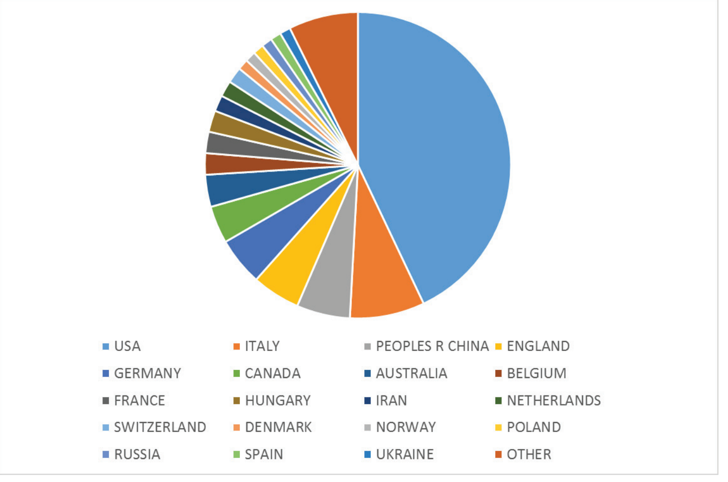

Figure 6. Science of science publications by countries. Analysis of the WoS dataset.

The shift in institutional structure of the science of science research also reflects the same trend. Since 2010 the significant contribution is from the US institutions (Tab. 2). Again, a growing share of Chinese participation is remarkable.

Institution	Publications (%)
Indiana University (USA)	10
University of Chicago (USA)	5,5
Carnegie Mellon University (USA)	4,7
Dalian University of Technology (CHN)	4,7
IMT School for Advanced Studies Lucca (IT)	4,7
Boston University (USA)	3,9
Northwestern University (USA)	3,9
Northeastern University (USA)	3,1
Santa Fe Institute (USA)	3,1
American Institutes for Research (USA)	2,3
Central European University (HUN)	2,3
NBER	2,3

Table 2. 10% of top institutions publishing in the area of science of science. Analysis of the WoS dataset.

3. Overview of the Recent Topics in the Science of Science

The science of science research has inherently interdisciplinary from its very inception. However, the computational turn pointed out in Section 2, is not only manifested by dominance of computer science as a research area, but also by its significant influence on the methods used in other research areas. This trend is only partially reflected in Figure 7 for many other disciplines, such as information science and library science in particular, use the computational techniques. As presented below, even the traditionally humanistic disciplines, such as philosophy of science, mark their contribution to the science of science insofar as they use computer modelling.

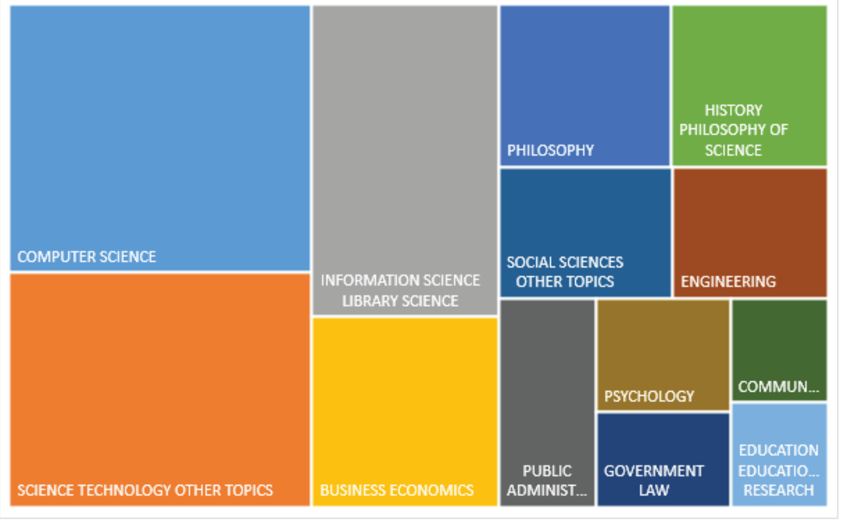

Figure 7. Disciplines represented in the science of science research by their share of the number of published papers (note that WoS allows multiple categorizations of each publication). Analysis of the WoS dataset.

Despite dominance of computational approaches, the most recent science of science studies are largely disintegrated with only 22% constituting the giant component of the interconnected source publications.[33]

[33] Giant component may be understood as an indicator of maturity of a given research routine with the critical mass surpassing 50% of all nodes in a given network that are connected (Kawalec, „Cognitive Dynamics of Research Routines").

Nonetheless, apparently the recent science of science developments flock around a few leading publications and areas representing: (i) computational science policy studies, (ii) applications to climate science and sustainability studies, (iii) science communication, (iv) computational philosophy of science and others (Fig. 8).

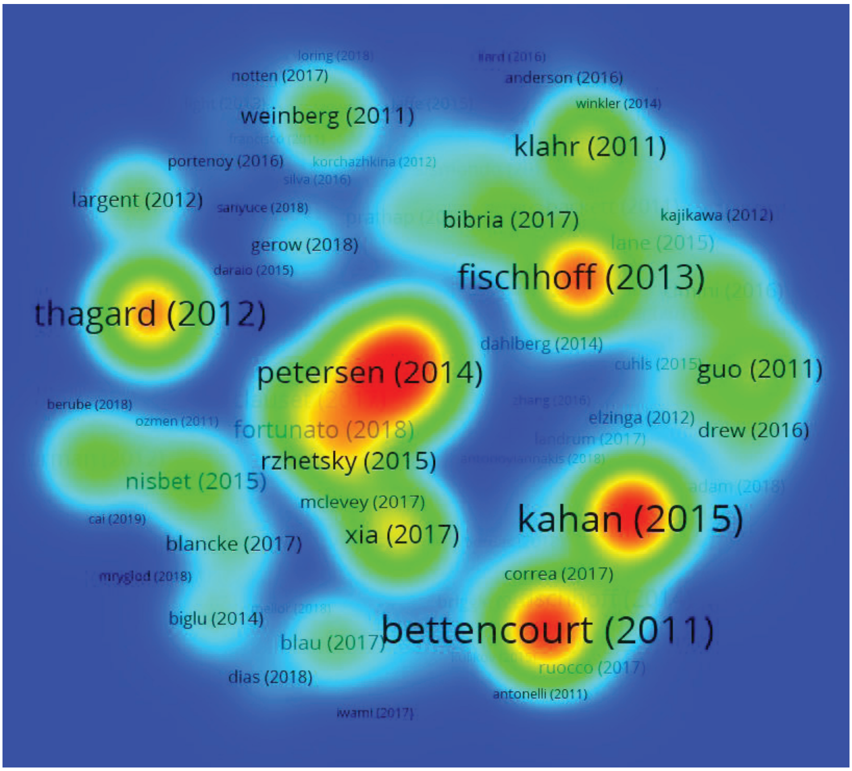

Figure 8. The most often cited references 2010–2019. Density analysis of WoS dataset for "science of science" as subject in the period 2010–2019.

Figure 9 brings out this early integration phase of development of the computational turn in the science of science studies. It displays the complete giant component of all linked publications, which constitute 22% of all contributions to the science of science after 2010.

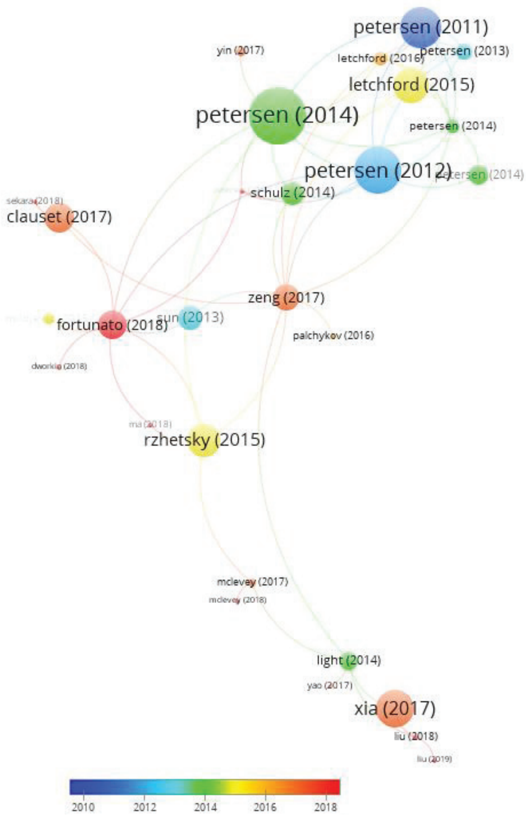

Figure 9. The giant component of cited references 2010–2018. It includes 22% of all publications. Analysis of WoS dataset for "science of science" as subject in the period 2010–2018.

Now, I proceed to a succinct characterization of the above mentioned areas of studies within the science of science.

(i) *Computational science policy studies*

Although there undoubtedly exists a continuity between the most recent and the original papers, such as Derek de Solla Price's or Robert K. Merton's,[34] one of the publications that paved the way for a grow-

[34] Derek J. de Solla Price, "A general theory of bibliometric and other cumulative advantage processes", *Journal of the American Society for Information Science*" 27, no. 5 (1976): 292–306; Derek J. de Solla Price, "Networks of Scientific Papers", *Science* 149, no. 3683 (1965): 510–515; idem, "Quantitative measures"; idem, *Little science, big science – and beyond* (New York: Columbia University Press, 1986); Robert K. Merton,

ing number of publications that heavily rely on computations was the paper by Alexander M. Petersen et al. *Statistical regularities in the rank-citation profile of scientists*.[35] Given the fact that "Recent science of science research shows that scientific impact measures for journals and individual articles have quantifiable regularities across both time and discipline", the authors set on to elaborate rank-citation profile to determine "the scientific impact distribution at the scale of an *individual* scientist" [emphasis – PK].[36] They claim to have identified "statistical regularities in the career achievements of scientists" that are common to all kinds of research areas. This research was further continued by investigation of how institutional changes affect career development in time and how an individual's reputation influences future impact of her or his publications.[37]

Apart from exploration of measures that focus on individual scientists, this line of influential science of science research uses computational techniques in order to uncover the potential for a faster advancement of science. A notable example is the paper by Andrey Rzhetsky et el. *Choosing experiments to accelerate collective discovery*, which analyzed experimentation strategies in biomedical research and demonstrated that the rate of discovery is compromised by career considerations and institutional arrangements.[38]

(ii) *Applications to climate science and sustainability studies*

Luís M. A. Bettencourt and Jasleen Kaur use "science of science" concepts and methods to assess the progress of sustainability studies as a scientific discipline.[39] It is granted that "The concepts of sustainable

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"Science and the Social Order", *Philosophy of Science* 5, no. 3 (1938): 321–337; idem, "The Matthew Effect in Science, II: Cumulative Advantage and the Symbolism of Intellectual Property", *Isis* 79, no. 4 (2988): 606–623; idem, "Priorities in Scientific Discovery: A Chapter in the Sociology of Science", *American Sociological Review* 22, no. 6 (1957): 635–659.

35 Alexander M. Petersen, Eugene H.. Stanley, Sauro Succi, "Statistical regularities in the rank-citation profile of scientists", *Scientific Reports* 1, no. 181 (2011): 1–7.

36 Ibidem, 1.

37 Alexander M. Petersen et al., "Persistence and uncertainty in the academic career", *Proceedings of the National Academy of Sciences* 109, no. 14 (2012): 5213–5218; Alexander M. Petersen et al., "Reputation and impact in academic careers", *Proceedings of the National Academy of Sciences* 111, no. 43 (2014): 15316–15321.

38 Andrey Rzhetsky et al., "Choosing experiments to accelerate collective discovery", *Proceedings of the National Academy of Sciences* 112, no. 47 (2015): 14569–14574.

39 Urszula Żegleń, "Potrzeba i perspektywy badań naukoznawczych w świetle dynamicznego rozwoju nauki i technologii", 163; Józef Bremer, "Nauka o zrównoważeniu – w poszukiwaniu transdyscyplinarnej metodologii", *Zagadnienia Naukoznawstwa* 52, no. 1(207) (2016): 15–32.

development have experienced extraordinary success since their advent in the 1980s.[40] They are now an integral part of the agenda of governments and corporations, and their goals have become central to the mission of research laboratories and universities worldwide".[41] But, as Bettencourt and Kaur emphasize, "it remains unclear how far the field has progressed as a scientific discipline, especially given its ambitious agenda of integrating theory, applied science, and policy, making it relevant for development globally and generating a new interdisciplinary synthesis across fields". Moreover, the pressing question remains: "is the field fulfilling its ambitious program of generating a new synthesis of social, biological, and applied disciplines ... ?".[42] To explore this question the authors decided to use "new concepts and methods from science of science", in particular those developed in their earlier publications.[43] It is noteworthy that the authors recognize the limitations of computational techniques and underscore the use of "a mixture of automated searches and active domain expertise".[44] This corresponds to the most recent methodological trends in science of science studies to use mixed-method research designs.[45] They were preceded by a recognition of the limitations of overly simplistic quantitative approaches and attempts to use multi-method quantitative designs, such as the paper by Hanning Guo et al., who use three different indicators to pin down emergence of new fields of research, namely sudden increases in the frequency of specific words; the number and speed by which new authors are attracted to an emerging research area, and changes in the interdisciplinarity of cited references.[46]

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[40] Bremer, "Nauka o zrównoważeniu – w poszukiwaniu transdyscyplinarnej metodologii".

[41] For an overview of the role of scientists as experts in democratic societies see Rafał P. Wierzchosławski, "Naukowcy w roli ekspertów: o pewnych problemach (re-)prezentacji prawdy w polityce", *Zagadnienia Naukoznawstwa* 53, no. 2(212) (2017): 207–232.

[42] Louis M. A. Bettencourt, Jasleen Kaur, "Evolution and structure of sustainability science", *Proceedings of the National Academy of Sciences* 108, no. 49 (2011): 19540.

[43] Louis M. A. Bettencourt et al., "Population modeling of the emergence and development of scientific fields", *Scientometrics* 75, no. 3 (2008): 495.

[44] Bettencourt, Kaur, "Evolution and structure of sustainability science", 19544.

[45] Paweł Kawalec, "Metody mieszane w kontekście procesu badawczego w naukoznawstwie", *Zagadnienia Naukoznawstwa* 50, no. 1(199) (2014): 3–22; idem, "W kierunku dojrzałości metodologicznej badań naukoznawczych", *Zagadnienia Naukoznawstwa* 52, no. 1(207) (2016): 33–44.

[46] Hanning Guo, Scott Weingart, Katy Börner, "Mixed-indicators model for identifying emerging research areas", *Scientometrics* 89, no. 1 (2011): 421–435.

(iii) *Science of science communication*

A reason why science of science communication is closely connected to publications concerning climate change and sustainability may be that these areas exhibit particularly high levels of societal risk.[47] Therefore, some of the main applications of science of science communication are precisely in those areas. For instance, Dan M. Kahan claims that "the central aim of a new *science of science communication*" is the resolution of "the science communication paradox": "Never have human societies *known so much* about mitigating the dangers they face but *agreed so little* about what they collectively know".[48] Although Kahan's aim is to demonstrate science of science communication by practicing it, he relegates the interested reader to consult the description of its methods and aims in earlier publications of Baruch Firschhoff and his collaborators.

Fischhoff[49] identifies the challenge for science of science communication as follows: "... worrying minorities of the general public reject conclusions that are widely accepted in the scientific community, such as the advisability of childhood immunization, the foundational role of evolution in biology, and the reality of anthropogenic climate change. Whole sciences find themselves in political cross-hairs (e.g., stem cell research in some jurisdictions, social sciences periodically at the National Science Foundation, genetically modified crops in large parts of Europe)". Thus, there is a pressing need to develop scientific approaches to address this challenge as "Better communication from the public and policy makers can provide scientists with clearer signals regarding the public's concerns and science's role in addressing them. The result would be a more productive dialogue about the science and the political, social, and moral implications of its application".

The kick-off event for science of science communication was the first Science of Science Communication Sackler Colloquium in 2012. In a follow-up publication Fischhoff identified the following four main tasks.[50] Science of science communication needs to (1) identify the science most relevant to the decisions that people face, (2) determine what people already know, (3) design communications to fill the critical gaps (between

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47 Rafał Wodzisz, "Wielkie wyzwania i złożone problemy jako główny przedmiot zainteresowania naukoznawcy", *Zagadnienia Naukoznawstwa* 53, no. 2(212) (2017): 233–242.

48 Dan M. Kahan, "What is the 'Science of Science Communication'?", *Journal of Science Communication* 14, no. 3 (2015): 1.

49 Baruch Fischhoff, Dietram A. Scheufele, "The Science of Science Communication II", *Proceedings of the National Academy of Sciences* 111, Supplement 4 (2014): 13583.

50 Baruch Fischhoff, "The sciences of science communication", *Proceedings of the National Academy of Sciences* 110, Supplement 3 (2013): 14034.

what people know and need to know) and (4) Evaluate the adequacy of those communications.

(iv) *Cognitive science of science*

The fact that among philosophical theories it is Paul Thagard's cognitive science of science that seems most influential in this new line of research on science of science is yet another demonstration of the effectiveness of the computational turn. Yet, there is a major difference between the former topics and philosophical theories of science – while the former have close affinities with practical applications to science policy and social practices,[51] the latter has strong theoretical orientation. Thagard admits that from its origins in 1950's cognitive science was closely related to advancements in computer science and the earliest ideas to apply it to study scientific inferences can be found in the writings of Herbert A. Simon and Ron Giere. The basic presumption was that: "thinking consists in applying processes to representations, just as computing consists in applying algorithms to data structures".[52] And it opens a way for new methodologies that make use of "writing and running computer programs".[53] In particular, Thagard indicates a series of steps that may lead to a normative description of scientific practices and elaboration of "norms for how it [science] might work better. These include identification of: ways of doing scientific research, norms of these practices and their respective aims (e.g. truth, explanation, technological applications) and evaluation of their success in achieving those aims, and finally, adoption as domain norms of those practices that best accomplish their goals.[54] So far, as Figure 8 makes clear, Thagard's program has not yet made it into the mainstream science of science research, but nevertheless there is a steady stream of publications that report new results in this area.[55]

Finally, a succinct overview of less dominant topics is in order. Given the dispersed state of science of science research since 2010 the

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[51] Wojciech Gasparski, "On practical disciplines and their methodology", *Zagadnienia Naukoznawstwa* 53, no. 2 (212) (2017): 129–134.

[52] Paul Thagard, *The Cognitive Science of Science: Explanation, Discovery, and Conceptual Change* (MIT Press, 2012), 6.

[53] Ibidem, 7.

[54] Ibidem, 12–13.

[55] As reported by Google Scholar, the annual citations of Thagard's book are around 20–30, far less than needed to draw attention of a broader scientific community. Also the majority of the examples brought out in his later publication (Paul Thagard, "Computational Models in Science and Philosophy", in: *Introduction to Formal Philosophy*, ed. S. O. Hansson, V. F. Hendricks (Cham: Springer International Publishing, 2018), 457–467, predate his 2012 book.

complete characterization of all of these topics would be a formidable task.[56] What follows, then, is a selection based on a subjective assessment of their relevance to the four topics discussed earlier in this section. I list those topics in chronological order, starting from 2011 up to 2017: (a) science education,[57] (b) the economic role of scientific knowledge,[58] (c) historical investigation of science policy,[59] (d) its new instruments,[60] and (e) accountability, as well as new forms of pseudoscience.[61]

4. Concluding Remarks

The paper identifies and documents the computational turn in the recent science of science research. It relies on citation analyses to indicate the earlier phases in the science of science as well as the focal areas of the most recent research. Admittedly, the citation analysis presented here has inherent limitations. Some of them have been discussed in more detail in earlier publications.[62] In particular large two notable examples may be mentioned here. First, the analysis of large full-text database[63] misidentified one of the emerging topics: it incorrectly dubbed it, combining basic and applied research, and determined 2006 as the year of origin that in fact was accomplished in the period 1993–2000. Second, a recent proposal to use "the gradient of flow vergence" as an index of

[56] Żegleń, "Potrzeba i perspektywy badań naukoznawczych w świetle dynamicznego rozwoju nauki i technologii", 181.

[57] David Klahr, Corinne Zimmerman, Jamie Jirout, "Educational Interventions to Advance Children's Scientific Thinking", *Science* 333, no. 6045 (2011): 971–975.

[58] Bruce A. Weinberg, "Developing science: Scientific performance and brain drains in the developing world", *Journal of Development Economics* 95, no. 1 (2011), Symposium on Globalization and Brain Drain: 95–104.

[59] Aant Elzinga, "The Rise and Demise of the International Council for Science Policy Studies (ICSPS) as a Cold War Bridging Organization", *Minerva* 50, no. 3 (2012), SI: 277–305.

[60] Mark A. Largent, Jane I. Lane, "STAR METRICS and the Science of Science Policy", *Review of Policy Research* 29, no. 3 (2012): 431–438; Christina H. Drew et al., "Automated Research Impact Assessment: a new bibliometrics approach", *Scientometrics* 106, no. 3 (2016): 987–1005.

[61] Stefaan Blancke, Maarten Boudry, Massimo Pigliucci, "Why Do Irrational Beliefs Mimic Science? The Cultural Evolution of Pseudoscience", *Theoria. A Swedish Journal of Philosophy* 83, no. 1 (2017): 78–97.

[62] Paweł Kawalec, "Transformations in Breakthrough Research: The Emergence of Mirnas as a Research Routine in Molecular Biology", *Open Information Science* 2, no. 1 (2018): 127–146; idem, „Cognitive Dynamics of Research Routines: Case Study of MicroRNA".

[63] Henry Small, K.evin W. Boyack, Richard Klavans, "Identifying emerging topics in science and technology", *Research Policy* 43, no. 8 (2014): 1450–1467.

"paradigm-shifting" papers[64] is at odds with the widely recognized and documented contributions in the case of microRNAs.[65]

The computational turn, discussed here, seems to be a robust phenomenon confirmed by different kinds of evidence, so the limitations of the citation analysis may perhaps affect its more precise description, but should not undermine its very presence in the science of science research. Yet, there is another aspect that underscores the importance of the recognized limitations of citation analysis, and similar quantitative techniques. It is indeed very important that the computational methods in the science of science be accompanied by more thoroughgoing and focused qualitative investigations, characteristic of the early humanistic phases of the science of science research. I my earlier publications I brought out some cases illustrating successful applications of such "mixed-methods" designs in the science of science research that seem to be adequate with regard to the complex nature of the problems posed for the future of science of science studies.

Acknowledgements

I am enormously grateful to Professor Wojciech Gasparski for his comments on an earlier draft of this paper that drew my attention to the Polish and Soviet contributions to the International Council for Science Policy Studies in 1970's and the transformative role of the *Mode 2* in the early 1990's.

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[64] Thara Prabhakaran et al., "Towards prediction of paradigm shifts from scientific literature", *Scientometrics* 117, no. 3 (2018): 1611–1644.

[65] Kawalec, "Cognitive Dynamics of Research Routines: Case Study of MicroRNA".

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Summary

The paper discusses some recent trends in the science of science studies. It provides evidence of the computational turn in the science of science studies since 2010. The four main topics within this trend are identified and shortly presented. The paper also presents the computational turn against the background of the earlier major phases of the development of the science of science as conjectured on the basis of citation analysis. It concludes by indicating the limitations of quantitative analyses and the need of mixed-methods approaches in science of science research designs.

Keywords: science of science, computational turn, cognitive science of science, mixed-method research design, Urszula Żegleń

Streszczenie

Najnowsze postępy naukoznawstwa

Artykuł omawia niektóre najnowsze trendy w naukoznawstwie. Wskazuje, że od 2010 roku dokonał się w tych badaniach wyraźny zwrot obliczeniowy. Cztery główne tematy w tym nurcie zostały zidentyfikowane i krótko omówione. W artykule przedstawiono również zwrot obliczeniowy na tle wcześniejszych głównych faz rozwoju naukoznawstwa na podstawie analizy cytowań. Artykuł kończy się wskazaniem ograniczeń analiz ilościowych i konieczności stosowania metod mieszanych w naukoznawstwie.

Słowa kluczowe: naukoznawstwo, zwrot obliczeniowy, kognitywistyka nauki, metody mieszane, Urszula Żegleń