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**The Emergence of Epistemic
Communities in the *Sphaera* Corpus:
Mechanisms of Knowledge Evolution**

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Keywords

Early modern cosmology, epistemic communities, multiplex network analysis,
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Abstract

The present work investigates the process of emergence of new epistemic communities. The research is based on semantic, content-related data extracted from a corpus of 359 printed editions, mainly of textbooks used to teach cosmology at European universities between 1472 and 1650. Epistemic communities are identified as families of editions, grouped according to their content, that eventually came to shape knowledge within and by way of the European educational framework. First, a method of classifying the textual content of the books is introduced. Second, a directed, multiplex network is constructed in five layers whose structures are defined specifically for the research question at hand. Then the network is analyzed, first by making use of



the aggregated graph—which accounts for the connectivity between books when any of the potential semantic relations are indistinctly considered—and second by showing the contribution of each layer to the emergence of new families of editions. Finally, we interpret the results within a historical framework and identify an epistemic community that represents continuity with the medieval tradition, plus two new scientific and diverging communities that originated in the cultural context of the Reformed countries, which appear in the 1530s. The characteristics of the identified epistemic communities are further analyzed in order to draw general inferences concerning mechanisms of emergence of epistemic communities and their identification in corpora of historical sources. The work concludes by describing future research endeavors related to the corpus, also based on new series of data.

1 Introduction¹

The project *Sphaera: Knowledge System Evolution and the Shared Scientific Identity of Europe* (sphaera.mpiwg-berlin.mpg.de) aims to investigate how scientific knowledge evolved during the early modern period, how it transformed from natural philosophy to practice-oriented modern science, and how knowledge became homogeneous over time. The present work focuses on deepening our understanding of one specific aspect of such a process of knowledge evolution, namely the establishment of new epistemic communities that eventually shaped knowledge during the period covered by the corpus of historical sources selected for analysis.

The selection of historical sources is focused predominantly on university textbooks, mostly used in teaching at the faculties of liberal arts, namely in those educational institutions whose growing number and network dramatically shaped the shared scientific identity of the entire European

¹ **Acknowledgements:** The Sphaera project (headed by Matteo Valleriani) is supported by Department 1 of the Max Planck Institute for the History of Science and by the Berlin Center for Machine Learning (www.bzml.de) (01IS18037), funded by the Federal Ministry for Education and Research of Germany. This work was accomplished in collaboration with the research unit *Nonlinear Dynamics and Time Series Analysis* (headed by Holger Kantz) at the Max Planck Institute for the Physics of Complex Systems.
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continent. To further limit the field, only one of the ordinary disciplines that belong to the quadrivium is taken into consideration: astronomy. Within this field a further limitation has been applied through the choice of a specific treatise around which the corpus of sources was built: the *Tractatus de sphaera* by Johannes de Sacrobosco.

To achieve a consistent corpus of historical sources and, thereby, a corpus that allows for reliable and representative historical conclusions, only the printed editions that are related to Sacrobosco's *De sphaera* are investigated here; the manuscript tradition is ignored, as no census of these sources is extant. As the first printed edition of *De sphaera* is dated to 1472, and because the relevance of this work in the frame of university teaching rapidly declined around 1650, the entire project is limited to a timespan of around 180 years. Moreover, as will be shown in the next section, the investigation reaches forty-one cities located all over the European continent. In the frame of such a corpus, an epistemic community, therefore, is materially represented by a subgroup of editions and books that belong to the corpus. They are a community when, because of their scientific content and their circulation, they impacted and diversified the educational paths of astronomy and cosmology during the early modern period in Europe.

First, we describe the corpus of historical sources selected for analysis. Then, by introducing the concept of a "text part" and the process of the "atomization" of historical sources, we describe a method of extracting and organizing data to accomplish the semantic analysis of early modern textual sources, whose texts are usually not yet machine readable. In the next section, we use the data to build a five-layer network and furnish the data structure. At that point we analyze the temporal influence of each book as it emerges from the data structure and discuss how long we can assume print-events influenced successive events in the frame of the corpus. Analysis of the topology and structure of the network will then illustrate the emergence of epistemic communities and their characteristics. Finally, we interpret the results from a historical perspective. In the conclusions, we cite further data and announce plans for our future research.²

² For a justification of this kind of approach to writing history, see also Matteo Valleriani, "Maths is revolutionising the study of history – here's how," *The Conversation* <https://theconversation.com/maths-is-revolutionising-the-study-of-history-heres-how-85710> (2018).

2 The Corpus

The corpus is constituted of 359 different editions that contain the text of Sacrobosco, all printed between 1472 and 1650. The corpus is collected in a database—CorpusTracer—accessible through the project website³ The dataset is modeled according to the formal ontology CIDOC-CRM and the FRBRoo extension for bibliographic records.⁴ As mentioned above, the editions were produced in forty-one different cities on the European continent (Figure 1).⁵

The *Tractatus de sphaera* of Johannes de Sacrobosco is an introduction to geocentric cosmology written in the framework of the quadrivium for teaching at the University of Paris about halfway through the thirteenth century. It became a standard text for teaching all over Europe as the number of universities and their corresponding European network grew. Sacrobosco, the lecturer in Paris who wrote the tract, became (over the centuries) identified with this specific knowledge and for the style and design of exposition that he conceived for his book. The corpus here is pivoted around this text in order to investigate which other texts were connected to it and, finally, the dynamics of appearance and disappearance of these connected texts. A text is considered connected to the original text of Sacrobosco if it appears in the same printed book.⁶

³ <https://sphaera.mpiwg-berlin.mpg.de>. Through the database, each historical source is provided with a permanent PID number. When such historical sources are mentioned in the following, they are referred to only by the PIDs.

⁴ We used the Erlangen OWL implementation of CIDOC-CRM and FRBRoo to represent the data in RDF (<http://erlangen-crm.org>). For more information, see Florian Kräutli and Matteo Valleriani, "CorpusTracer: A CIDOC Database for Tracing Knowledge Networks," *Digital Scholarship in the Humanities* (2017).

⁵ One edition of a commentary on Sacrobosco's treatise moreover was published in what is now Mexico City. See, <http://hdl.handle.net/21.11103/sphaera.101292>.

⁶ Scholarly attention to the edition history around Sacrobosco's treatise has grown in recent years. For an overview of the literature as well as an introduction to the entire project, see Matteo Valleriani, "The Tracts on The Sphere. Knowledge Restructured over a Network," in *Structures of Practical Knowledge*, ed. Matteo Valleriani (Dordrecht: Springer, 2017), 421–73. For a critical edition of Sacrobosco's treatise, see Lynn Thorndike, *The Sphere of Sacrobosco and its Commentators* (Chicago: The University of Chicago Press, 1949). See also, Olaf Pedersen, "In Quest of Sacrobosco," *Journal for the History of Astronomy* 16, no. 3 (1985): 175–220; Corinna Ludwig, "Die Karriere eines Bestsellers. Untersuchungen zur Entstehung und Rezeption der Sphaera des Johannes de Sacrobosco," *Concilium medii aevi* 13 (2010): 153–85.

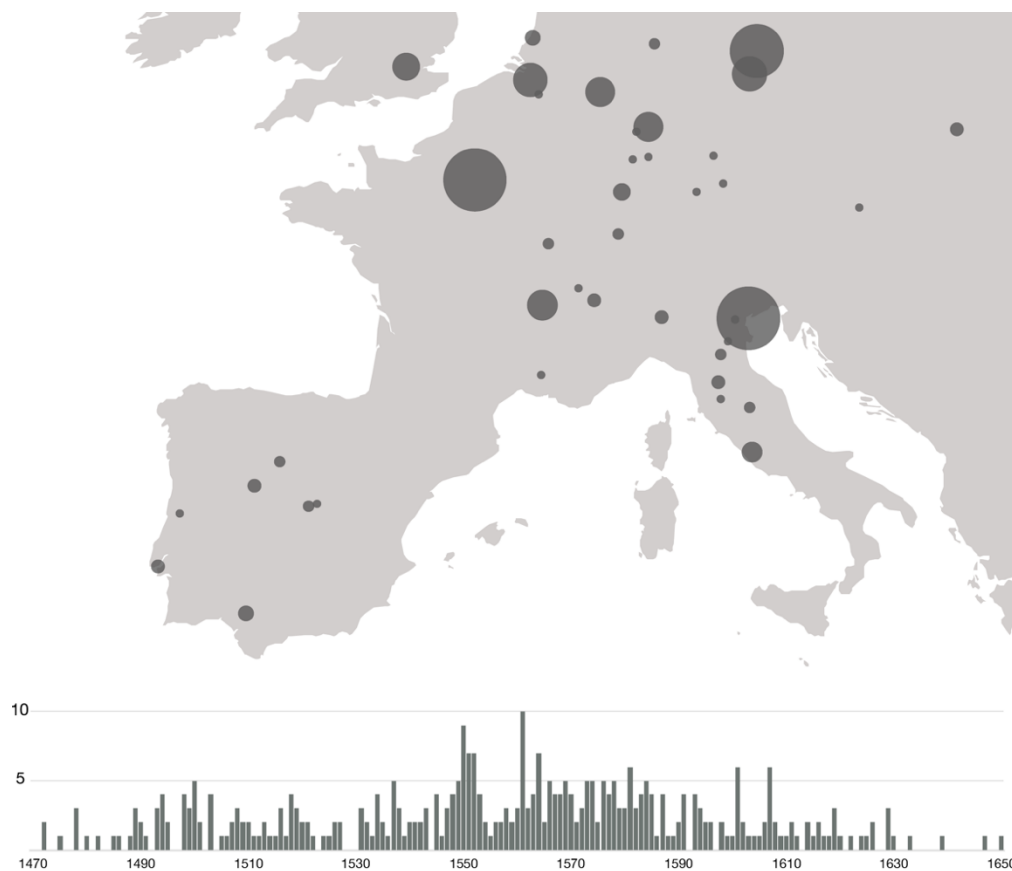


Figure 1. Geotemporal distribution of the production of the treatises belonging to the corpus considered here. The visualization is made by using Palladio at <http://hdlab.stanford.edu/palladio-app>.

The geographical distribution concerned with the production of these commentaries covers the entire continent, from Krakow to Lisbon and from London to Rome. Nevertheless, the production was not equally distributed: if only those centers of production are considered where at least ten different editions were printed, only nine cities remain (Figure 2). The two most relevant centers were Venice and Paris, both hubs of the transnational European market for printed books.⁷ Wittenberg, in the third position, is all the more relevant if

⁷ For a comprehensive overview of the economy of the printed book in the early modern period, see Angela Nuovo, *The Book Trade in the Italian Renaissance* (Leiden: Brill, 2013). For a more specific investigation concerned with the academic book market related to medicine, see Ian MacLean, *Learning and the Market Place: Essays in the History of the Early Modern Book* (Leiden: Brill, 2009).

one considers that it entered the academic book market as late as 1531, fifty-one years after the first printed edition of *De sphaera*. Antwerp deserves special mention too; its position at number five is due to production that, though it began in 1543, was prolific only between 1560 and 1585, when production of these editions was at its peak across the continent.

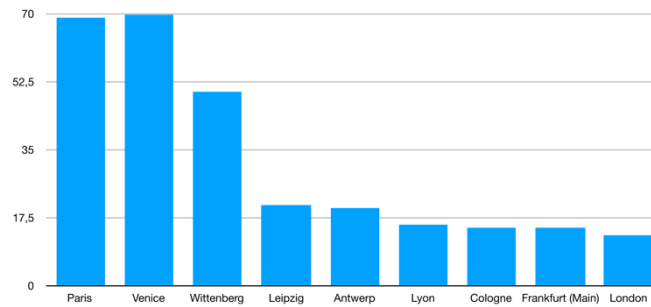


Figure 2. The top nine places where early modern printed commentaries on the *Sphaera* of Johannes de Sacrobosco were produced.

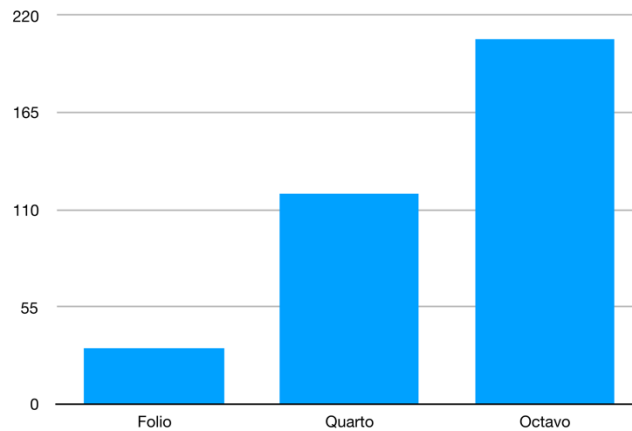


Figure 3. Book formats of the early modern printed commentaries on the *Sphaera* of Johannes de Sacrobosco.

The books of the corpus were mostly destined for the student market. This is reflected in the predominant formats of the editions (listed here in order of decreasing size and price): *folio*, *quarto*, and *octavo* (Figure 3).⁸ The *in-octavo* books dominate the material identity of the corpus. Moreover, the *folio* format was mostly produced only during the first fifty years of the history of *Sphaera* editions.⁹

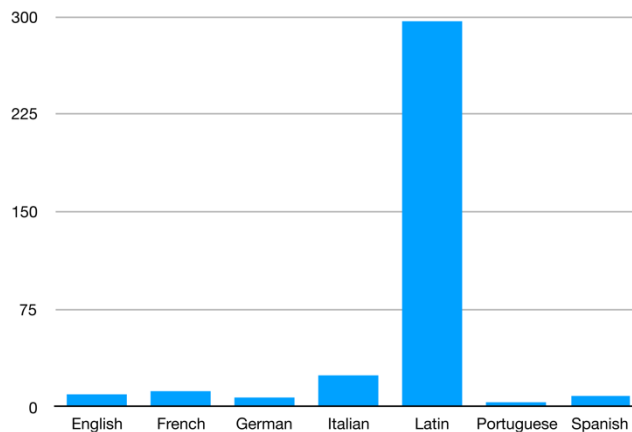


Figure 4. Languages in which the editions of the early modern printed commentaries on the *Sphaera* of Johannes de Sacrobosco were printed.

Finally, it is worth considering the languages of the corpus. The dominance of Latin over other languages is the clearest indicator of the function of these books in university teaching (Figure 4).¹⁰ This does not necessarily imply that treatises compiled in different languages—in many cases one-to-one translations of books published in Latin—were not used for teaching, but probably not at the universities.¹¹ Other kinds of educational

⁸ Two editions are in *sextodecimo* format.

⁹ For an extensive description of the corpus of the early modern commentaries on *De sphaera*, see Matteo Valleriani, "Prolegomena to the Study of Early Modern Commentators on Johannes de Sacrobosco's *Tractatus de sphaera*," in *De sphaera of Johannes de Sacrobosco in the Early Modern Period: The Authors of the Commentaries*, ed. Matteo Valleriani (Dordrecht: Springer Nature, In press).

¹⁰ Richard J. Oosterhoff, "A Book, a Pen, and the «Sphere:» Reading Sacrobosco in the Renaissance," *History of Universities* 28, no. 2 (2015): 1–54.

¹¹ Kathleen M. Crowther et al., "The Book Everybody Read: Vernacular Translations of Sacrobosco's *Sphere* in the Sixteenth Century," *Journal for the History of Astronomy* 46, no. 1 (2015): 4–28.

institutions (in Portugal, for instance) used both manuscripts and printed books that were not written in Latin, as Henrique Leitão has shown.¹² It is interesting to note that, in spite of the fact that the majority of editions produced in local languages and dialects were in Italian, the first Italian edition did not appear on the market before 1537, at which point editions had already been produced in Portuguese (first edition: 1509), German (first edition: 1516), and French (first edition: between 1525 and 1529) with a printed version of the medieval commentary of Nicole Oresme.

3 The Semantic Analysis of the Textual Element of the Corpus

To investigate a long-term knowledge transformation process on the basis of a collection of 359 historical sources, it is necessary to identify elements—atoms of knowledge—that unequivocally characterize the knowledge represented by each historical source, in turn represented by a material object: the book. At the same time, such atoms have to allow for a comparison between the knowledge of different contemporary sources if we are to detect the dynamics of transformation. To identify such atoms, we first distinguished among different “representations” of knowledge in historical sources such as books: texts, illustrations, and tables. In what follows we will consider only the textual element.¹³

By means of electronic copies of all sources, the texts were carefully atomized into “text parts.” A text part is a textual passage that cannot be formally smaller than a paragraph and covers a well-defined subject with completeness. A text part in the corpus of Sacrobosco’s *De sphaera*, for instance, might be the *Theoricae novae planetarum* of Georg von Peurbach,¹⁴ as this text began being printed together with the *Sphaera* as early as 1482 and had been reprinted together with the *Sphaera* seventeen times by 1537. If literary compositions—ordinarily printed in scientific books beginning in the sixteenth century—are considered, a text part can be much more modest in length. A

¹² Henrique Leitão, ed. *Sphaera Mundi: A Ciência na Aula de Esfera. Manuscritos científicos do Colégio de Santo Antão nas coleções da BNP* (Lisboa: Biblioteca Nacional de Portugal, 2008); “Um Mundo Novo e uma Nova Ciência,” in *360° · Ciência Descoberta, Catálogo da Exposição*, ed. Henrique Leitão (Lisboa: Fundação Calouste Gulbenkian, 2013), 16–39.

¹³ The ongoing investigation concerned with the scientific illustrations and tables extracted from the corpus, as well as the intended future use of these data, are briefly discussed in the last section of the present work.

¹⁴ For Georg von Peurbach’s role in the frame of the corpus of *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.100965>.

representative example might be the short *carmen* written by Donato Villalta and dedicated to the scholar Pierio Valeriano,¹⁵ printed for the first time in 1537¹⁶ and then reprinted another thirty-two times. Another example of text part—which can be seen as both a literary composition and a scientific contribution—is the famous letter to Simon Grynaeus, written by Philipp Melanchthon¹⁷ in defense of astrology as a teaching subject in the Reformed countries. The letter was printed, together with Sacrobosco’s text, for the first time in 1531¹⁸ and then another sixty-four times.

Atoms of knowledge such as text parts are useful not only to identify a source but also to compare among one another, because such atoms re-occur systematically. Only the re-occurrence of such atoms is considered here: we represent such re-occurrences in the form of a network and then we analyze it. By considering only re-occurring parts, the total number of books analyzed during the last three years in this study is 350 and their publication period ranges from 1472 to 1647 (175 years).

In the following, we first introduce the taxonomy of text parts specifically conceived to investigate the corpus, which allows us to analyze each single source.

¹⁵ For Pierio Valeriano’s role in the frame of the corpus of *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.100963>.

¹⁶ Donato Villalta’s *carmen* was printed for the first time in <http://hdl.handle.net/21.11103/sphaera.101194>.

¹⁷ For Philipp Melanchthon’s role in the frame of the corpus *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.101002>.

¹⁸ Philipp Melanchthon’s letter to Grynaeus was printed for the first time in <http://hdl.handle.net/21.11103/sphaera.100138>.

3.1 The Taxonomy of the Parts and the Methods of Scientific Production

We distinguish between two different types of text parts, “original part” and “adaption,” where “adaption” is further distinguished into “annotation” and “translation.”¹⁹

Original part

Original parts can be both paratexts and content-related texts. In both cases they played the role of reference text, though in different ways.

As content-related text parts, namely as scientific texts, they were rarely updated or significantly changed. Their role as reference texts becomes evident either through the fact that printers were publishing them in uncommented form or together with commentaries written on the same original fundamental text. This second option includes the usual early modern commentary-like book in which the original text and the commentary are printed on the same page but kept clearly distinct through the layout. Many such texts were produced a long time before the date of publication of the books—for instance, the treatise of Sacrobosco itself is an original text part written in the thirteenth century. This means that, in spite of the age of the text, it was still considered a legitimate scientific contribution. Because of this characteristic, original parts are interpreted as the scientific milestones in the time period under investigation.

Paratexts are a type of text whose presence in printed books became common over the course of the sixteenth century. They were therefore always contemporary creations. A paratext could serve as a scientific introduction or a social or institutional contextualization—a role for instance played by a dedication to a patron. In the first case, no difference between content-related texts and paratexts emerges. In the second case, they are considered reference texts because they indicate the level of prestige of an entire edition. As will be shown in what follows, however, this particular kind of original part played a marginal role in the knowledge transformation process, as most of these text parts did not experience any diffusion.

¹⁹ The textual analysis made use of the category “fragment,” too. In particular, we identified fragments of adaptations and translations of fragments. These data are however not used in the present work.

Adaption

Text parts classified as adaptations may be translations or what is usually known as a scientific commentary. “Adaption” is an inclusive category needed to capture different kinds of connections among books (see below, layers se14, se15, and se16) in reference to both commentary parts (Category: “Annotation” below) and translated parts (Category: “Translation” below).

Annotation

Text parts classified as “Annotations” are commentary texts. They have to be seen as dependent on an original part and as expressing the authority of that part. Commentary was the ordinary means of keeping a scientific debate alive during the early modern period. Because of the tendency to “carry” the original part unchanged, commentaries are texts that could easily convey innovations in science—innovations whose scientific credibility was based, among other things, on the fact that they were expressed in conjunction with an old and authoritative text. Nevertheless, commentaries themselves could rise to the status of “standards” almost as authoritative as those original parts. It is not rare, for instance, to find late medieval commentaries on the *Sphaera* of Sacrobosco, such as Pierre d’Ailly’s,²⁰ re-published many times among the early modern editions. Moreover, such standard commentaries sometimes became the object of second-order commentaries, an aspect that we capture in layer se17 as expressed in the next section.

Translation

Text parts classified as “Translations” are translations of any part from one language to another. Due to historical realities, most of the texts of origin are in Latin and, correspondingly, most of the translations were adapted from Latin into the other languages present in the corpus.

As this taxonomy clearly shows, the historical sources constituting the corpus are analyzed by the methods of production of scientific knowledge rather than by the content of the single parts or their association with specific scientific fields, such as mathematical astronomy, astrology, or medicine.²¹

²⁰ For Pierre d’Ailly’s role in the frame of the corpus of *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.100741>.

²¹ We consider the methods of production of scientific knowledge to be fundamental in recognizing the processes of emergence of epistemic communities, as the results of this work clearly show. Further content-related taxonomies will be added in the future in order to be able to interpret these results from the perspective of the transformation of scientific knowledge.

In the next section we set up the multiplex network on the basis of the data describing the re-occurrence of text parts.

4 The Network and its Layers

The text-part analysis applied to the editions of the corpus results in the identification of a total of 563 text parts. Their identification is based on the principle of first appearance along the chronological line. These text parts are subdivided into 444 original parts and 119 (part) adaptations. As our goal is to build a longitudinal network, from this point on we consider only those text parts that were reprinted and re-published at least once, at least one year after the first appearance. By applying these criteria, 239 text parts remain, meaning that 324 text parts were published either only once or more than once but in the same year. Focusing on the remaining 239 text parts, their total number of re-occurrences (in the total timespan of 175 years considered here) is 1,653.²²

A further consideration should be made here concerning the paratexts. These constitute 251 text parts of the original 444. Their total number of re-occurrences is 623. Nevertheless, most of these re-occurrences take place in the context of the so-called re-issuances of printed books. A re-issuance is when the same publisher or printer re-published (re-issued into the market) exactly the same book several times in several different years. In these cases, the books were printed all at once and put on the market in different successive years by producing only a new title page with a different year of publication on it. The role of re-issuances in the general context of circulation of knowledge is a recognized subject, but this aspect cannot be taken into consideration here because of lack of data.²³ However, if we consider only the paratexts that were

²² In the corpus we found 28 text parts that we were unable to identify in terms of authorship. This amounts to only ca. 5% of all 563 text parts. These anonymous parts are assigned to the author handle “Anonymous,” each disambiguated by the year in which the respective part assigned to this specific “Anonymous” appeared for the first time within our corpus. This leads to twenty-three authors with handles like “Anonymous_1488” or “Anonymous_1508.” In three cases it seems highly probable that one “Anonymous” authored more than one part; when two parts seem to depend on and are followed by each other in the book(s), these parts (eight in total) have been assigned to only one “Anonymous,” as in the example of “Anonymous_1564.” In three cases, however, different anonymous text parts (eight in total) may have appeared in the same year(s) (1488, 1538, and 1543) for the first time in our corpus but are very likely not the product of one single author. In these cases, they have been distinguished by adding “a” and “b” to their handle (e.g., “Anonymous_1488a” and “Anonymous_1488b”).

²³ To detect re-issuances, it is necessary to first extract the fingerprints of the books. Fingerprints are codes extracted through a standard system from the material books as

republished by different publishers and/or printers—in which case those text parts undoubtedly geographically and temporally moved along the network—then their number amounts to only thirty-five text parts; nineteen of them are dedication letters like Melanchton's letter to Grynaeus, three are *proemia* and therefore also on the edge between literary and scientific compositions, and a total of twelve are pure literary compositions (three *carmina*, four epigrams, one *hexastichon*, and four sonnets). The number of publishers and/or printers involved in the circulation of pure literary paratexts is nineteen, while their total number in the corpus is 206. In addition, about 85% of the cases when a literary paratext circulated happened during the twenty years between 1530 and 1550—a very small window compared to the entire interval considered here. All these figures imply that in the following argument, the role of genuinely literary paratexts is marginal.²⁴

4.1 The Semantic and the Structure of the Layers

As our goal is to understand the emergence of epistemic communities, we conceived a graphic connectivity structure that enables us to relate such new epistemic communities to specific forms of production of scientific knowledge. In particular, we want to know whether new epistemic communities were established because of the historical realization of one or more of the following options, each concerned with the production of new historical sources and related to the appearance of new text parts: a) production and publication of new original texts, b) publication of old texts that were however either new to the corpus or to the general scientific context of the period, c) production and publication of new commentaries, d) production and publication of new translations, e) publication of new combinations of text parts. With this dataset at hand, we built a longitudinal network constituted of five layers. Each graph is defined on the basis of one specific kind of relationship, where all relationships involve 239 text parts and their total 1,653 re-occurrences. The structure of the layers therefore is as follows:

Layer *se13* - Same Original Part: Two books are in relation to each other if they contain exactly the same original part, for instance the same dedication letter or the same treatise in the same language and by the same author.

preserved nowadays in libraries and archives. Fingerprints are expressions of the printing procedure. The extraction of fingerprints from the sources of the *Sphaera* corpus is ongoing.

²⁴ The identification of the paratexts in the corpus was executed by Irina Tautschnig in the institutional collaboration between the *Sphaera* Project and the Project NOSCEMUS - *Nova scientia*. Early Modern Scientific Literature and Latin (<https://www.uibk.ac.at/projects/noscemus>).

Layer se14 - Same Adaption: Two books are in relation to each other if they contain exactly the same part and this text part is an adaption, for instance a commentary on the *Tractatus* of Sacrobosco. For instance, the two books <http://hdl.handle.net/21.11103/sphaera.101112> and <http://hdl.handle.net/21.11103/sphaera.101056> are in relation to each other because they both contain Élie Vinet's²⁵ commentary on the *Sphere* of Sacrobosco.

Layer se15 - Translated Same Original Part: Two books are related to each other when they both contain a translation of the same original part. The translations do not have to be into the same language.

Layer se16 - Annotated Same Original Part: Two books are related to each other if they both contain commentaries that are not the same but are on the same original part, as for instance the commentary of Francesco Capuano, published in the source book <http://hdl.handle.net/21.11103/sphaera.100047>, and the commentary of Francesco Giuntini, published in the target book <http://hdl.handle.net/21.11103/sphaera.101101>; both commentaries are written on the same original part, namely the *Theorica novae planetarum* of Peurbach.

Layer se17 - Annotated Same Adaption: Two books are related to each other if they both contain commentaries that are not the same but are on the same "adaption," which is in turn a commentary on or a translation of an original text part. For instance, the source book <http://hdl.handle.net/21.11103/sphaera.101114> is related to the target book <http://hdl.handle.net/21.11103/sphaera.100656> because they respectively contain Francesco Giuntini's commentary and Alberto Hero's commentary on Élie Vinet's adaption of Sacrobosco's *Sphaera*, the latter being an original part.²⁶

The nodes in each layer are a subset of the printed books (Figure 5).²⁷ These are connected to each other according to the relations defined above. The relations among books are as numerous as their parts allow. This means that if two books have more than one related part, then we assume that there are as

²⁵ For Élie Vinet's role in the frame of the corpus of *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.100903>.

²⁶ If two parts that are the same "Annotation on a Part Adaption" are present in two editions, then the corresponding relation between the two editions is listed in layer se14, as it falls under the category "same adaption."

²⁷ The decision to use books as nodes of the graphs is justified by the fact that this will allow us to correlate these graphs with other graphs expressing relations of social and material nature by means of metadata extracted from the books and through the analysis of the books as material objects. See also the last section below.

many links between these two nodes as there are part-based relations. The drawback of this way of representing links lies in the fact that, if we wanted to describe the links by an adjacency matrix, we should do this on the level of parts and not of books. However, we never explicitly use the parts adjacency matrix or a weighted version of the adjacency matrix of books and thus avoid this complication.

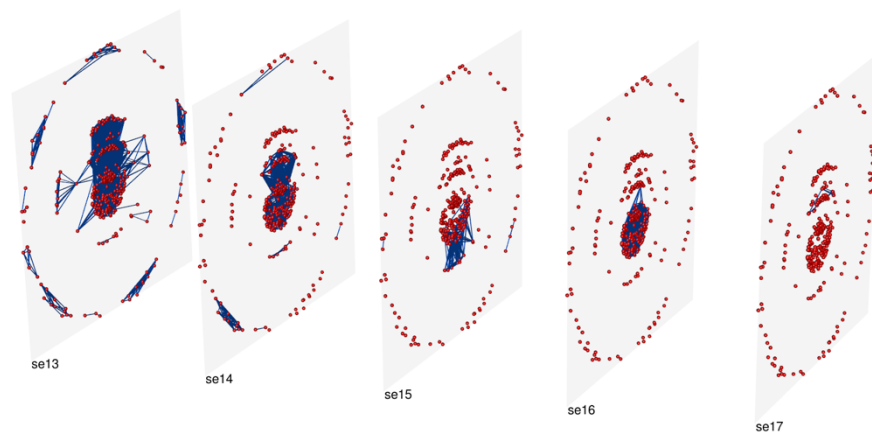


Figure 5. Visualization of the multi-layer network by means of muxViz (muxviz.net).

The network we consider is a multiplex network: its nodes are connected in different layers that describe various types of edges, but cross-links between layers are not considered. A multiplex network is hence a special case of multi-layer network.²⁸ This allows us a) to keep and handle relations between books

²⁸ For an introduction to multi-layer networks as well as a formal definition of the aggregated graph, see Mikko Kivelä et al., "Multilayer networks," *Journal of Complex Networks* 2, no. 3 (2014): 203–71; G. Bianconi, *Multilayer Networks: Structure and Function* (Oxford: Oxford University Press, 2018); Alberto Aleta and Yamir Moreno, "Multilayer networks in a nutshell," *Annual Review of Condensed Matter Physics* 10 (2019): 45–62. For an introduction to multiplex networks, see E. Cozzo et al., *Multiplex Networks: Basic Formalism and Structural Properties*, Springerbriefs in Complexity (Cham: Springer Nature, 2018). For the utility of the application of a multi-layer-network approach to historical studies, see Charles van den Heuvel, "Mapping Knowledge Exchange in Early Modern Europe Intellectual and Technological Geographies and Network Representations," *International Journal of Humanities and Arts Computing* 9, no. 1 (2015): 95–114. For an illuminating example on how a dataset extracted from historical sources can be systematized in terms of multi-layer networks, see Ingeborg van Vugt, "Using Multi-Layered Networks to Disclose Books in the

according to their parts differently in the different layers of the model, and b) to avoid assigning weights in advance as the number of links between pairs of books is instead considered.²⁹

5 How Knowledge is Produced over Time

As described in section 4, the different types of semantic relationships yield different connectivity structures, which can be represented as distinct graphs. Each of these five graphs consists of a set of nodes (representing a subset of books from the corpus), links (depicting pairs of books sharing at least a part relevant to the examined semantic relation), and weights attached to those links (representing the number of parts shared between each pair of connected books).³⁰ It is important to note that these graphs are directed, with directionality imposed by the chronological ordering of book publication. Thus, links are always directed from older (source) to newer (target) books. The analysis also includes the so-called aggregated graph (single layer), which accounts for the connectivity between books when any of the potential semantic relations are indistinctly considered. Therefore, the aggregated graph includes all the semantic pairwise relations between books in the corpus. As a reference we include some basic descriptors (number of nodes, number of links, and total weight) of the different graphs mentioned (Table 1).

Because of the long period of time between the first and last publications of the corpus, we first approach the interesting question of the temporal length of the influence of an event of the past (such as the production of a book) on successive events. In this respect, we first assess the distribution of link ages, L_{age} , within each of the different graphs. L_{age} is simply computed as the difference between the year of publication of the target and source books connected by a link. In Figure 6 we present the distribution of L_{age} for the

Republic of Letters," *Journal of Historical Network Research* 1 (2017): 25–51. See also *The Structure and Dynamics of Scholarly Networks Between the Dutch Republic and the Grand Duchy of Tuscany in the 17th Century (PhD Thesis)* (Amsterdam: Amsterdam School of Historical Studies, University of Amsterdam, 2019).

²⁹ The creation of links between books is based on SPARQL queries to the *Sphaera* database. A resulting edge CSV file and the metadata for all books are published in <https://doi.org/10.20375/0000-000c-1f68-e>. Based on the link information, the post-processing of the network of layers is detailed in two Jupyter Notebooks, accessible at <https://gitlab.gwdg.de/MPIWG/Department-I/sphaera/sphaera-semantic-data>. A link to an interactive view of the Notebooks is provided to allow a reproduction of the post-processing steps.

³⁰ We refer the reader to S. Boccaletti et al., "Complex Networks: Structure and Dynamics," *Physics Report* 424, no. 4–5 (2006): 175–308; Mark Newman, *Networks: An Introduction* (Oxford: Oxford University Press, 2010).

graphs corresponding to each of the semantic layers and for the aggregated graph. We also summarize some relevant descriptors for L_{age} in Table 2.

Layer	Nodes	Links	Weights
se13 (same original)	321	5681	13401
se14 (same adaption)	199	2173	3163
se15 (same original translated)	43	341	342
se16 (annotated same original)	183	15326	20874
Se17 (annotated same Adaption)	8	15	15
Aggregated graph	350	20293	37795

Table 1. Number of nodes, links, and total weight in each layer and in the aggregated network.

We observe that the vast majority of links are under ninety years old, which can be explained due to the higher production of books in the central part of the time period 1530–1580 (e.g., a book published exactly in the middle of the time period can be at most the source or target of a link with $L_{age}=88$ years). In fact, we compare the percentage of links with ages greater than ninety years in the aggregated graph to a reference scenario in which every book is connected to all other books published afterwards (e.g., from the perspective of the semantic relation se13, this reference scenario corresponds to a corpus where all books share at least one original part). The connectivity structure between books in this reference scenario translates into a fully connected directed graph, given the chronological ordering constraint. Note that the connectivity structure of the reference graph is only a function of the publication timing of the various books in the corpus, and therefore its structure encodes the variable production rates reported and shown in Figure 1. Indeed, by analyzing this reference scenario, we find that only 9.15% of the links have an age greater than ninety years. We want to note that the percentages shown in Table 2 for the reference scenario do not constitute a higher bound in terms of percentage, but they serve to give some intuition about how production rates affect L_{age} .

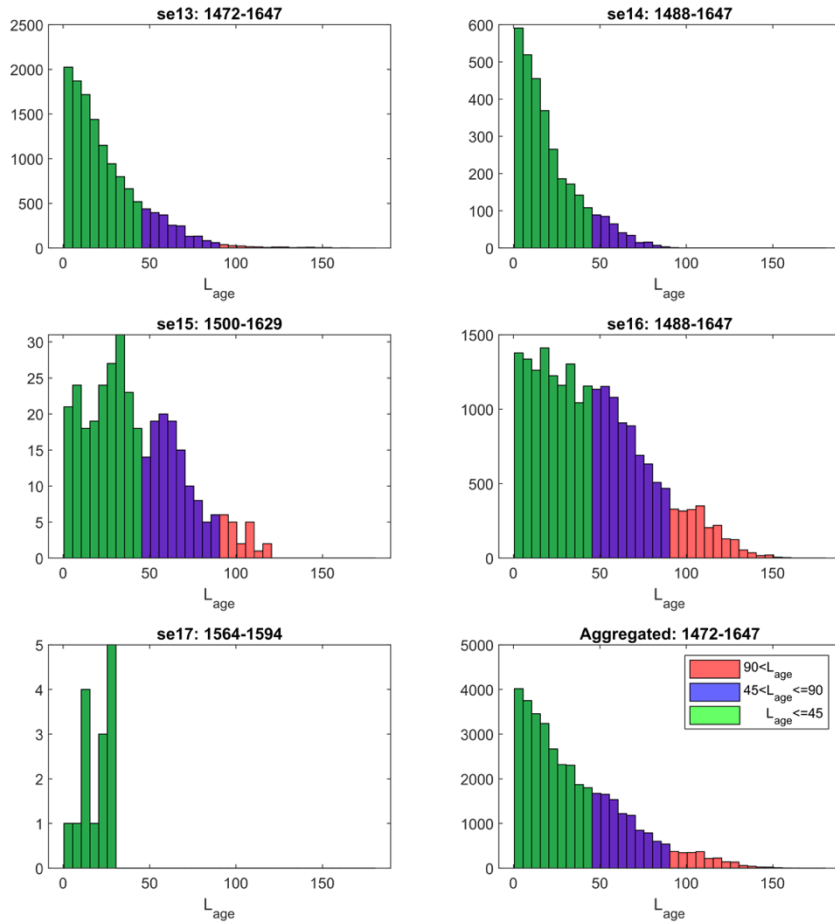


Figure 6. Histograms of link ages for each layer and for the aggregated graph.

We further observe that the two graphs that show a relatively older population of links are the graphs corresponding to layer se15 (same original translated) and se16 (annotated same original), an aspect that will be discussed in section 5.2.

Layer	Period	L_{age}	$\sigma(L_{age})$	$L_{age} \leq 45$	$45 < L_{age} \leq 90$	$90 < L_{age}$
se13	1472–1647	25.56	21.99	83 %	15.75 %	1.25 %
se14	1488–1647	20.89	14.47	88.75 %	11.22 %	0.03 %
se15	1500–1629	41.99	27.03	59.94 %	33.92 %	6.14 %
se16	1488–1647	46.05	31.48	54.01 %	35.75 %	10.24 %
se17	1564–1594	19.80	8.59	100 %	0 %	0 %
Aggr.	1472–1647	36.63	29.40	67.27 %	26.57 %	6.16 %
Reference	1472–1647	43.19	31.50	58.88 %	31.97 %	9.15 %

Table 2. Link Age statistics.

Given the reasonable values of L_{age} shown in Table 2, and to avoid arbitrary thresholds, we include all the links extracted from the analysis of the parts as explained in section 4. We further argue that this approach is the most suitable to study the structure of knowledge underlying the corpus.

5.1 Emergence of Edition Families and Influential Editions within the Corpus

In the following, we describe a method for investigating whether different epistemic communities can be identified in the corpus along its timeline and what their characteristics are. An epistemic community is identified by a family of editions.

We first assess the number of connected components in the aggregated graph. For undirected networks, a connected component is a set of nodes, so that a path (sequence of links) between any pair of those nodes exists. For directed networks, as the matter at hand, the so-called weakly connected components can be equivalently defined by ignoring the directionality of the links. The interpretation of the internal network structure of weakly connected components is not straightforward in our case, since the temporal ordering of books is a crucial property. However, the emergence of different connected components is particularly relevant in the analysis of the aggregated graph, when interpreted in terms of books belonging to different components. Thus, if any given pair of books are known to belong to two different components, we can immediately infer that those two books do not share any semantic relation (from those included in section 4.1). Our analysis reveals the emergence of 14 connected components (Figure 7), although the network is clearly dominated

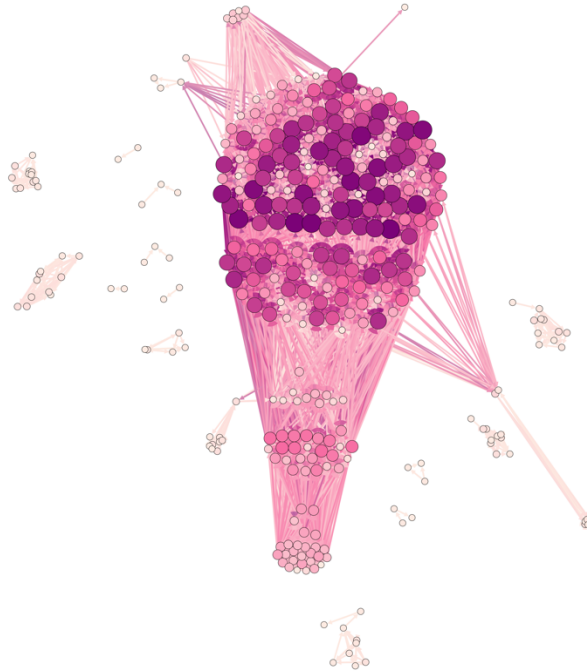


Figure 7. Network's components. The network is constituted of one large component and thirteen small ones.

by the largest component, which includes 274 out of the 350 books (compared with the twelve books forming the next component in terms of size). Due to this fact, the analysis distinguishes between the books that belong to the largest connected component versus those which belong to any of the other components.

Next, we assess the influence of the different books in the corpus. One of the simplest and most intuitive metrics to quantify the influence of a given book within the corpus is the percentage of books published afterwards to which that given book connects. From the network perspective, this is equivalent to what we define as the normalized node out-degree. The out-degree of a node in a directed graph is simply defined as the number of links departing from that node (i.e., book pairwise relations in which the given book is the source). We show the computed book out-degree as a function of the book publication year for the aggregated network (black circles represent

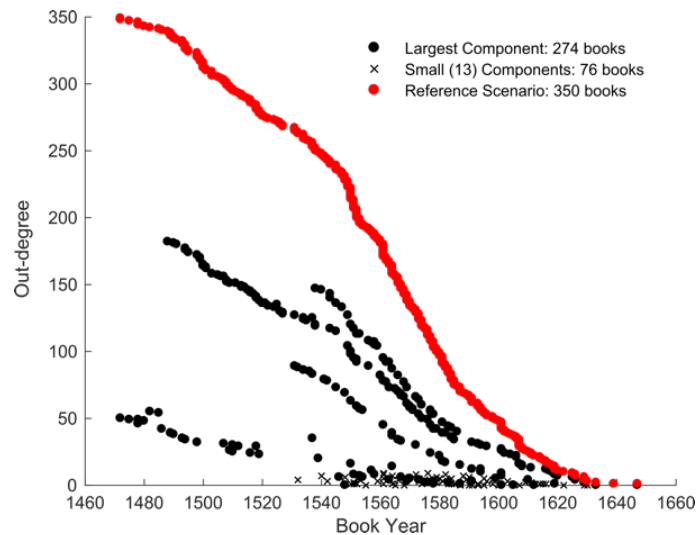


Figure 8. Book out-degree as a function of publication time for the aggregated graph (black) and the reference scenario (red).

books in the largest connected components and black crosses are used for books belonging to any other connected component)³¹ in Figure 8.

We also display in the same figure the values of book out-degree for the above-mentioned reference scenario (red) (i.e., each book is connected to every book published thereafter), which corresponds to the end-member connectivity structure where all the books are as influential as they can potentially be, given their time of publication.

The first obvious point that becomes apparent from Figure 8 is that the book out-degree as an absolute number (e.g., the total number of books to which a given book connects) is not a good metric for book influence, since it is by definition a decreasing function of time due to the chronological ordering of book publication (i.e., a link cannot be established from a book published at a given time to a book published earlier). Therefore, we define the normalized book out-degree as the ratio of the number of links departing from a node to the number of nodes corresponding to books published afterwards (it

³¹ Editions that belong to other components are considered in the following for the normalization procedure. Below in this section, we show the reason why these seventy-six editions do not enter the scheme described in section 4 and, in the last sections, we discuss how they can be integrated in future analysis and interpretation and what their historical meaning might be.

corresponds graphically to the point-wise ratio of black and red points in Figure 8).

The normalized book out-degree as a function of time of publication is shown in a different plot (Figure 9), revealing the emergence of four time periods characterized by the presence of a specific number of families of editions:

1) The early period (approx. 1472–1488): The first editions that appear in the record are characterized by a relatively low value of normalized book out-degree, meaning that their content was reproduced or adapted by a small percentage of books published afterwards (~15%).

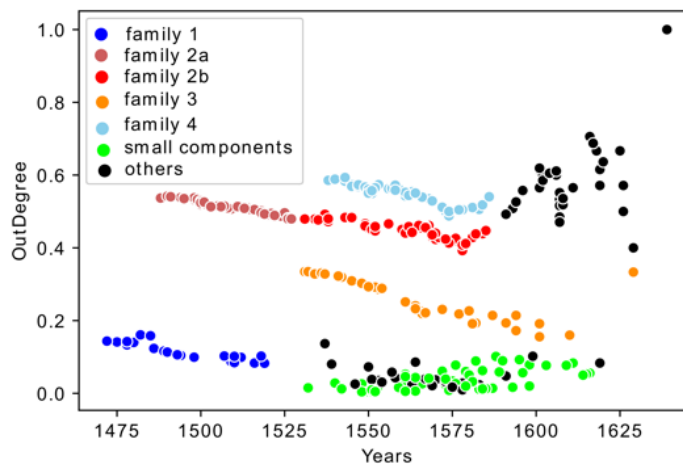


Figure 9. Normalized book out-degree as a function of publication time for the aggregated graph.

2) The second period (approx. 1488–1531): A new edition was published in 1488,³² which is significantly more influential than the previous editions, as shown by the increase in the normalized book out-degree from 15% to 55%. After this publication two families of books (branches) are distinctly depicted: (i) Family 1: a first family of books that mostly follows the content in the books published in the early period as indicated by the lower branch with normalized book out-degree values around 15–10% (similar to those for the books in the early period); (ii) Family 2a: a second family of books whose content is related to the book published in 1488 as inferred from a similar

³² This 1488 edition is <http://hdl.handle.net/21.11103/sphaera.100822>.

values (branch) of the normalized book out-degree in the range of 55–48%. Note that this family became clearly dominant, that is, most of the books published in this period are associated with this family (as shown by a higher density of points in this branch). The appearance of a dominant branch can be interpreted as the emergence of a period characterized by knowledge convergence, namely an epistemic community.

3) The divergence period (approx. 1531–1600): Several new editions with significant changes appeared during this period, resulting in the divergence of content in the corpus as shown by the emergence of several competing families of editions, shown as branches in Figure 9. We highlight the coexistence of four families during this period: (i) Family 2b: there exists a family of books that continues the dominant tradition in the previous period, as shown by the branch of points that continues the trend previously existing in Family 2a with values of the normalized book out-degree in the range of 48–40%; (ii) Family 3: a new edition was published in 1531,³³ which introduced changes that reduced the normalized book out-degree from 48% to 34%. These changes, though not very popular in the bigger picture (as shown by the above-mentioned reduction in the normalized out-degree), were reproduced in several subsequent editions, as shown by the emergence of the branch of points in the normalized book out-degree range of 34–18%. (iii) Family 4: a new edition was published in 1538.³⁴ The changes adopted in this new book increased the normalized out-degree from 48% to 59%. The emergence of a branch of points which exhibits similar values of normalized book out-degree suggests that those books form a family of books with similar content; (iv) Family 5: there is a large set of books that were published after 1532, which have relatively low value of normalized book out-degree (below 10%). Family 5 does not exhibit a clear branch structure when all its books are considered. However, when we distinguish between books belonging to the largest connected component (circles) and those belonging to different (small) components, a clearer pattern emerges. The subset of books in Family 5 within the largest connected component form a branch structure, which shows a trend compatible with that exhibited by books in Family 1 (second period). On the other hand, the books that belong to Family 5 and that are part of the smaller components show more heterogenous, although always small, values of normalized book out-degree. These low values are expected due to the reduced size of each of the connected components. The internal variability of the out-degree within the family can be attributed to their heterogeneity in terms of the semantic content, indicating that these books, although catalogued in the same family, are actually quite

³³ This 1531 edition is <http://hdl.handle.net/21.11103/sphaera.100138>.

³⁴ This 1538 edition is <http://hdl.handle.net/21.11103/sphaera.101106>.

different from one another, their main commonality being their relatively low influence on future books (low normalized book out-degree).

4) Final period (1600–1647): The significant decrease in the rate of book production in this period, together with finite effects, make this period difficult to interpret.

In order to better contextualize the results obtained from the analysis of the normalized book out-degree, we present a series of plots (Figs. 10, 11, 12) that show the normalized book out-degree as a function of time of publication, where the points are colored according to the normalized book in-degree (defined for each book as the percentage of books published beforehand that connect to that given book) (Figure 10), city of publication (Figure 11), and book format (Figure 12). Several interesting remarks can be made from this analysis:

1) The early period (approx. 1472–1488): Most of the books in this period were published in Venice and all of them were in quarto format.

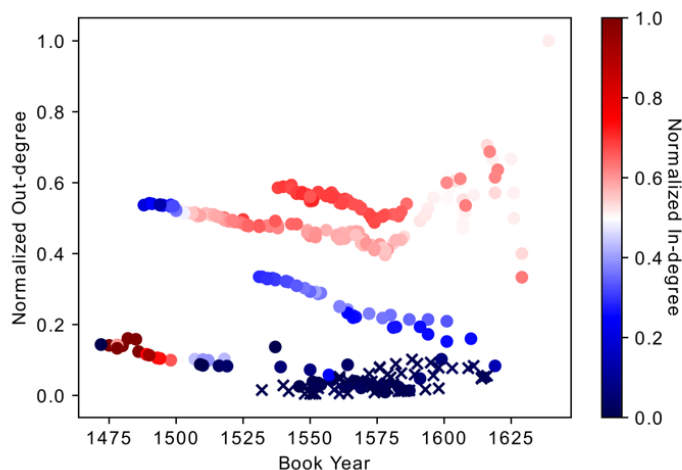


Figure 10. Normalized book out-degree as a function of book publication year. The points are colored according to the normalized book in-degree. Circles identify editions that belong to the biggest connected component and cross symbols represent books in the small components.

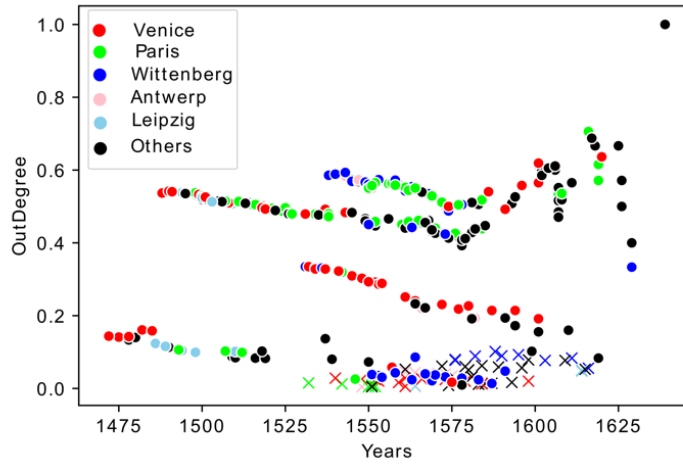


Figure 11. Normalized book out-degree as a function of book publication place. The points are colored according to the city where each book was printed. Circles identify editions that belong to the biggest connected component and cross symbols represent books in the small components.

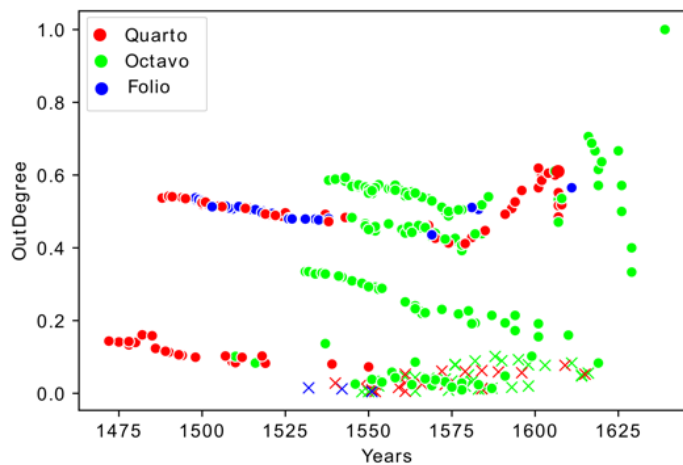


Figure 12. Normalized book out-degree as a function of book publication year. The points are colored according to the book format. Circles identify editions that belong to the biggest connected component and cross symbols represent books in the small components.

2) The second period (approx. 1488–1531): (i) Family 1 is also mostly characterized by *quarto* format. (ii) Family 2: The first editions that triggered this new branch were published in Venice in *quarto* format. These early

editions within Family 2 are also characterized by a low value of normalized book in-degree (i.e., a low amount of information/parts shared with previous books), which supports the argument that a significant amount of new information was included in these editions. Interestingly, the books belonging to this family were published in different locations, but a clear predominance is shown by Paris, where another format, the *folio*, can also be found.

3) The divergence period (approx. 1531–1600): The first striking observation is that the divergence period coincides with the massive adoption of the *octavo* format. We highlight that both Family 3 and Family 4 were triggered by two distinct new editions, both published in Wittenberg. We also observe the predominance of Venice as the city where most of the subsequent books belonging to Family 3 were published. Regarding the normalized book in-degree, we observe that both families 2a and 4 carry high values, meaning that they are significantly connected to previous books, while books within families 3 and particularly 5 show very low values of normalized book in-degree, indicating that those books introduced a fair amount of innovation and removed traditional parts. As mentioned, seventy-six books that appear in Family 5 belong to smaller components. As a matter of fact, these books constitute a peculiar subgroup of books within the corpus. These books are considered to be strongly influenced by the text of reference, namely the *Tractatus de sphaera* of Sacrobosco, but they *do not contain it* and do not comment directly on it. They are considered to be influenced by it because they discuss the same subjects, either all of them or the majority of them. Moreover, they discuss them by following either the same or a very similar order. Finally, they largely make use of the same visual apparatus.³⁵ Nevertheless, they do often contain different scientific arguments and different views, though on the same subjects. These books therefore represent the first strong departure from the tradition of textbooks associated with Sacrobosco's treatise. They are, in other terms, at the boundaries of the corpus from a content-related point of view and therefore represent a category of books that will be taken into consideration for further analysis in the future, as discussed in the final section.

During the previous analysis we have pointed out specific books of particular relevance, since they were the seed for the convergence/divergence of knowledge triggering the emergence of different epistemic communities.

³⁵ Owen Gingerich, "Sacrobosco Illustrated," in *Between Demonstration and Imagination. Essays in the History of Science and Philosophy Presented to John D. North*, ed. Lodi Nauta and Arjo Vanderjagt (Leiden, Boston, Köln: Brill, 1999); Kathleen M. Crowther and Peter Barker, "Training the Intelligent Eye: Understanding Illustrations in Early Modern Astronomy Texts," *Isis* 104, no. 3 (2013): 429–70.

But of all these books, we want to highlight three particularly disruptive editions:

1) The 1488 Venice edition: This book, which we used to define the beginning of Family 2, broke with the tradition of the early period of the printed corpus (as shown by the low value of normalized book in-degree), introducing new knowledge that became tradition over time, and exhibiting semantic connections with more than 50% of all the books in the corpus.

2) The 1531 Wittenberg edition: This book, which we use to define the beginning of the divergence period (Family 3), is also highly disruptive since it broke with the dominant tradition by introducing new content that clearly diverged from previous editions (as shown by the low value of normalized book in-degree). Although the new knowledge in this book did not replace the previous tradition, it remained relatively influential (it connects to 34% of books published afterwards) in a period where several distinct book families co-existed.

3) The 1538 Wittenberg edition: This book, which established the emergence of Family 4, does not seem particularly disruptive at first sight as its high value of normalized in-degree indicates. Nevertheless, the high value of normalized out-degree suggests an interpretation according to which this edition exerted a strong influence. As discussed in the next section, in fact, its relevance in the corpus and, in particular, its innovative character become more apparent when families 3 and 4 are considered together.

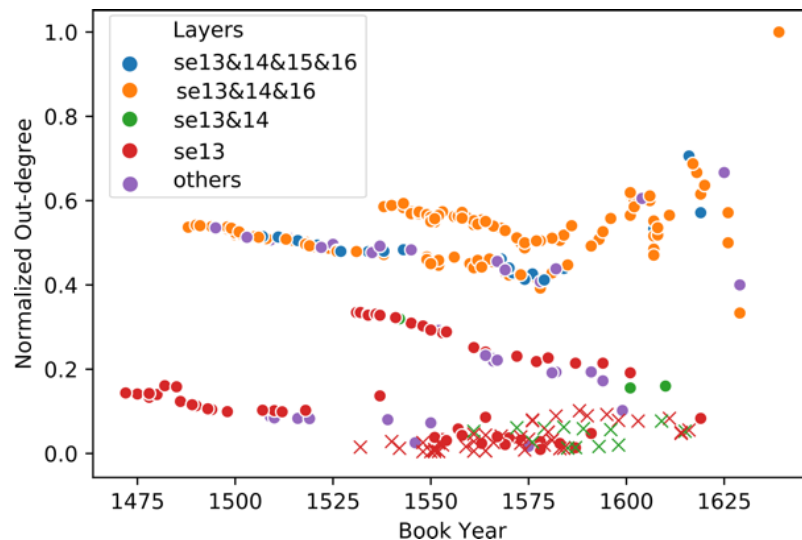


Figure 13. Composition of the families in function of the layers of the network. Circles identify editions that belong to the biggest connected component and cross symbols represent books in the small components.

Lastly, we examine the role of each of the semantic relations defined in section 4 in shaping the book families. To do so, the contribution of each layer to the final aggregated graph is investigated in order to assess which of the layers control the different families (emerging branches) in the normalized out-degree graph (Figure 13). In particular, families 2 and 4 are more dominated by a composition of layers se13 (same original part), se14 (same adaption), and se16 (annotated same original part). Families 1 and 3, on the other hand, are clearly shaped almost exclusively by layer se13. Cross symbols, finally, correspond to the books that do not belong to the main component and that, from a content-related point of view, further depart from the Tractatus of Sacrobosco.

5.2 Interpretation

The average age of the links and especially the low number of links eliminated when the assumption of influence is limited to ninety years are important factors in a very fundamental question of historical research, namely for how long it can be assumed that an event in the past has influenced a successive event. Obviously, this question can only be answered in the frame of a specific historical context. In this case, therefore, it can be said that scientific knowledge (externally represented by means of *Sphaera* editions between the end of the fifteenth and the half of the seventeenth century in Western Europe) reached a maximal age, the age before being forgotten, of about ninety years. This finally implies that longer knowledge traditions were possible only through re-instantiation of the same knowledge—in this case through the process of re-publishing.

Furthermore, the relative older age of links in layer se15 (same original translated) compared to layer se13 (same original part) could indicate that translations used a well-established (i.e., older) source-book, increasing the influence of some original parts in time. Regarding layer se16, the relational connections used to establish connectivity in this layer could explain the potential older age of its links. In particular, a link is established in layer se16 when two books contain commentaries on the same original part. This allows for a scenario in which two books distant in time are not connected by direct influence, but by re-publication of an original part in the context of subsequent commentaries published in between (*temporal evolution* of an original part).

As for the interpretation of the process of emergence of families as representatives of epistemic communities, we focus especially on families 2, 3,

and 4.³⁶ As the plots (Figures. 10, 11, 12) show, there are three branches (Families 2a and 2b, Family 3, and Family 4), each distinguished by a relatively stable, slightly decreasing normalized out-degree.

The books collected in families 3 and 4 seem relatively similar in several regards. Both branches begin with similar editions published in Wittenberg by the same publisher: Joseph Klug. These editions, as well as the subsequent books in these two families, contain a limited number of short text parts. These parts are distributed differently over the books under consideration, but re-occur frequently; so these books are similar with regard to their content but can be seen as “samplers” of a rather limited set of text parts (compared to the overall number of parts), often combined slightly differently in the various editions. Most of the text parts that appear in the books from which the new families originate are indeed new *in the corpus*. Namely, they appear here for the very first time. In many cases however they actually originate in works from earlier decades or even centuries.

The background for the selection of parts can only be speculated upon, but one scenario seems most likely: these collective volumes were intended mainly for teaching purposes and were closely related to the educational endeavor of Philipp Melanchthon and his circle in Wittenberg and Protestant Germany in the 1530s. Almost all books under consideration for the two families include the above-mentioned dedication letter by Philipp Melanchthon himself, safeguarding the use of natural astrology and cosmology within the Christian educational context.³⁷

The major difference between the books collected in families 4 and 3 is that those of Family 4 tend to contain more parts and are thus longer books. Nonetheless, with regard to many text parts, books of both families overlap to

³⁶ The interpretation of families 2, 3, and 4 is based on the editions published in the frame of the first thirty years of each family’s life. A full historical analysis of the scientific trends and epistemic communities, based on the results of the present work, will be accomplished in the future.

³⁷ Isabelle Pantin, “La lettre de Melanchthon à Simon Grynaeus: Avatars d’une défense de l’astrologie,” in *Divination et controverse religieuse en France au XVIe siècle*, Cahiers V. L. Saulnier, Collection de l’Ecole Normale Supérieure de Jeunes Filles (Paris: Ecole Normale Supérieure de Jeunes Filles, 1987), 85–101; Sebastian Lalla, “Über den Nutzen der Astrologie: Melanchthons Vorwort zum „Liber de sphaera“,” in *Gedenken und Rezeption: 100 Jahre Melanchthonhaus*, ed. Günther Frank (Heidelberg: Verlag Regionalkultur, 2003), 147–60; Karin Reich and Eberhard Knobloch, “Melanchthons Vorreden zu Sacroboscus «Sphaera» (1531) und zum «Computus ecclesiasticus»,” *Beiträge zur Astronomiegeschichte* 7 (2004): 13–44. See also, Claudia Brosseder, *Im Bann der Sterne: Caspar Peucer, Philipp Melanchthon und andere Wittenberger Astrologen* (Berlin: Akademie Verlag, 2004).

a high degree. This means that the text parts of the Family 3 editions are mostly also included in the editions of Family 4—which later also partially spread over Family 2. In particular, and in chronological order, the 1531 edition that opens Family 3 contains four text parts: a) the above-mentioned letter by Melanchthon, b) the original treatise by Sacrobosco, c) a short epigram also by Melanchthon, and d) a chapter from the famous work in astronomy by Johannes Regiomontanus: his *Epitome* on Ptolemy's *Almagest* (published for the first time in 1496), a work that elaborates on Ptolemy's astronomy by combining it with fifteenth-century mathematical astronomy. Melanchthon's letter and Regiomontanus's *Epitome* are the text parts that make this family turn out to be a new epistemic community within the corpus. In the first thirty years after the beginning of this family, we encounter eighteen books. In these books, the *Epitome* was republished seventeen times and Melanchthon's letter eleven times.

Looking at the text parts of the 1538 edition, by means of which Family 4 began, it is surprising that this family created a branch by itself. In fact, the 1538 edition republishes three of the four text parts that appear in the 1531 edition in exactly the same way. This aspect contributes to about half of the difference between the in-degree value of Family 4 (1538 edition) and Family 3 (1531 edition). To fully understand such value, however, a closer look at the composition of the 1538 edition is due. The first change that can be recognized in Family 4 is related to Sacrobosco's *Tractatus*. While this was contained in the 1531 edition as an original part, therefore repeating the late medieval text, the 1538 edition contains an expanded version of the treatise that was published in this edition for the first time. This is not an explicit commentary in the usual terms, but the result of an anonymous intervention in the original medieval text itself. Following our taxonomy, however, this text is categorized as an anonymous commentary on Sacrobosco's *Tractatus*. This in turn implies that it is formally captured by the semantic of layer se16, whose higher number of links and weights contributed for a bit over half of the difference between the in-degree value of Family 4 (1538 edition) and Family 3 (1531 edition) as well.³⁸

This early modern expanded version of Sacrobosco's treatise, which was published under the name of Sacrobosco himself, experienced considerable

³⁸ This result therefore shows that, to achieve a more precise determination of the in- and out-degree values, a further category should be included that is able to distinguish more clearly between explicit commentaries and other sorts of interventions on the texts for all text parts. Apart from the obvious difficulty that could emerge while distinguishing between literary-stylistic interventions—due for instance to the humanistic imperative to emend medieval Latin on one side, and scientific interventions on the other—this information can be systematically collected only on the basis of a textual analysis executed on electronic transcriptions. No technology is available to produce such transcriptions at the moment.

success and, as it turns out, is one of the main reasons for the constitution of Family 4. If only the first thirty years of Family 4 are considered, we encounter thirty-two books, twenty-two of which contain such a variation of Sacrobosco's *Tractatus*. Considering that this text part was re-published a total number of twenty-six times in the total corpus, this text can be almost uniquely associated with this family. Besides these four parts, the 1538 edition also contains a) Sacrobosco's treatise on *computus*,³⁹ b) a *Cisiojanus*,⁴⁰ and c) a chapter of a late medieval Latin translation, made by John of Seville, of a work on mathematical astronomy originally written in the year 833 by the Arab scholar al-Farghani, a work that entered Western culture under the title *Liber de aggregatione stellarum*. This text part was published in the 1538 edition for the first time in the corpus and was re-published twenty-three times until 1568. The treatise on *computus* and the *Cisiojanus* are published in this edition for the first time as well and were always re-published together. Within the same time interval, their re-occurrences amount to twelve in Family 4, while their total amount in the corpus until 1650 is twenty.

Families 3 and 4 represent new epistemic communities in the history of the corpus. There is a series of reasons for this. The first is the fact that new text parts, namely parts that were not yet present in the corpus of printed treatises, appeared for the first time. The second is related to the behavior of their re-occurrences; they were not only successful but were often especially successful in the frame of the family itself. They were successful because the absolute number of their re-occurrences was often high and, additionally, they remained strongly present within the respective families. Considering these aspects together, it implies that the establishment of the families as new epistemic communities was due to the fact that the new text parts re-appeared together. In other words, they formed bundles of atoms of knowledge represented by text parts. The appearance of a new text part is an innovation in the corpus but not necessarily a knowledge innovation, as many of these texts

³⁹ Treatises on *computus* or *computus ecclesiasticus* were textbooks by means of which late medieval students learned to calculate the date of Easter for successive years and, with it, could assign a date to all movable feasts and complete the liturgic calendar. *Computus* was a widespread study in the late medieval period and many different treatises circulated on the topic. For Sacrobosco's treatise, entitled *De anni ratione* during the early modern period, see Jennifer Moreton, "John of Sacrobosco and the Calendar," *Periodicals Archive Online* 25 (1994): 229–44.

⁴⁰ A *Cisiojanus* is a short text, written in the form of a poem, intended to be learned by heart. Its apparently nonsensical verses allowed the students to remember the rules to calculate the dates of the movable feasts of the Christian liturgic calendar. For more information, see Rolf Max Kully, "Cisiojanus. Studien zur mnemonischen Literatur anhand des spätmittelalterlichen Kalendergedichts," *Schweizerisches Archiv für Volkskunde* 70 (1974): 93–123.

were actually already centuries old. The fact that a new trend emerged because of a new combination of texts (rather than new texts) implies that novelty in science emerged on a higher level, namely at the level of the shared scientific identity based on the study of a new combination of text parts. These families of editions indeed represent processes of the circulation of scientific knowledge in specific temporal and geographical areas—knowledge acquired by university students. This also shows that innovation of scientific knowledge, as far as concerns this corpus and the educational pattern in cosmology, was brought about more by the publishers than by the authors. The publishers were ultimately responsible for the composition of their books.

Returning to the structural and bibliographical similarities of the books belonging to both branches, a few more observations are noteworthy. First, and as already mentioned, these books exhibit the success of books printed in a smaller format, namely in *octavo*. This tendency to “convert” *Sphaera* volumes from *folio* into *octavo* format has been observed in previous scholarship, but is borne out here not only with more rigor but also in a specific historical context and in a quantified manner.⁴¹ Moreover, on a more political and confessional note, books of these branches testify to a “bridge” from Protestant Wittenberg to the Republic of Venice, Paris, and Antwerp. Those places of book production were all officially Catholic at the time of the emergence of these new communities. As has been observed in existing scholarship, Melancthon’s humanist approach in particular was valued highly among certain humanist and Catholic circles in Italy.⁴² This affinity might have compelled or enabled the cooperation of printers and publishers north and south of the Alps or might at least have triggered printers to copy the Wittenberg edition(s) as they felt the demand for this type of publication among their own clients and peers.

A final relevant aspect concerning families 3 and 4 is related to the printer of the books that establish both families—a fact that ultimately explains why families 3 and 4 can be considered together and why the high value of normalized in-degree of Family 4 should actually be balanced by the low normalized in-degree value of Family 3. As mentioned, the books were both

⁴¹ Owen Gingerich, “Five Centuries of Astronomical Textbooks and Their Role in Teaching,” in *The Teaching of astronomy*, ed. J. M. Pasachoff and J. R. Percy (Cambridge: Cambridge University Press, 1990), 189–211; Isabelle Pantin, “Borrowers and Innovators in the Printing History of Sacrobosco: The Case of the “in-octavo” Tradition,” in *De sphaera of Johannes de Sacrobosco in the Early Modern Period: The Authors of the Commentaries*, ed. Matteo Valleriani (Dordrecht: Springer Nature, In press).

⁴² Christoph Sander, “Johannes de Sacrobosco und die Sphaera-Tradition in der katholischen Zensur der Frühen Neuzeit,” *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin* 26, no. 4 (2018): 437–74.

printed by Joseph Klug. Klug began offering his services in Wittenberg in 1523, when the center of the Protestant Reformation was attracting numerous printers. He began working for the Reformers in 1525 by publishing the first editions of three works of Martin Luther. He became a relevant printer especially for the production of the *Geystliche gesanck Buchleyn*, a collection of chants edited directly by Martin Luther. It remains unclear how close Klug was with the Reformers on a personal level, but he was later put in charge of publishing several other particularly important theological works by Philipp Melanchthon. Until now, it was completely unknown that Klug was at the vanguard of producing extremely influential university textbooks as well.⁴³

Turning now to Family 2, the books belonging to this family are very different from those just analyzed. As this family begins much earlier, in 1488, the books belonging to its first phase are representative of the passage from the manuscript tradition to the print, a point that can be at least partially demonstrated by comparing the books published during the first thirty years of Family 2 with the so-called medieval *Corpus astronomicum*.⁴⁴ Focusing on the characteristics of the printed editions of Family 2, two observations seem to corroborate this strong connection to a manuscript culture. Some of the earliest editions of this family are printed in *folio* and contain many long and complete works, such as the long and hitherto neglected commentary of Francesco Capuano on the *Theoricae novae* of Peurbach.⁴⁵ This very much resembles the appearance and content of late medieval “cumulative” manuscripts in the field of cosmology.

In strong contrast to the two branches corresponding to families 3 and 4, the first phase of Family 2 hardly contains books in *octavo* format, though this format had been circulating since 1495 thanks to the publication of the first of

⁴³ Unfortunately, the activity of Joseph Klug has not been as investigated by book historians as the subject deserves. For a short biographical sketch, see Hans Volz, “Die Wittenberger Gesangbuchdrucker Joseph Klug und Hans Lufft,” *Jahrbuch für Liturgik und Hymnologie*, no. 4 (1958): 129–33. For Joseph Klug’s activity in the frame of the corpus *De sphaera*, see <http://hdl.handle.net/21.11103/sphaera.100802>. On print culture in early modern Wittenberg, see Stefan Oehmig, ed. *Buchdruck und Buchkultur im Wittenberg der Reformationszeit* (Leipzig: Evangelische Verlagsanstalt GmbH, 2015).

⁴⁴ For the medieval *Corpus astronomicum*, see O. Pedersen, “The Corpus Astronomicum and the Traditions of Mediaeval Latin Astronomy,” *Copernicana*, no. 13 (1975): 57–96. The manuscript tradition obviously began in the thirteenth century when the *Tractatus* was first written. Hundreds of manuscripts containing the *Tractatus* and other text parts have come down to us, but as there is no census and no closer reading of them, no punctual analysis can be accomplished at this stage.

⁴⁵ For an edition that belongs to Family 2 and that contains Capuano’s commentary, see for instance the 1499-published treatise <http://hdl.handle.net/21.11103/sphaera.100273>.

the Aldine, by Aldo Manuzio in Venice. These editions are in *quarto* and *folio*. Those formats were less used by students than by scholars, teachers, and collectors, as they were more expensive. These editions, moreover, also have no clear geographical center or distribution. They were published widely all-over central Europe, from Rome to Cologne, and from Salamanca to Krakow. Also, in contrast to the books of families 3 and 4, those of Family 2 do not have an immediate “shared identity” with regard to their content and their authors. What does seem to connect them is their individuality on the one hand and their success on the other. This means that we find very different sets of editions belonging to this family—for example, a *folio* volume from Paris re-published three times,⁴⁶ or a set of similar *folio* volumes containing, among other things, either the commentary on the *Sphaera* by Francesco Capuano di Manfredonia or the commentary of the *Sphaera* by Jacques Lefèvre d’Étaples (both printed primarily in Paris and Venice),⁴⁷ or the edition of Sacrobosco’s treatise both introduced and commented upon by Wenzel Faber, usually entitled *Opus sphaericum* or *Opusculum spericum* and published in Cologne, Strasbourg, and Leipzig in *quarto* format as well.⁴⁸ These three sets of editions are not only rather peculiar (each in its own way) and different among themselves, but also mutually successful, as they all saw multiple editions that belong to the same family.

A common feature of the editions of Family 2, therefore, seems to be their attempt to re-structure and confirm the established cosmological knowledge—represented by Sacrobosco’s treatise—in the path of tradition. The Paris editions, beginning in 1498, do so by adding a number of (often medieval) reference works and a few commentaries on the *Sphaera*. The second set does so mostly by combining the two rather contemporary commentaries by Capuano and d’Étaples with many more, often medieval works (some of which had already appeared in the Paris *folio* editions) beginning only one year later,

⁴⁶ The Paris *folio* volume is published twice in 1498: <http://hdl.handle.net/21.11103/sphaera.100038> and <http://hdl.handle.net/21.11103/sphaera.100274> and then, for instance, again in 1508: <http://hdl.handle.net/21.11103/sphaera.100642>.

⁴⁷ This set of editions, characterized by very different titles but very similar content, is particularly large. In chronological order, some of these *folio* editions are: (Venice 1499): <http://hdl.handle.net/21.11103/sphaera.100273>, (Venice 1508) <http://hdl.handle.net/21.11103/sphaera.100915>, (Paris 1511) <http://hdl.handle.net/21.11103/sphaera.100919>, (Paris 1516) <http://hdl.handle.net/21.11103/sphaera.100990>.

⁴⁸ Editions of Wenzel Faber’s commentary are numerous. See for instance the following: (Leipzig [1495]) <http://hdl.handle.net/21.11103/sphaera.100886>, (Leipzig 1499) <http://hdl.handle.net/21.11103/sphaera.100888>, and (Cologne 1508) <http://hdl.handle.net/21.11103/sphaera.100183>.

in 1499 in Venice.⁴⁹ Faber's commentary in turn was printed as a monograph and not together with other commentaries, as early as 1495 (in Leipzig). His work seems to mirror the attempt to pave the way toward the emergence of a commentary style more tailored to teaching purposes, especially in universities in German territories.⁵⁰

On a formal and statistical level, it is persuasive to argue for structural differences between families 3 and 4 in comparison to Family 2. Books in families 3 and 4 tend to combine and re-combine a limited set of text parts: while in Family 3 and Family 4 we find twenty-six and forty-nine text parts, re-combined to a total of 177 and 419 times respectively, Family 2 is represented by 128 text parts recombined so as to let them appear 411 times. This gives the impression of a relatively stable content profile built around a constellation of a small number of text parts or atoms of knowledge for the first two families, while the content profile, the shared identity, of Family 2 can only be established if a large number of text parts is considered.

To summarize, we would interpret Family 2 as the continuation, in a new medium, of the late medieval tradition, though this came at a high cost, namely the necessity to vary as much as possible the offering of new text parts, be they original parts or adaptations, while remaining at the closest possible proximity to the original medieval treatise. This implies continuity and great variation at the same time. Families 3 and 4, instead, show the establishment of new epistemic communities that slightly depart from the tradition represented by Family 2 and that were established by means of a more efficient mechanism, as this involved smaller formats and, above all, because they were compilations of a more limited number of text parts.⁵¹

Apparently, this result was achieved through the two following steps, which occurred respectively in 1531 and 1538. The first, highly disruptive, was

⁴⁹ The two commentaries by Francesco Capuano and Jacques Lefèvre d'Étaples were first published in 1499, in the same edition (<http://hdl.handle.net/21.11103/sphaera.100021>). d'Étaples's commentary was first published in 1494. (<http://hdl.handle.net/21.11103/sphaera.101126>)

⁵⁰ Family 2 remains stable along the timeline. However, beginning in 1543 we see vernacular translations enter it as well, and later on even translations that include text parts typical for families 3 and 4, indicating an increasingly large component and, therefore, a wider and perhaps faster circulation of knowledge.

⁵¹ The hypothesis could also be formulated at this stage that the degree of variation of parts that characterizes the families was also dependent on the print runs of the editions. Unfortunately, such dependence cannot be investigated because systematic data concerning the print runs are missing. But it could be speculated that smaller print runs are associated to higher variation of text parts.

the insertion of a compilation where three parts out of four were new to the corpus. Thus, both the parts and their combination were novel. The second step built upon the first and enriched the compilation with new parts. Through analysis of the single layers of the network, therefore, we are now able to analyze this double step more closely. As mentioned, the more disruptive changes (Family 3) are fully represented by layer se13 (Figure 13), namely by a graph of books connected to each other because they contain the same original (in this case, new) text parts. The second step (Family 4), however, is achieved by mixing this characteristic with those indicated by layers se14 and se16, namely by either re-publishing exactly the same commentaries or commentaries on the same (small number of) original parts. This means that, once the fundamental change was accomplished, to become influential in European educational paths the editions had to increase their degrees of variation similarly to the behavior of the editions of Family 2.⁵² As the high value of normalized out-degree of Family 4 shows (being the highest among the families), in this way Joseph Klug built up the most influential new epistemic community. This particular circumstance clearly describes the mechanisms the Reformers used to influence the scientific educational paths of Europe.

The investigation, based on the different methods of production of scientific knowledge, represented here by the taxonomy of the text parts and the semantic structures of the layers, offers the opportunity to disclose the most fundamental of the mechanisms of emergence of new epistemic communities. The emergence, establishment, and disappearance of such new epistemic communities, namely communities that display new knowledge, are processes that illustrate how knowledge evolves over time, in this case during the early modern period.

⁵² The huge *folio* editions contained in Family 2 might have inspired the printers of the editions contained in Family 4. Although these printers (esp. Klug) made a completely different choice regarding the actual text parts compared to those of Family 2, they nonetheless might have observed that the *folio* volumes of Paris and Venice proved successful and thus applied their compositional pattern (esp. the inclusion of many text parts and the combination of mediaeval original parts with contemporary commentaries) to a new selection of text parts and a new book format.

6 Discussion

On the basis of the data used for the present work, further analyses will be performed to assess the maximum time of influence of editions to address (1) whether there is a characteristic expiration time for each link, in the sense that each editions has a maximum lifetime in terms of influence, (2) how link influence depends on book production rates, (3) how link lifetime depends on the semantic layers, and (4) whether and how non-semantic factors (e.g., publisher, city of production, book format) affect link lifetimes.

A further analysis will include a new graph able to formally capture the small components. This graph will connect those books that, as a result of this analysis, turned out to be particularly distant from the content-related tradition as determined by the content of the work of reference: Sacrobosco's treatise. This will allow us to compare the results of this work, concerned with the core of the knowledge system pivoted around Sacrobosco's *Tractatus*, with those achieved by looking at what might turn out to be the beginning of a new, even more disruptive family.

More fundamentally, the project will continue first and foremost through the release of further data, producing a higher number of layers of the network. These in turn will generate connections enabling modeling that will disclose which of these layers are relevant for the historical argument.

On the level of semantic atoms to identify each single historical source and to allow the comparison among them, we are extracting and analyzing illustrations and numerical tables. We consider these kinds of "knowledge atoms" as ontologically different from text parts. In spite of the fact that texts, images, and tables are all connected to each other in each source, the same text part, in its re-occurrences, could be enriched by unique illustrations. Illustrations are carriers of knowledge; they will therefore be considered to be a specific form of commentary. Numerical tables in the frame of astronomy and cosmology did not convey only observational knowledge. More often, they are representative of computational methods that were not made explicit in the texts and become apparent only through the analysis of the numbers listed in the tables. While the content in reference to geocentric cosmology might have remained constant, algorithms for the necessary computations might have evolved and changed over time. Meanwhile, ca. 20,000 illustrations and 11,000 tables have been extracted from the sources of the corpus. Further work is ongoing to cluster this data and, accordingly, to prepare new graphs concerned with the diffusion of visual material and of computational tables. After this work is concluded we will have the ability to cross the new data with

the metadata and thereby to establish new layers expressing the diffusion and circulation of visual knowledge as well as of computational algorithms in the sources and to compare them with the behavior of the text parts.⁵³

Furthermore, a dataset is being completed that includes aspects of social and material nature that can be extracted from the printed books directly. This will allow us to create nine further graphs to represent collaborations among authors, printers, and publishers of the editions, each according to a specific semantic.⁵⁴ Finally, we will a) investigate the correlations between layers expressing semantic behaviors and those closely related to the social and material aspects of book production and b) measure the hierarchical structure and study the driving forces that might make the structure of the network converge to hierarchy.⁵⁵

Another exciting avenue of research will be studying dynamical processes on the multilayer networks to model the spread of knowledge in this historical period. Pioneering studies on diffusion⁵⁶ and the dynamics of the spread of disease⁵⁷ in multilayer networks have shown a priori unexpected behavior in the dynamical response of systems, which emerge due to the coexistence of paths between nodes of different natures, in the sense that those paths integrate the connectivity of the various layers. More recently, it has been shown that when multilayer networks include directed graphs⁵⁸ the dynamic enriches even more, wherein diffusion dynamics can exhibit optimality (i.e., the system can achieve maximum spreading rates). Thus, given the multilayer structure and directionality of the network extracted from the corpus,

⁵³ The identification of the scientific illustrations as well as of the numerical tables and their clustering according to different levels of "sameness" is being executed in the frame of the Berlin Center for Machine Learning, of which the *Sphaera* Project is also part. For more information, see <https://www.bzml.de>.

⁵⁴ Jürgen Renn et al., "Netzwerke als Wissensspeicher," in *Die Zukunft der Wissensspeicher. Forschen, Sammeln und Vermitteln im 21. Jahrhundert*, ed. Jürgen Mittelstraß and Ulrich Rüdiger (München: UVK Verlagsgesellschaft, 2016), 35–79.

⁵⁵ Maryam Zamani and T. Vicsek, "Glassy Nature of Hierarchical Organizations," *Scientific Reports* 7, no. 1382 (2017); Maryam Zamani, L. Camargo-Forero, and T. Vicsek, "Stability of Glassy Hierarchical Networks," *New Journal of Physics* 20, no. 023025 (2018).

⁵⁶ S. Gómez et al., "Diffusion Dynamics on Multiplex Networks," *Physical Review Letters* 110, no. 028701 (2013).

⁵⁷ Manlio De Domenico et al., "The Physics of Spreading Processes in Multilayer Networks," *Nature Physics* 12 (2016): 901–06; Guilherme Ferraz de Arruda, Francisco A. Rodriguez, and Yamir Moreno, "Fundamentals of Spreading Processes in Single and Multilayer Complex Networks," *Physics Reports* 756, no. 1 (2018): 1–59.

⁵⁸ Alejandro Tejedor et al., "Diffusion Dynamics and Optimal Coupling in Multiplex Networks with Directed Layers," *Physical Review X* 8, no. 031071 (2018).

questions of interest include: (1) how the time-evolving structure of book connectivity is characterized in terms of its potential to spread information, (2) whether the period with the highest book production rates corresponds to the connectivity structure that allows the fastest spread of knowledge, and (3) whether there are key books that might not be influential from the point of view of topological influence (e.g., normalized book out-degree) but are critical in the spreading of information across different communities (e.g., geographical areas). Finally, from the data analysis point of view, it will be interesting to study the corpus according to a phylogenetic tree, as is the practice in biology for the evolution and interrelation of species. More generally, we intend first to introduce a similarity measure between items of the corpus in order to visualize and quantitatively analyze changes of the contents over time and, on a more speculative level, to investigate employing models used in evolutionary biology to describe the process of evolution of knowledge.

7 Authors' contributions

Data collection: S. Bertram, G. Funke, C. Sander, M. Valleriani

Data repository and curation: F. Kräutli

Dataset creation: F. Kräutli, M. Vogl

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