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Socio-Epistemic Networks: A Framework for History of Knowledge

Abstract: Focusing on methodologies such as network analysis, co-citation networks, and topic modelling, this paper analyses historical knowledge dynamics and evolution by means of the socio-epistemic networks (SENs) framework using computational methods. By applying the framework to two case studies (transnational scientific practices of Polish migrants and the evolution of general relativity and gravitation research) and integrating the social, semiotic/material, and semantic layers to analyse historical sources, the paper highlights the importance of studying interactions, material objects, and cognitive elements in combination in order to understand how knowledge systems develop over time.

Keywords: evolution of knowledge, historical network research, multi-layer networks, history of science, digital methods

1 Introduction

The advancement of technology has expanded the range of physical representations of knowledge and the ways in which we manage these. Digital archives, multimedia recordings, and virtual simulations offer new avenues for storing and studying knowledge, while digital workflows improve the accessibility of existing traditional archives. At the same time, we see the emergence of increasingly comprehensive and sophisticated computerised methods for processing these sources. New technologies thereby contribute to the exponential growth of records and sources available for study while at the same time expanding the ways in which they are handled. Historical research needs to adjust to this changing landscape if historians are to address the opportunities and new research questions presented by this situation. In this article, we present the framework of socio-epistemic networks (SENs), which aims to integrate large-scale exploration and analysis of historical sources using computational methods, thereby complementing traditional historical research.

The framework is intended to explore the intricate, multidimensional dynamics governing the formation and evolution of knowledge systems. It combines ap-

https://doi.org/10.1515/9783111291383-012

proaches of network analysis and digital methods with structural questions concerning knowledge production, formalisation, and dissemination, which are typically of interest to historians of knowledge. We envision that this framework will integrate and add to existing research methods, which will allow us to broaden and corroborate qualitative research outputs using a quantitative, structural approach.

1.1 Conceptual Framework

The ModelSEN project seeks to create a quantitative, network-inspired approach to the history of knowledge, which integrates micro-history with macro-history while accounting for global, transregional effects of knowledge processes.[1] While appreciating the breadth of research focusing on knowledge networks, the SENs framework presented here serves as a continuation of work initiated by Jürgen Renn and others in the early 2010s.[2] Renn et al. define knowledge as a "codified experience and potential for problem-solving".[3] Codification occurs through the formation of cognitive, material, and social structures. Examples of such structures include mental models, but also material representations of knowledge, or sign systems, all within a realm of interactions between social actors. Accordingly, cognitive, material, and social dimensions of knowledge emerge. We argue that these dimensions can be modelled by multi-layered, time-evolving SENs: the social, the semiotic/material, and the semantic (see Figure 1 for a schematic representation). In addition to these layers, however, we argue there are also constraints concerning knowledge-related interactions in and between each of these layers governing the formation of these structures.

1 ModelSEN Project, "Theory", Socio-Epistemic Networks: Modelling Historical Knowledge Processes, 2021, https://modelsen.mpiwg-berlin.mpg.de/theory/.

2 Jürgen Renn et al., "Netzwerke als Wissensspeicher", in *Die Zukunft der Wissensspeicher: Forschen, Sammeln und Vermitteln im 21. Jahrhundert* (Munich: UVK Verlagsgesellschaft Konstanz, 2016), 35–79, https://pure.mpg.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_2347024. For other approaches to historical knowledge networks, see, for example, Kapil Raj, "Networks of Knowledge, or Spaces of Circulation? The Birth of British Cartography in Colonial South Asia in the Late Eighteenth Century", *Global Intellectual History* 2, no. 1 (2 January 2017): 49–66, https://doi.org/10.1080/23801883.2017.1332883; Emily Erikson, *Trade and Nation: How Companies and Politics Reshaped Economic Thought*, The Middle Range Series (New York: Columbia University Press, 2021), https://doi.org/10.7312/erik18434; Cécile Armand, Christian Henriot, and Huei-min Sun, *Knowledge, Power, and Networks: Elites in Transition in Modern China* (Leiden: Brill, 2022).

3 Renn et al., "Netzwerke als Wissensspeicher", 36.

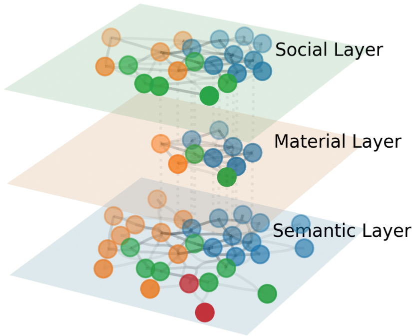

Figure 1: A schematic representation of the socio-epistemic network framework with social, material (also referred to as Semiotic), and semantic layers and both inter- and intra-layer links. For examples of nodes and edges in the different layers, see Table 1.

1.2 Case Studies and Research Questions

Before applying SENs, researchers must ask themselves if this framework is suitable for answering the research questions they wish to pursue. It is also vital to consider whether the available sources are sufficiently detailed to observe the changes in focus. As a framework, SENs are based on the conceptualisation that knowledge is culturally and physically embedded. It combines social networks, where a traditional approach of closely reading a large corpus might suffice, with networks of material outputs of that social network and the cognitive processes (represented by language) used to encode that output. The framework situates these in a temporally evolving multilayer frame.

Furthermore, this framework aims to uncover structural changes in the constructed networks and reflect on these changes from both quantitative and qualitative historical perspectives. This type of approach thereby forces historians to a) structurally think about the sources used and their relations, b) formulate their research hypothesis in this regard as well, and c) make their data and/or analysis reproducible and reusable for other scholars, which, unfortunately, is not always the case for quantitative research involving computer analysis.[4] In cases where software and data are produced, they should be findable, accessible, interoperable, and reusable (FAIR). Quantitative answers to questions related to historical

4 For more on the replication crisis in the humanities, see Rik Peels, "Replicability and Replication in the Humanities", *Research Integrity and Peer Review* 4, no. 1 (9 January 2019): 2, https://doi.org/10.1186/s41073-018-0060-4.

phenomena are only truly reproducible when other researchers have access to both the data and the software used to obtain results and are thus able to check if they can arrive at the same results.

An example of a historical research question possible to explore by using the SEN framework is how the complex connections of Polish migrants along professional and geographical lines enabled their transnational scientific practices to function in the nineteenth century.[5] Which individuals or communities were important for developing ideas and practices, whose role might nevertheless have been unacknowledged until now due to the dominant "great men" or "centre-periphery" narratives? How was the knowledge they contributed circulated transnationally? And how did their work affect broader scientific debates? In the 1930s, Stanisław Zieliński, a Polish historian, independence activist, and editor, authored a few detailed compilations containing extensive lists of Polish intellectuals working abroad, along with their notable professional achievements and published works.[6] The data contained in Zieliński's compilation enables us to create a socio-epistemic network of Polish migrants working around the world in the nineteenth and early twentieth centuries. The social network reconstructed for the purposes of this case study connects the Polish migrants working around the world during the period 1830–1930. It is linked to the semantic network containing their professional achievements and expertise, which, in turn, is linked to the semiotic network of their publications and material outputs of their work, such as infrastructure projects to which they contributed. Such a SEN can be used to address the questions mentioned above in this paragraph.

Another question concerns the dynamics of scientific disciplinary formation, exemplified by applying the SEN framework to the so-called "Renaissance of General Relativity" in the field of general relativity and gravitation research (GRG).[7] In the social layer, an analysis of the networks of research centres and individual collaboration networks reveals how exchanges of personnel and the deliberate densification of relationships contributed to the emergence of the largest and

5 For more on this topic, see Aleksandra Kaye, "Mapping Transnational Knowledge Networks: Polish Scientific Professionals in Latin America, 1830–1889" (PhD diss., University College London, 2022).
6 Stanisław Zieliński, *Wybitne czyny Polaków na obczyźnie* (Wilno: Polska Drukarnia Artystyczna "Grafika", 1935); Stanisław Zieliński, *Bibljografia czasopism polskich zagranicą 1830–1934* (Warszawa: Drukarnia Społeczna, 1935); Stanisław Zieliński, *Mały słownik pionierów polskich kolonialnych i morskich: podróżnicy, odkrywcy, zdobywcy, badacze, eksploratorzy, emigranci – pamiętnikarze, działacze i pisarze migracyjni* (Warsaw: Instytut Wydawniczy Ligi Morskiej i Kolonialnej, 1933).
7 Roberto Lalli, Riaz Howey, and Dirk Wintergrün, "The Socio-Epistemic Networks of General Relativity, 1925–1970", in *The Renaissance of General Relativity in Context*, eds. Alexander S. Blum, Roberto Lalli, and Jürgen Renn, Einstein Studies (Cham: Springer International Publishing, 2020), 15–84, https://doi.org/10.1007/978-3-030-50754-1_2.

most stable component in the field of GRG, thus emphasising the role of active community-building in the formation of a scientific field (see section 2.1). The semiotic or material aspects of this formation can be seen in structural changes of citation patterns, such as co-citations, widely recognised as methods for identifying the emergence of research fields and routinely employed in scientometrics (see section 2.2). Lastly, the central topics of clusters in these co-cited papers and their structural positions serve to illustrate the semantic sphere over time, revealing conceptual shifts and the reorganisation of knowledge connected to the above-mentioned changes in the other two layers (see section 2.3). We argue that it is hardly possible to satisfactorily explain the phenomenon of the Renaissance of General Relativity or Polish contributions to scientific debates by only considering one of these layers. Additionally, an explanation that does not take into account large amounts of data over long periods of time is unlikely to fully account for this complexity.

2 Socio-Epistemic Networks in Practice

In this section, we illustrate the conceptual framework using the examples presented above. The section is structured by the different layers to highlight the relevant aspects of data gathering, network creation, and necessary steps in the analysis. Table 1 presents an at-a-glance summary of the different layers of SENs together with examples from the case studies presented in the text.

Table 1: Definition and examples of the layers of the socio-epistemic network framework.

Description	Nodes	Edges
Social layer		
Structures of social relations between individuals and/or groups	*General:* Individual people or groups of people (e.g., kinship unit, friendship/professional group)	*General:* Social relations (e.g., meetings, relationships, friendship bonds, professional ties, family ties)
	Polish Case Study: Polish migrants across the world in the nineteenth and early twentieth centuries	*Polish Case Study:* Acquaintanceship between migrants who worked together
	General Relativity Case Study: Scientists working in the field of GRG	*General Relativity Case Study:* Co-authorship, supervision relationships, working at the same institution at the same time

Table 1 (continued)

Description	Nodes	Edges
Semiotic/Material layer		
Structures of relations between material or formal representations of knowledge	*General:* Objects, artefacts, symbols, institutions (e.g., books, articles, journals, periodicals, instruments, images, buildings)	General: Semiotic relations (e.g., representation in the same object, citations, physical ties)
	Polish Case Study: Maps and publications by the migrants; infrastructure projects, such as the Trans-Andine Railway in Peru	*Polish Case Study:* Publishing in the same journal, using the same type of railway bridge truss in different viaducts, etc.
	General Relativity Case Study: Publications	*General Relativity Case Study:* (Co-)citations
Semantic layer		
Structures of semantic relations between knowledge elements	*General:* Cognitive elements (e.g., language entities, concepts, topics, keywords, theories, methods)	*General:* Semantic relations (e.g., co-occurrence, proximity in meaning, reuse of word groups)
	Polish Case Study: Areas of expertise of the migrants, such as oil exploration or railway construction	*Polish Case Study:* Similarity in terms of the focus of work (e.g., two migrants working on mapping oil fields regardless of geographical location)
	General Relativity Case Study: Topics of clusters of publications	*General Relativity Case Study:* Ties between topic clusters

2.1 The Social Layer of SEN

Social networks are networks whose nodes represent individual or collective actors and whose edges represent interactions between these actors. For examples of other types of nodes and edges that may be mapped in a social network, see Table 1. In the context of knowledge systems, these nodes and edges revolve around knowledge-related interactions (collaboration, teacher/student, master/apprentice, colleague, attending the same conference, supervisor/supervisee, etc.).

In the context of SENs, the social network is one of the three layers that need to be analysed in tandem with the semiotic/material and semantic networks discussed in the following sections. Formal social network analysis has a long "prehistory", which Linton C. Freeman traces back to the nineteenth century.[8] Using networks to understand the development of scientific knowledge can be observed as early as 1923.[9] Over the years, social network methods became more formalised and gained wider recognition among scholars across different disciplines. Phelps et al. have conducted a systematic review of research published in twelve management, psychology, sociology, and economics journals between 1970–2009, showing that an increasing amount of empirical research focused on "knowledge" centred around networks based on social ties.[10] Hence, it is perhaps not surprising that social network analysis concepts and methods are more familiar and thus more frequently chosen by scholars using network science in their historical research.[11] Furthermore, many programs and study resources have been developed to aid scholars in digital network analysis.[12]

For a social connection to exist, at the most basic level, two individuals are necessary. The interpersonal connections between a pair of individuals can be categorised in several different ways depending on the nature of the relationship; for instance, connections such as kinship, organisational and religious ties, etc. These interactions are subject to various constraints such as traditions, rules, conventions, and norms or, more broadly, by power dynamics and hierarchies that shape how these interactions unfold. To recreate a historical social network, it is necessary to use the sources to distil the relationships between individual historical actors or groups and to record this information in a structured way. This re-

8 Linton C. Freeman, *The Development of Social Network Analysis: A Study in the Sociology of Science* (Vancouver, BC: Empirical Press, 2004).

9 Giovanni Paoloni, "S for Scientometrics: Or How to Analyse and Measure Scientific Production", *Lettera Matematica – International Edition* 5, no. 2 (2017): 179.

10 Corey Phelps, Ralph Heidl, and Anu Wadhwa, "Knowledge, Networks, and Knowledge Networks: A Review and Research Agenda", *Journal of Management* 38, no. 4 (1 July 2012): 1115–1166, doi:10.1177/0149206311432640.

11 Lea Weiß, Laura von Welczeck, Malte Vogl, Marten Düring, Aleksandra Kaye, Jascha M. Schmitz, Raphael Schlattmann and Bernardo S. Buarque, "Past, Present, and Future of HNR: Reflections on the Practices and Methods in Historical Network Research Based on a Quantitative Survey" [Manuscript submitted for publication] (Berlin: Max Planck Institute for the History of Science, May 2024).

12 For programs, see, for example, Mathieu Bastian, "Gephi – The Open Graph Viz Platform", accessed 1 April 2023, https://gephi.org/; Pim van Bree and Geert Kessels, "Nodegoat: a Web-based Data Management, Network Analysis & Visualisation Environment", accessed 8 May 2024, http://nodegoat.net. For tutorials teaching network science from scratch, as well as a list of network science software and a glossary, see the Archeological Networks website and accompanying textbook: Tom Brughmans, "Archaeological Networks", Archaeological Networks, accessed 9 October 2023, https://archaeologicalnetworks.wordpress.com/; Tom Brughmans and Matthew A. Peeples, *Network Science in Archaeology*, Cambridge Manuals in Archaeology (Cambridge: Cambridge University Press, 2023).

quires the researcher to make interpretative choices concerning who should be included in the network, how they would be represented by the nodes (individually or as groups), and which types of relations should be denoted by the edges. Furthermore, a researcher may choose to include the strength of the connections identified in a social network. Determining the strength of the ties frequently relies on participants reporting and rating the strength of their relationships. However, such information is not typically accessible for historians studying historical actors who are no longer alive. Should historians want to use weighted ties, they would need to consider which suitable proxies are available in the sources. For example, they may choose to weight family ties as stronger than friendships, even if that would not necessarily be true in all cases. These initial choices that go into the recreation of a historical social network will impact which sort of analysis may then be conducted. Even without knowing the directionality or strength of the connections, a lot can be learned about the structure of a network.

The position of an individual within a social network may provide clues regarding their importance for the generation of new ideas or the transfer of knowledge in this network. In social network analysis, betweenness-centrality and eigenvector-centrality are often employed to compare different individuals in the network and rank them by their importance: first, in terms of group cohesion and generating new ideas, and second, in terms of their significance for transmitting ideas between different groups in the network. The individuals scoring highly in the eigenvector-centrality measure may, for example, be conceptualised as influential or important for generating and developing ideas within the group. Here, we find the likes of Jan Sztolcman, who worked for many years in Latin America and, later among many roles, was the first director of the Branicki Museum in Warsaw between 1887 and 1919. As the network evolves and changes over time, different figures come to the fore. Hence, in the early twentieth century, we observe the increased importance of Polish editors working in the United States, such as W. Halicki at Detroit's *Dziennik Polski* (now *The Polish Weekly*). The ideas of these individuals would be influential and more likely to be accepted by others in the group. Those with high betweenness-centralities, on the other hand, are the ones who connect the most different individuals and communities in a network. Among Poles with the highest betweenness-centrality, we find expected figures, such as Joachim Lelewel, Władysław Czartoryski, or Ignacy Domejko, and the lesser-known such as Bronisław Antoni Szwarce. These individuals contribute significantly in terms of transferring knowledge from one community to another, and their removal would make the exchange of information more difficult and slower, as the number of steps required for information to travel between two distant individuals in the network would increase.[13] There are different reasons for why these individuals arrived at the privileged position of bridging different groups – Czartoryski, for example, was a Polish prince, closely associated with Hôtel Lambert (a Polish political salon in Paris) who worked on diplomatic missions in many countries, while Domejko, the rector of the University of Chile between 1867 and 1883, published profusely and corresponded widely with colleagues across Latin America and Europe. Questioning the idea of betweenness-centrality, Damon Centola proposes the concept of wide bridges, arguing that the presence of multiple shared social ties across communities is more important than individual brokers in terms of driving changes in ideas and behaviours.[14] Much can be gleaned from the structure of the network and the location of the individual nodes regarding the spread of knowledge within and between communities. Not least, important individuals who have hitherto been overshadowed by better-known colleagues come to the fore.

Using a network-based approach when studying historical migration shifts the focus from individual migrants towards their relationships with others in their communities, which, in turn, highlights that knowledge is a collaborative effort involving contributions from many individuals, not just a select celebrated few.[15] It is possible, for example, to use network methods to determine communities of practice within a network; that is, groups of people working closely together who develop joint expertise. In the Polish case studies, such communities include a group of Poles working with oil prospecting in Argentina in the 1880s or those working closely with Henryk Arctowski with regard to exploring Antarctica.[16] What is more, the evolution of the network structure can easily be observed. This is evident in the general relativity and gravitation research case study. With regard to the social networks of GRG, built by ties of collaboration and socio-institutional cooperation between actors, the late 1950s marked a crucial transformation. It went from a fragmented to a unified research network, driven mainly by the increasing mobility of postdoctoral researchers, and is re-

13 The importance of such bridging individuals was observed by Ronald Burt when studying the significance of the different positions in the social capital network. He posited that a person acting as a mediator between two or more closely connected groups of people is in a privileged position to access novel information. For more, see Ronald S. Burt, “Structural Holes: The Social Structure of Competition”, in *Structural Holes* (Cambridge, MA: Harvard University Press, 2009), doi:10.4159/9780674029095.

14 Damon Centola, *How Behavior Spreads: The Science of Complex Contagions*, eds. Damon Centola, Karen S. Cook, and Peter Hedström (Princeton: Princeton University Press, 2018), https://doi.org/10.2307/j.ctvc7758p.

15 Kaye, “Mapping Transnational Knowledge Networks”.

16 For more on Poles in Argentina, see Aleksandra Kaye, “Piecing Together ‘Big Pictures’ with Social Network Analysis and Digital Tools”, *BJHS Themes* 9 (2024): 1–19, https://doi.org/10.1017/bjt.2024.5.

flected in the fusion of the largest components of the network. This shift towards greater connectivity and group integration occurred before key astrophysical discoveries, which supports the view that the gradual evolution of the field was actively pursued rather than being driven by research advancements, thereby supporting the findings of Blum et al.[17]

Despite its merits, exclusively analysing social networks can only offer a partial picture when studying the evolution of knowledge, which is why it needs to be supplemented with analysing the types of networks discussed in the following sections.

2.2 The Semiotic/Material Layer of SEN

Semiotic networks are networks whose nodes represent material objects or externalised representations and whose edges represent interactions or physical transformations between these objects. These may, for example, concern books in the same library or publications citing each other. These interactions are also subject to constraints such as citation conventions, archiving practices, or certain book production techniques. Semiotic networks mostly are the starting point for constructing the other levels of SENs, simply due to the fact that access to historical events frequently occurs via archival materials.

Written texts are intentionally produced manifestations of knowledge in the authors' minds. While approaches from psychology or neuroscience might pay more heed to the internal workings of the human mind, the physical representations of knowledge – be it written documents, recordings of conversations, paintings, scientific instruments, buildings, etc. – provide historians with rich evidence for the study of the outputs of human knowledge. Human knowledge is dynamic and constantly evolving, but physical representations freeze moments in time, thereby allowing us to observe the state of knowledge at specific points in history.

As an example, consider the question of the scientific history of a research organisation.[18] Using the publication output of the Max Planck Society generated in

17 Alexander Blum, Roberto Lalli, and Jürgen Renn, "The Reinvention of General Relativity", *Isis* 106, no. 3 (2015): 598–620, https://doi.org/10.1086/683425; Alexander Blum, Roberto Lalli, and Jürgen Renn, "The renaissance of General Relativity", *Annalen der Physik* 528, no. 5 (2016): 344–349, https://doi.org/10.1002/andp.201600105; Alexander Blum, Roberto Lalli, and Jürgen Renn, "Gravitational waves and the long relativity revolution", *Nature Astronomy* 2, no. 7 (2018): 534–543, https://doi.org/10.1038/s41550-018-0472-6.

18 For an in-depth online tutorial, see Malte Vogl, "The Max Planck Society and Its Scientific Context", ModelSEN, accessed 10 October 2023, https://modelsen.mpiwg-berlin.mpg.de/jupyterbooks/book/scigraph/.

all journals of the Springer/Nature publishing house between 1950 and 2005 as a corpus, we may create one realisation of a socio-epistemic network for each year with three different kinds of nodes. Authors are connected if they co-authored a publication while they are also connected to their respective publications. Publications are linked to the used word groups of length 2 (“2-gram” or more general “n-gram”). A scoring algorithm weights the link between a publication and the 2-gram.[19] In other words, the time-sliced multi-layer network thus has intra-layer links for the case of the author layer (authors are connected to co-authors) and inter-layer links between author, publication, and word layers (authors are connected to publications, and publications to 2-gram).

In order to find structural change in this set of essentially independent networks for each year, existing software such as the Infomap algorithm can be used.[20] This software enables finding communities in multilayer networks by applying concepts from information theory. A random walker traverses the network and records its path. The algorithm minimises the description of these paths by grouping nearby nodes into communities until an optimal description is found. It visualises these communities and their relations by connecting two communities in adjacent years if the majority of constituting nodes remain the same. The result (see Figure 2 for a static image) represents the starting point of a dialogue between the person building the SEN and a historian.[21] This dialogue may lead to a re-evaluation of the historian’s hypotheses or a critical rebuilding of the networks.

The next example considers the following challenge often faced by historians of knowledge: how to create a useful sub-corpus for a specific research question from a larger corpus of literature without a useful classification with regard to the problem at hand?

For scientific literature, one approach is to define core papers, which, together with papers citing them and the references of these citing papers, thus make up the corpus to be analysed.[22] This approach typically requires detailed knowledge regarding the field at hand.[23]

19 Hidenao Abe and Shusaku Tsumoto, “Evaluating a Temporal Pattern Detection Method for Finding Research Keys in Bibliographical Data”, in *Transactions on Rough Sets XIV*, eds. J.F. Peters et al. Lecture Notes in Computer Science, vol. 6600. (Berlin and Heidelberg: Springer, 2011).

20 Martin Rosvall and Carl T. Bergstrom, “Maps of Random Walks on Complex Networks Reveal Community Structure”, *Proceedings of the National Academy of Sciences* 105, no. 4 (29 January 2008): 1118–1123, https://doi.org/10.1073/pnas.0706851105.

21 https://www.mapequation.org/alluvial/.

22 R. Sinatra et al., “A century of physics”, *Nature Phys* 11 (2015): 791–796.

23 Lalli et al., “Socio-Epistemic Networks”.

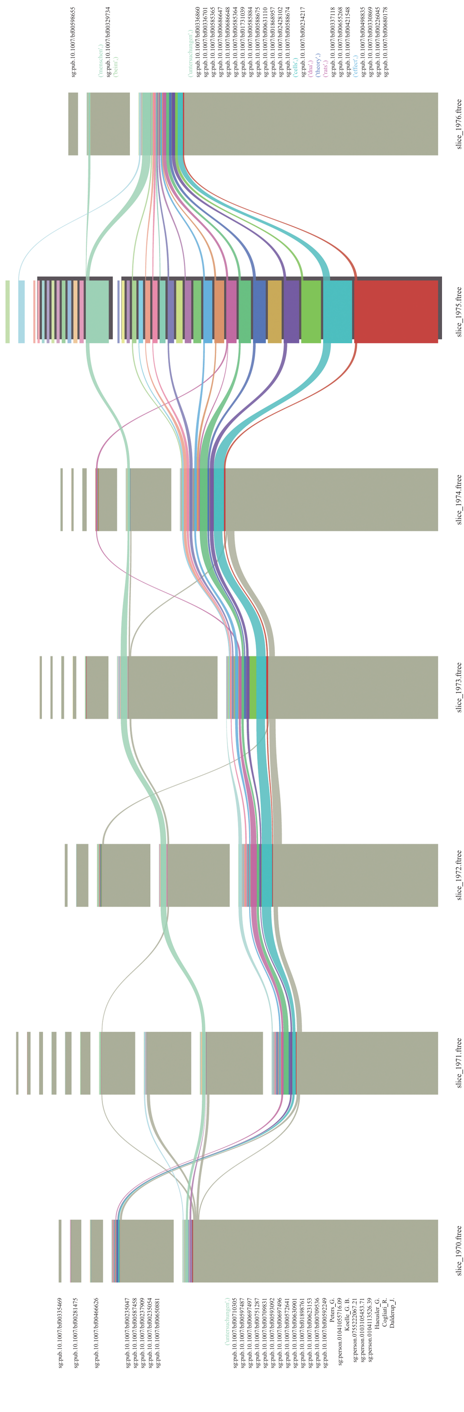

Figure 2: Flow between multilayer communities created from Max Planck Society publications in Springer/Nature during 1950–2005. The figure shows an excerpt from 1970–1976. Colours chosen so that nodes from communities in 1975 share the same colours in other years. The plot was created using Mapequations Alluvial Generator.

In the framework of SENs, a structure contained in the publications themselves can be used: their references. Using the notions of scientific fronts and the mainstream for each publication in each year, an edge entry is created between each referenced publication.[24] If the edge reoccurs in other publications, its weight is increased by one. This process is then repeated for each year. All referenced publications in the corpus must have stable and unique identifiers across the entire timespan. Due to its very nature, the resulting network is part of the semiotic layer of the SEN and contains a large number of nodes and edges. Furthermore, an edge in a given year, say 1950, can be created in this co-citation network between potentially much older literature. Hence, a co-citation is often interpreted as an expression of the authors of the publication finding that two other publications belong together to support an argument. While this may be contested given the different mechanisms of why publications are cited, such effects are negligible for larger corpora.

Existing software can also be used to retrieve information on structural changes in such a dense co-citation network. This time, the Leiden algorithm, which is an extension of the well-known Louvain algorithm, allows us to find communities in networks across temporal layers.[25] Just like the Louvain algorithm, this algorithm is also density-based, meaning that a density parameter must be determined so that nodes inside one community are more closely connected compared to nodes in other communities This necessitates another iteration cycle between the person building a SEN and a historian. The result of such an iteration is a list of publications grouped in communities for a range of years. To support the historical analysis, the software package semanticlayertools,[26] developed in the framework of the project ModelSEN, uses additional metadata related to the publications, such as authors and affiliations, and a fast topic modelling on the titles of each community as a reporting routine. After each iteration, the historian can decide which communities should remain part of the analysis and which are to be ignored. After several iteration cycles, the result is a more focused and narrower corpus in relation to the research question in conjunction with the researcher's interpretation. See Figure 3 for the example of astrophysics research literature related to the GRG case in the NASA Astrophysical Data System (ADS).[27]

24 For more on the notions of scientific fronts and the mainstream, see: M. B. Synnestvedt, C. Chen, and J. H. Holmes, "CiteSpace II: Visualisation and knowledge discovery in bibliographic databases", *AMIA Annual Symposium Proceedings* (2005): 724–728.

25 V.A. Traag, L. Waltman, and N.-J. Van Eck, "From Louvain to Leiden: Guaranteeing Well-connected Communities", *Scientific Reports* 9, no. 1 (2018): 5233.

26 Malte Vogl, SemanticLayerTools (0.1.3). Zenodo (2022). https://doi.org/10.5281/zenodo.6401221.

27 See "Astrophysics Data System", NASA/ADS, accessed 10 October 2023, https://ui.adsabs.harvard.edu/.

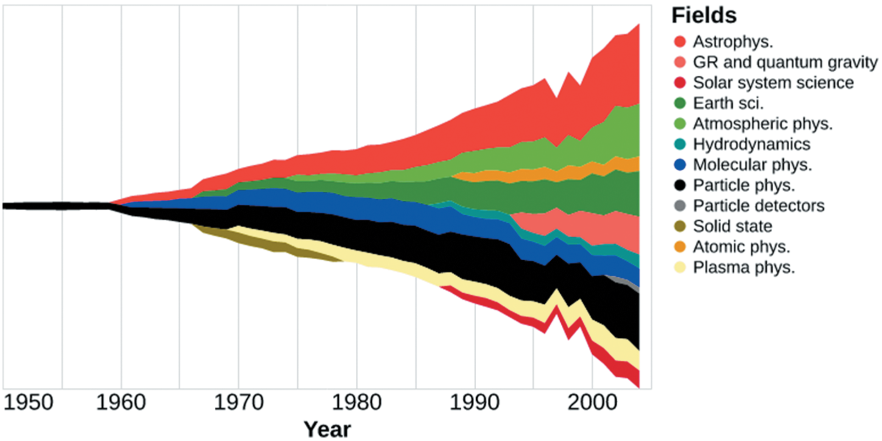

Figure 3: A streamgraph showing the temporal development of the size of co-citation clusters related to astrophysical research. The labelling was created manually by Roberto Lalli. Data retrieved from the NASA Astrophysical Data System, see main text.

For the GRG case, the analysis of co-citation networks highlights a dynamic evolution in the field. By examining the largest components, it can be observed that early periods underwent radical changes, which transitioned into stabilisation and the emergence of small-world network characteristics in later years. This transformation, demonstrated by long-term shifts in the largest components, points to a complex, two-phased (theoretical renaissance and astrophysical turn) but gradual development and consolidation of the field over the analysed decades rather than a sudden shift. This process is compatible with the community-building processes starting after World War II observed in the social layer and mentioned in section 2.1.

With regard to the Polish case study, the semiotic network highlights the changing interests and geographical distribution of the Polish diaspora. For example, a rise and decline of Polish political publications in the French language can be seen in the period between 1830 and 1870 – likely a reflection of the Great Emigration[28] – or an increase in Polish special-interest publications of Brazilian and Argentinian origin in the late nineteenth century and the later sharp rise of US-based publications in the early twentieth century as more and more Polish immigrants headed there. Linking the findings from this layer to the social layer through the different actors involved in the production of these periodicals allows

28 In Polish historiography, the “Great Emigration” refers to the large-scale emigration of Poles following the November 1830 uprising and later failed uprisings. This migration wave ends roughly in the 1870s, the decade following the January 1863 uprising.

us to determine the importance of the different publications in terms of bringing together various professionals, while linking this layer to the semantic layer (see section 2.3) could clarify which periodicals were pioneering in terms of the content they published.

2.3 The Semantic Layer of SEN

Semantic networks comprise nodes representing cognitive elements, while the edges represent cognitive operations or interactions between these elements, which may be concepts, mental models, or other cognitive entities.[29] The significance here, as with the networks described above, concerns understanding the entire network as a carrier of knowledge compared to the individual elements. Institutionalisation or community-building processes are crucial for knowledge formation in social knowledge networks, while the ongoing reproduction and normalization of certain cognitive interactions are key for semantic knowledge structures. For example, continuously combining mental representations such as “negative charge”, “particle”, “spin” when dealing with the mental representation of “electron”. In this regard, both processes are mirrored in systemic structures that can be represented by networks.

Unlike the other two types of networks, however, semantic networks are constructed more “indirectly” through language or other methods of culturally embedded, codified meaning, thereby making a mapping less tangible than, say, a social connection such as a record of a meeting between two individuals. In most cases in the history of knowledge, written texts are the foundation for constructing semantic networks, meaning that the process of extracting meaning in terms of concepts or similar structures is a complex one.[30] Adding a word to a sentence or even just a character may alter the whole meaning conveyed by this sentence. For instance, frequently co-occurring words (e.g., “energy”, “level”, “low”, “high”) may be seen as a rough operationalisation of a concept (“energy levels”) but could convey very different meanings across different actors, contexts, or languages (e.g., physics, chemistry, sports, gaming, etc.). The example chosen is deliberately simplistic to highlight general difficulties that may be minimised by a clear definition of the realm of analysis and reflecting on the accuracy of the assumptions made, still permitting the construction of structurally useful approxi-

29 Renn et al., “Netzwerke als Wissensspeicher”, 16.
30 Jürgen Renn, *The Evolution of Knowledge* (Princeton and Oxford: Princeton University Press, 2020), 324.

mations of semantic structures represented as networks. However, the level of abstraction is usually greater compared to the other layers.

Again, there are constraints for these interactions, which organise the development of these structures and are dynamic in nature. Examples include collective belief systems or systematisations such as the "scientific method"; in other words, underlying cognitive principles that govern or give order to these interactions, thus structuring cognitive elements into a system of knowledge.

The notion of semantic networks has been around for quite some time and has been utilised in various contexts such as psychology, linguistics, neuroscience, or computer science to model conceptual knowledge representation and organisation. They have been operationalised through various methods, such as word association tasks,[31] co-occurrence networks,[32] feature-based semantic networks,[33] semantic parsing,[34] or quantum semantics.[35] These approaches involve creating networks in which nodes represent either spoken or written words, phrases, or other n-grams, while edges represent associations, co-occurrences, proximity, shared features, or other semantic relationships. The specific method used depends on the research goals and the type of data being analysed.

For the GRG case, an example of a (semio-)semantic network is a network of topics built on top of a co-citation network.[36] The network formed from papers (nodes) of the subdiscipline general relativity and gravitation having been co-cited (edges) within a range of years (e.g., 1946–1975) has already been mentioned in section 2.2. The co-citation or, more generally, the network models underlying citation analysis are widely utilised and well-established across disciplines. The key assumption is simplified: nodes primarily represent a paper (semiotic/material layer) but also, secondly, certain topics (the content of the paper: semantic layer), while edges primarily represent a co-citation but also, secondly, a cognitive link between

31 Mark Steyvers and Joshua B. Tenenbaum, "The Large-Scale Structure of Semantic Networks: Statistical Analyses and a Model of Semantic Growth", *Cognitive Science* 29, no. 1 (2005): 41–78, https://doi.org/10.1207/s15516709cog2901_3.

32 Elad Segev, ed., *Semantic Network Analysis in Social Sciences* (London and New York: Routledge, 2021).

33 Ray Grondin, Stephen J. Lupker, and Ken McRae, "Shared Features Dominate Semantic Richness Effects for Concrete Concepts", *Journal of Memory and Language* 60, no. 1 (2009): 1–19, https://doi.org/10.1016/j.jml.2008.09.001.

34 Hoifung Poon and Pedro Domingos, "Unsupervised Semantic Parsing", *Proceedings of the 2009 Conference on Empirical Methods in Natural Language Processing*, 2009, 1–10.

35 Ismo Koponen and Ilona Södervik, "Lexicons of Key Terms in Scholarly Texts and Their Disciplinary Differences: From Quantum Semantics Construction to Relative-Entropy-Based Comparisons", *Entropy* 24, no. 8 (2022): 1058, https://doi.org/10.3390/e24081058.

36 Lalli et al., "Socio-Epistemic Networks".

these topics made by the authors who cited them. Many edges between two co-cited papers are then interpreted as topic proximity. These co-citation networks can be clustered using various methods (e.g., Louvain, Leiden, Girvan-Newman, etc.), and these clusters may be thought of as representing a specific topic mixture. There are several ways to extract them, one of which is to aggregate all texts (e.g., reduced to nouns or proper nouns) in a cluster and build a semantic network based on these texts.[37] For that, an ordered list of non-overlapping terms may be transformed into a semantic network representing the topic structure of the co-citation cluster. In this second-order network, each term is represented by a node, while edges link this term to other terms that co-occur within a specified window of terms around it, so that we get a co-occurrence network. The creation of links between nodes (terms) in the semantic network is determined by the window width. If it is set to 10, then an edge is created between two terms if they co-occur within a window of 10 terms. This is done for every cluster in the co-citation network so that a semantic network is created for each cluster. For these semantic networks, centrality measures such as eigenvector-centrality can then be calculated to find the most central words for every cluster, thus resulting in a list of words representing the encoded topics. Since these clusters are dynamic, this is done for all time slices of length x in the period of interest.

An analysis of this kind confirms the dynamic evolution in the GRG case, identifying clusters outlining the development and transformation of research topics from the late 1950s through to the early 1960s similar to the transition into a phase characterised by small-world networks mentioned in section 2.2. Notably, a significant cluster concerning general relativity marks a focused return to the foundational problems of the field, followed by the emergence of clusters related to astrophysical and cosmological topics, thus indicating a transition in research interests to relativistic astrophysics and the study of black holes.[38] This substantiates what we have seen in the semiotic layer: After World War II, GRG research initially experienced a refocusing on fundamental questions (theoretical renaissance), followed by a transition to astrophysical questions (astrophysical turn).

Two different semantic networks were created in the Polish case study: one focused specifically on narratives related to petroleum and one visualising the different forms of expertise of the migrants and how these changed over time. The first highlighted the change in petroleum being perceived as a medical curiosity through its application in kerosene lamps and later as a fuel for combustion engines, thereby allowing Polish Galician entrepreneurs to trade petroleum on

37 Lalli et al., "Socio-Epistemic Networks", 47.

38 Lalli et al., "Socio-Epistemic Networks".

the international markets until it transitioned into a commodity of national importance in relation to the war effort. The latter example enabled observing the shifts in contributions made by Polish migrants globally during the century between 1830 and 1930, thus suggesting avenues for further research.

Other methods used to extract and relate semantic information from groups of texts to other groups of text on a large scale include topic modelling and/or text embedding[39] or other information-theoretical techniques.[40] Unlike utilising second-order networks built from structures of another layer, these methods directly employ the underlying texts to create interpretable groups or clusters. Embeddings, for example, convert text into multidimensional numerical vectors that can be treated algebraically; for instance, similarities between words, sentences, paragraphs, and documents can easily be calculated. These techniques open up a strategy for responding to a wide array of intriguing questions. How does the context of the term "graviton" evolve over time? Or, in the Polish case study, how do the Poles conceptualise and write about petroleum and its applications? How do discourses change over time? Which topics are gaining popularity, which are dwindling, and which individuals or texts are driving these developments? Which publications in the year 2000 use language similar to the mainstream of their discipline as it looked in the 1950s, or how do those in 1910 compare to those in 1850?

Coupled with an iterative structural analysis of the social and semiotic/material layer, addressing these sorts of questions aims to systematise research across all dimensions of knowledge, thus offering broader perspectives and uncovering otherwise undiscovered correlations.

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39 Maarten Grootendorst, "BERTopic: Neural topic modeling with a class-based TF-IDF procedure" (2022), http://arxiv.org/pdf/2203.05794v1; Adji B. Dieng, Francisco J. R. Ruiz, and David M. Blei, "Topic Modeling in Embedding Spaces," *Transactions of the Association for Computational Linguistics* 8 (2020), https://doi.org/10.1162/tacl_a_00325, https://aclanthology.org/2020.tacl-1.29/; Yuri Bizzoni et al., "Linguistic Variation and Change in 250 Years of English Scientific Writing: A Data-Driven Approach", *Frontiers in Artificial Intelligence* 3 (2020), https://doi.org/10.3389/frai.2020.00073, https://www.frontiersin.org/articles/10.3389/frai.2020.00073/full.

40 Stefania Degaetano-Ortlieb and Elke Teich, "Toward an Optimal Code for Communication: The Case of Scientific English", *Corpus Linguistics and Linguistic Theory* 18, no. 1 (2022), https://doi.org/10.1515/cllt-2018-0088, https://www.degruyter.com/document/doi/10.1515/cllt-2018-0088/html#j_cllt-2018-0088_ref_042.

3 Challenges, Limitations, and Rigour of Results

One of the greatest challenges linked to the broad implementation of the framework proposed in this chapter concerns the quality of the data available for analysis, from a complete lack of digitalisation to issues with digitised material, such as poor OCR or incorrect metadata. As a result, historians of knowledge interested in this method will need to invest significant time in data preparation tasks before they can embark on their analysis. While in many cases, the effort involved is worth the investment, as clean data can be used in many ways beyond just network analysis, scholars need to ask themselves if the knowledge they potentially gain justifies the effort involved in attaining it. A careful selection of methods and tools in the search for new knowledge is necessary. SENs may be one framework among many that scholars can use to better understand the evolution of knowledge rather than an ultimate means to an end. Before deriving conclusions from these networks, researchers should critically examine their hypothesis, data, and models. Indeed, as Albert-László Barabási and others write, "for any network, before attempting to model it, we need to understand the limitations of the data collection process and test their effect on the quantities of interest for us."[41]

When it comes to the case study on the Max Planck Society (see section 2.2), a critique of the result might be the missing historical interpretability of a community consisting of agglomerations of authors, publications, and words. While the rise and fall in the importance of one such community is hard to interpret, the structure of these changes may hint at where to direct traditional historical research. In this sense, as mentioned above, SENs do not constitute a method to an end but the combination of a certain perspective with certain methodologies in an iterative workflow between quantitative and qualitative analysis. Another criticism could be raised with regard to using publication time stamps to temporally order the publication material. It is well-known that the publication date is not the time of the creation of the semantic content, and a cut at each end of a calendar year when creating slices in the material is rather arbitrary (e.g., submission dates that are much earlier than publication dates). Statistics can mitigate data noise issues to some extent if the dataset used for the analysis is sufficiently large to identify relevant trends.

Other common challenges involve the biases encoded in source data and erroneous information on, for instance, authorship or time, as well as these resulting from the gaps and silences in the archival record. Furthermore, the need for elaborate

41 A. L. Barabási et al., "Evolution of the Social Network of Scientific Collaborations", *Physica A* 311, no. 3 (2002): 590–614, https://doi.org/10.1016/S0378-4371(02)00736-7.

tools or expertise to efficiently extract information, and the biases (often language-based) inherent in available tools and digital infrastructure are also challenging. These and similar challenges and limitations lead to a central question: how can a researcher quantify whether a historical analysis is rigorous?

Consider a scenario in which a researcher seeks to assess the impact of a particular variable on another. For example, they might want to learn how the historical number of oil wells in the region of Galicia (now Poland and Ukraine) affects its current air quality. Or they may want to measure the influence of Polish immigrants in Latin America on oil exploration across the continent. In other words, they want to test an existing hypothesis about the world. Hence, based on the relevant literature, they would need to construct a statistical test to address their specific questions. They would use the available data and methods to estimate whether oil wells lead to significantly worse air quality in Poland and Ukraine. But, after doing so, they would need to consider the robustness or reliability of the results from their test. Do the data and methods accurately represent the problem and theory in question? Could some other unaccounted third variable be impacting the results (e.g., the number of coal mines) and thus should be taken into consideration? If that is the case, they would need to perform the test again, this time including the third parameter. If so, what happens to the results? Does adding coal mines to the regression completely change it, or do the initial outputs still hold even after controlling for this aspect? Such an iterative process of refinement and modification is, in short, the core principle behind a robustness check.

With regard to the Polish case study, when conducting a social network analysis, one should ask whether the frequency of ties between Polish immigrants in a specific region is significantly greater than what would be expected by chance. To answer this question, a randomisation process, permutation analysis, or generative model could be applied. These are all tests commonly agreed upon and adopted throughout other research fields but not yet established in the fields of history of knowledge or history of science.

Researchers make inferences based on their assumptions about the world. Every mathematical model or statistical test is based on these assumptions – some explicitly, others not. Thus, researchers constantly need to remind themselves how changing these assumptions might influence the underlying results. This is the core logic behind robustness checks. For the emerging interdisciplinary research using digital sources in the history of knowledge, a coordinated toolkit of robustness checks that can be used to add greater confidence in the results thus far remains an urgent and much-needed desideratum.

4 Conclusion

This article illustrates the potential of SENs as a robust, interdisciplinary framework for examining the evolution of knowledge systems. By integrating social, semiotic/material, and semantic spheres, this framework takes into account the assumption that knowledge is inherently multidimensional. The computational aspects of this framework (i.e., multi-layered networks) underscore the necessity of addressing large-scale historical phenomena using a large-scale, structural approach. Knowledge systems can be represented as clearly defined (i.e., simplified), quantifiable/calculable, and reproducible structures, not only using networks but also other approaches of operationalisation, such as text embeddings. The principal argument is that knowledge is multidimensional and that large-scale developments require robust computational operationalisation to analyse structural changes. However, at this point in time, we believe that networks still represent the best way to accommodate this perspective, having reached a level of epistemic and methodological maturity enabling the realisation of these objectives. They capture the embeddedness and relationality of knowledge production and dissemination, while also offering tools to explore structural and temporal questions. As shown with the case studies presented, other computational methods such as topic modelling are necessary in order to complement the network approach. This further highlights the necessity of scrutinising the rigorousness of results by applying both digital source and tool criticism. The socio-epistemic networks framework then offers a structural approach to the evolution of knowledge systems that enables uncovering novel perspectives for the history of knowledge.

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