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Modeling the Structure and Dynamics of Science Using Books

1 Introduction

Scientific research is a major driving force in a knowledge-based economy. Income, health, and well-being depend on scientific progress. The better we understand the inner workings of the scientific enterprise, the better we can prompt, manage, steer, and utilize scientific progress. Diverse indicators and approaches exist to evaluate and monitor research activities—from calculating the reputation of a researcher, institution, or country to analyzing and visualizing global brain circulation. However, there are very few predictive models of science that are used by key decision makers in academia, industry, or government interested in improving the quality and impact of scholarly efforts.

Other scientific communities rely extensively on predictive models to simulate events such as weather, seismic hazards (UNAVCO Facility, 2010), or epidemics (Colizza et al., 2006). Recent efforts have sought to forecast science and technology in the form of an "innovation accelerator" (Van Harmelen et al., 2012). However, the heterogeneous and proprietary datasets required to model science remain scattered, cultures of algorithm and model sharing are slow to evolve, and a unified theory that interlinks validated models of science does not yet exist.

According to the Oxford English Dictionary (2002), the term model may function as: a representation of structure or system; an object of imitation; and a type and design. The latter two definitions of model are used to indicate an object's status as an exemplar meant to be imitated or a prototype to be copied and are irrelevant for what is discussed in this chapter. The first function, i.e., a representative model, is the focus here and may either describe a targeted system or phenomena (e.g., a science model); represent a broader theoretical interpretation of the laws, axioms, and models of a discipline (e.g., a model of science); or perform both functions simultaneously (Frigg & Stephan, 2012).

In this chapter—building on prior work (Scharnhorst et al., 2012)—we define a model of science as "a systematic description of an object or phenomenon that shares important characteristics with its real-world counterpart and supports its detailed investigation" (Börner et al., 2012a, p. 1). Models of science put forward a theoretical and/or empirical understanding with predictive power and are validated based on the accuracy of their predictions. Focusing on scientific models of science, we purposefully exclude anecdotal evidence and narratives, e.g.,

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the analysis of science fiction literature to identify possible future developments (Steinmueller, 2010). Instead, we focus on models of science that explain and help to predict the activities of scholars (also called authors, researchers, scientists) because they are the generators of ideas and innovation—papers don't write papers, authors do (Cronin, 2005)—and it is scholars who collaborate and read and write papers leading to the diffusion of ideas, knowledge, innovations, and the "making of science" (Cronin, 2008).

The remainder of the chapter is organized as follows. The next section discusses challenges and opportunities when attempting to delineate and map the space of existing models of science. Subsequently, we present a novel "bibliographic-bibliometric" analysis which we apply to a large collection of books relevant for the modeling of science—we explain the data collection together with the results of the data analyses and visualizations. In the final section we discuss how the analysis of books that describe different modeling approaches can inform the design of new models of science.

2 Prior Work: Context and Focus

Models of science are developed in many scientific disciplines and use different (mathematical) approaches and terminology that are difficult, if not impossible, to align across disciplinary boundaries.

Descriptive models of science can be found in philosophy of science, history of science, sociology of science, and science and technology studies—in short, in all those areas of social sciences and humanities which have knowledge production as their object of study. Bernal's encyclopedic work, "The Social Function of Science" (1939, 1967), has influenced many of those reflecting about science in a systematic manner (Garfield, 2007). Since 1981, the Society for Social Studies of Science[1] awards the *John Desmond Bernal Prize* annually to scholars that have made a distinguished contribution to the field. The first three award recipients were Derek de Solla Price (1981), Robert K. Merton (1973), and Thomas S. Kuhn and their books–*Little Science, Big Science* (Price, 1963), *The Sociology of Science* (Merton, 1973), and *The Structure of Scientific Revolutions* (Kuhn, 1962)—are included in this analysis.

Predictive models of science (computational and mathematical) are developed in scientometrics, bibliometrics, system dynamics, physics, mathematics, and, more recently, in a new branch of philosophy of science and cognition

1 http://4sonline.org/

(Payette, 2012). One of the first predictive models was introduced by Goffman—he used a model originally developed to predict the spread of diseases to describe the spreading of ideas (Goffman & Nevill 1964; Goffman 1966; Harmon 2008). The so-called SIR model orders researchers in three categories: the number of researchers 'susceptible' to a new idea but not yet infected with it (S), the number of 'infected' researchers (I), and the number of 'recovered' researchers (R) who lost interest and will not return to the idea. The model presumes that boundaries of scientific fields and/or invisible colleges (Crane, 1972) can be defined. Goffman's work showcases the complex relationship between mathematical and theoretical models, and empirical validation. Using Goffman's model, it is possible to define the probability that a researcher will become 'infected' with an idea and the predicted growth rate of a new scientific field can be compared with the actual growth rate (Wagner-Döbler, 1999) (see also Lucio-Arias and Scharnhorst [2012] for a review). However, case studies have demonstrated that it is difficult to validate all processes inscribed in Goffman's model (Burger & Bujdoso, 1985).

There are very few comparisons of existing models or attempts to combine multiple models to arrive at a more holistic understanding of the structure and dynamics of science. The isolation of mathematical models was demonstrated in an empirical study of journals using Lotka (1926), Price (1965; 1976), and Goffman (1966) as models (Lucio-Arias & Scharnhorst, 2012). Textbooks that provide an overview of different types of models can only be written if an acknowledged and shared body of validated models exists—which is not yet the case, though an inventory of models in certain domains has been attempted, e.g., see Scharnhorst et al. (2012) and Schulze (2014).

As with any system, there are many different ways one can study and model the science system: e.g., from the perspective of the cognitive structure (Collins, 1988); political-economic base (Nowotny et al., 2005); institutions, politics, and social actors (Gibbons et al. 1994); or communications (Kaufer & Carley 1993). Those cognizant of the problems of studying science are scattered across multiple domains, all of which have their own epistemological and methodological emphases. There are few who try to bridge between different epistemic perspectives, and even fewer who reflect about science in a wider historic context of knowledge production. Among them, Blaise Cronin stands out as a scholar able to play on all strings of the harp of scientific reflection about science. He looks at current forms of scholarly communication from a macro perspective which encompasses scholarship from the Enlightenment to Force11 (Cronin & Sugimoto, 2014). His early book *The Citation Process* (1984) called for a study of science as a social system taking into account "norms and values which guide and constrain the actions of individual scientists" (p. 1).

It is from a broad perspective that we evaluate and describe the relationships among books on the topic of models of science. World Cat data[2] of library catalog records and subject headings plus library classification codes were used to identify a set of relevant books, to identify major topical clusters, and to show interlinkages. The resulting semantic networks were then explored to determine the spheres of influence, relevance, and context around specific sets of books on models of science, subject headings, and library classification codes.

3 Bibliographic-Bibliometric Data Collection and Analysis

Currently there exists neither a "Models of Science" handbook nor a comprehensive annotated bibliography. A search for "models of science", "models of science dynamics", "modeling processes of science", "modeling of scholarly communication", or similar phases using any major citation index is of limited value when aimed at identifying relevant literature. Our starting point is the collection *Models of Science Dynamics* (Scharnhorst et al., 2012), which presents a review of major types of and applications for models of science. While this book does not claim to cover all relevant works across the landscape of science, the authors of each chapter reviewed a specific branch of models of science developed in different areas of science. Using references to books on modeling science, library classification data and subject headings can be retrieved and used to map the evolving topical space in which models of science are researched and developed.

3.1 Identification of Relevant Books

To map the concept "model of science", a book list was generated using the references from the *Models of Science Dynamics* (Scharnhorst et al., 2012). Using a bibtex file that captured all 589 references cited in the book, 196 citations were identified as book references. Two additional books were added: the *Models of Science Dynamics* (2012) book itself and the book *The Web of Knowledge: A Festschrift*

2 World Cat is a database managed by the Online Computer Library Center (OCLC) that collects library catalog records from around the world into a single information resource discovery system. http://www.worldcat.org

in Honor of Eugene Garfield (2000), edited by Blaise Cronin and Helen Barsky Atkins.

3.2 Identification of Associated World Cat Subject Headings

The resulting list of 198 books was then searched in World Cat to collect all English language subject terms and to determine the accuracy of the document type. Twenty-one titles were removed from the seed list for three reasons: (a) the citation was not a book [e.g., conference proceedings that were not published as a book, and therefore not cataloged (9), journal articles (3), or self-published program instruction manuals (4)]; (b) the book reference lacked subject headings in English (4); or (c) the book reference duplicated a book in the data (1). For the frequency distribution of the final 177 titles by type—*book, ebook, incollection*, and *inproceedings*[3]—see Table 1.

For a distribution of all 198 book titles and the 177 final books references per publication year (binned by 5-years) see Figure 1. Most of the cited books in *Models of Science Dynamics* were published between 2001 and 2005 (bin label 2005). This age-distribution for cited work is in line with other studies on obsolescence of literature (Lariviére et al., 2008), but could also signal the relative youth of the domain of science modeling.

Tab. 1: Number of reference types of book titles.

Initial Reference Types		Final Reference Types	
article	3	Book	147
book	151	Ebook	1
ebook	1	Incollection	18
electronic (handbook)	1	inproceedings	11
incollection	21		
inproceedings	21		
Grand Total	**198**		**177**

3 Each citation collected for this analysis had a bibtex category assigned that defined its genre. The categories include: *article* indicates that a citation is an article published in a *book* and *ebook* that indicate that a citation is either a book or an electronic book without a print publication; *electronic (handbook)* indicates that a citation is for software tool handbooks; *inproceedings* indicates that a citation was published in a conference proceeding rather than a book; last, the category *incollection* indicates that a citation is chapter included a multi-author or edited book.

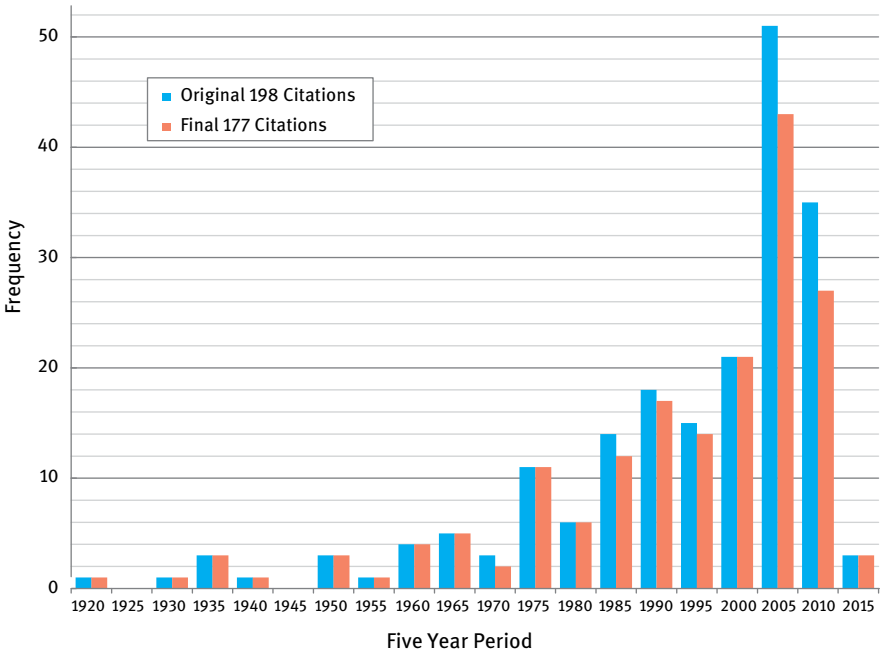


Fig. 1: Number of initial 198 (blue) and final 177 book titles (red) per publication year.

The bibliographic record for books in World Cat contains, among others, a field called *subject*. This field contains the *subject headings, genre terms and forms, and unindexed subject keywords* attributed to a book by a librarian or cataloguer when the book is purchased and added to the collection of a library. Modern information systems may allow librarians to identify already attributed subject headings for a work, and wide-spread bibliographic classification systems as Dewey, Unified Decimal Classification, and Library of Congress lead to some standardization. Still, libraries have idiosyncratic classification schemes and indexing practices, whereby a number of distinct subject headings can be assigned to the same item.

To harvest the various subject headings, we selected "View all editions and formats" in the publically displayed bibliographic records on World Cat. Collecting from all unique editions of a book allowed us to gather the full variety and scope of subjects assigned by catalogers around the globe. This method provided a substantial number of different subject headings for each book and all distinct terms per book were identified using a semi-automatic process.

The collected subject headings were then normalized for spelling, topicality, and relevance. The initial list of 1313 subject headings for all 177 books was consolidated into a list of 876 unique subject headings after removing duplicate oc-

currences. The unique subject headings were refined a second time to combine related topics and remove extraneous headings. Subject headings were *combined* if: the subject varied in spelling or punctuation (e.g., *Biology – Mathematical models*[4] also includes *Biology/Mathematical model*); the subject heading contained a designation of the type of material (e.g., *Biology – Mathematical models – Textbooks* would appear under *Biology – Mathematical models*), geographic region (e.g., *Alcoholism and crime – Wales – Cardiff* is grouped with *Alcoholism and crime*), or temporally (e.g., *Economic history – 16th century* would appear under *Economic history*); or the subject headings were topically similar enough that a work could be found using the chosen variant (e.g., *Biophysics/Biomedical Physics* is grouped under *Biophysics*; *Comprehension (Theory of knowledge)* is grouped under *Comprehension*). Subject headings were *removed* if they described the materiality of a book (e.g., electronic book), a geographic place without a proceeding topic (e.g., Japan, Great Britain), or were the name of a researcher (e.g., Lotka). The final list contains 675 unique subject headings.

These subject headings are distributed unevenly over the 177 books: there were an average of 6.31 subject headings per book, ranging from 1 to 31. A book's set of subject headings indicate the topics that indexers and catalogers determine are coextensive to the work, i.e., the concepts that most accurately represent a book's subject. Coextensive subject headings indicate a co-occurrence relationship between concepts. The co-occurrence of subject headings have been used to identify inter-index consistency and to map concept-spaces based on indexer perceptions of subject headings (Olson & Wolfram, 2008; Gabel & Smiraglia, 2009). Within this analysis, the co-occurrence of subject headings across multiple books is used as a proxy measure of the relationships between science domains.

3.3 Identification of Associated Library of Congress Classification Codes

Using the Library of Congress online catalog,[5] the Library of Congress Classification (LCC) shelf numbers[6] were collected for 171 books (six books did not have LCC such numbers). The number of books and the number of subject headings for each of the nine LCC classes is given in Table 2. For example, seven of the

4 Throughout the text, book subject heading are *italicized;* subject heading domains groups are **bold.**

5 Library of Congress Online Catalog http://catalog.loc.gov/vwebv/searchAdvanced

6 Library of Congress Classification codes http://www.loc.gov/catdir/cpso/lcc.html

Tab. 2: Library of Congress Classifications and Respective Book and Subject Heading Counts.

Library of Congress Classification	Book Count	Subject Heading Count
B – Philosophy, Psychology, Religion	**7**	**36**
B – Philosophy – General	2	12
BF – Psychology	2	12
BC – Logic	1	7
BD – Speculative philosophy	1	4
BJ – Ethics	1	1
H – Social Science	**63**	**429**
HM – Sociology	18	155
HB – Economic Theory, Demography	15	75
H – Social Sciences – General	9	52
HD – Industries, Land use, Labor	8	68
HC – Economic history and conditions	4	30
HV – Sociology – Social pathology …	3	21
HQ – Sociology – The family …	2	8
HA – Statistics	2	6
HF – Commerce	1	9
HG – Finance	1	5
J – Political Science	**1**	**10**
JN – Political Institutions …	1	10
L – Education	**2**	**25**
LC – Special Aspects of Education	2	25
Q – Science	**77**	**563**
Q – Science – General	38	253
QH – Natural History, biology	15	141
QA – Mathematics	13	98
QC – Physics	7	50
QP – Physiology	2	13
QD – Chemistry	1	4
QL – Zoology	1	4
R – Medicine	**2**	**23**
RC – Internal Medicine	1	12
RA – Public Aspects of medicine	1	11
T – Technology	**10**	**121**
T – Technology – General	5	42
TK – Electrical Engineering …	4	65
TA – Engineering – Civil Engineering	1	14
U – Military Science	**1**	**8**
UG – Military Engineering, Air forces	1	8
Z – Bibliography. Library Science …	**8**	**63**
Z – Books (General), Writing …	7	56
ZA – Information resources	1	7
Books without LCC Codes	**6**	**27**
Total	177	1305

171 books have been classified under **B – Philosophy, Psychology, Religion**. How these seven books and their subject headings distribute over the next level in the classification is also shown in the table. That is, the table interlinks LCC classes to books and subject headings. Note that different subject headings might appear simultaneously in different LCC classes.

LCC numbers were then used to define a crosswalk of LCC classes to a wider scientific domain coding system (Table 3). We use the thirteen major scientific disciplines identified in the UCSD Map of Science (Börner, et al., 2012b) as a proxy for upper-level knowledge organization. For example, **QH**, **QP**, **QL** are assigned to **Biology**. Four domains from the UCSD map did not appear in the LCC codes: **Health Professionals**, **Infectious Diseases**, **Biotechnology**, and **Earth Sciences**. **Earth Sciences** was given a code because it could not be subsumed under a secondary code; **Biotechnology** was grouped with **Biology, Health**

Tab. 3: LCC class and science domain code crosswalk, with related book counts.

Code	Domain	LCC Class	Book Count	Notes
0	Science General	Q	37	Subjects that can be applied across domains.
1	Biology	QH, QP, QL	18	UCSD domain Biotechnology grouped here.
2	Medical Specialties	R (all)	2	UCSD domains Health Professionals grouped here.
3	Engineering	T, TA, UG	5	LCC class T is split between code 3 and 6.
4	Chemistry	QD	1	
5	Earth Science	—	0	
6	Electrical Engineering & Computer Science	T, TK, Z, ZA	14	Library and Information Science included
7	Brain Research	BC	1	Cognitive Science and Psychology
8	Humanities	B, BD, BF, BJ, LC	8	History, Philosophy, Education
9	Math & Physics	QA, QC	20	
10	Social Sciences	H (all), JN	65	Sociology, Economics, Business, etc. UCSD Infectious Diseases grouped here.

Professionals with **Medicine**, and infectious diseases with **Epidemiology** in the **Social Sciences**. A **Science General** category was also added to categorize subjects that either could be applied across domains (e.g., the subject heading Research is coded zero) or relates a specific domain's study of science broadly (e.g., **Science – social aspects** is coded zero and twelve to indicate connection between social science and the general study of science).

The division of domains within LCC classes does not align cleanly with the domains identified in the UCSD map. In particular, **Social Science** books are dispersed across and combined within LCC class divisions, while works related to modern technology are classified within the general **Technology** class. This is not unusual—classification and knowledge organization systems have a history within, and moreover are tailored towards, the collection for which they are designed (Smiraglia, 2014).

We then applied the same domain coding system to assign the book subject headings a scientific domain using a common code book. Each subject heading was assigned one to two of the eleven domain codes shown in Table 3. A subject heading's domain code was identified by analyzing its topic coverage and the LCC number(s) assigned to the book(s) using the particular subject heading. The goal of coding subject headings in this manner is to see where topics (as expressed by subject headings broadly) overlap across domains and disciplines. We treat subject headings as terms of a controlled vocabulary. Individually, or in combination with one another, they characterize a topic. Domain codes were applied in an as needed fashion; some subject headings have only one associated domain and secondary domain codes were only made when the subject is studied across multiple domains. Subject headings with broad application were mapped into the domain code zero. The resulting code matrix is unbalanced because some subject headings were given both a primary code for a domain most associated with a subject and a secondary code indicating the second domain associated with a subject. Likewise, many subjects were not coded twice.

The result of these multiple mappings is a co-occurrence of domains by the number of subject headings associated with both domains related to books on modeling science (Table 4).

Of the 675 unique subject headings, 317 subjects were coded with one domain. Conversely, 358 subject headings were assigned two domain codes as they were either complex subject headings, multiple concepts and domains imbedded in them (e.g., the subject heading *Science – Psychological aspects* would be coded for **Science (General)** and **Psychology**) or a subject heading topic was associated with multiple domains (e.g., the subject *Social Networks* is a methodology used within the **Electrical Engineering & Computer Science** and **Social Sciences** domains). The subject *Communication in science – Data processing* was coded **Science (Gen-**

Tab. 4: Cross tabulation of domain codes assigned to book subject headings.

Domain Name	Domain Code	0	1	2	3	4	6	7	8	9	10	Single Domain Code	Grand Total
Science (General)	0		1				1		2	6	15	17	42
Biology	1	2		3		3			4	13	3	23	51
Medicine	2		4							2	4	3	13
Engineering	3						1		2	5	6	5	19
Chemistry	4		1		2					3		6	12
Earth Science	5		3								2	0	5
Elect. Eng. & Comp. Science	6	3			6				1	**23**	**29**	**56**	**118**
Brain Research	7	1	7				1		5	2	**24**	9	49
Humanities	8	2	1				3			1	15	10	32
Math & Physics	9	2	4	1	7	2	14		1		10	**61**	**102**
Social Sciences	10	5	5				**23**	1	**50**	**21**		**127**	**232**

eral) and **Electrical Engineering & Computer Science** because *Communication in science* could refer to research by any number of domains, while the secondary topic *Data processing* is a topic most relevant to **Information and Computer Science.**[7]

The domains of **Social Sciences** (sociology, economics), **Math & Physics**, and **Computer and Information Science** are most strongly associated with subject headings from the 171 books, followed by **Biology, Psychology**, and general science domains. Domains with the most domain intersections are bolded in Table 4: **Social Sciences** and **Humanities** (50); **Electrical Engineering & Computer Science** and **Social Sciences** (29); **Brain Research** and **Social Sciences** (24); **Electrical Engineering & Computer Science** and **Math & Physics** (23); **Social Sciences** and **Electrical Engineering & Computer Science** (23); **Social Sciences** and **Math & Physics** (21). Please note that these intersections are created by the content of our specific set of books. In other words, books relevant to modeling science combine knowledge between social sciences, mathematics

7 Throughout the text, book subject heading are *italicized;* subject heading domains groups are **bold.**

(and physics), computer and information science. This also suggests that to be able to study models of science, readers and authors needs to be familiar with several areas of research.

4 Topical Space of Books Relevant for Modeling Science

Using the data detailed in the previous section, different topical spaces can be extracted, analyzed, visualized, and interpreted.

4.1 Major Subject Headings Linked to Books

To understand the topical space of books and subject headings, a bipartite network of the 177 books and their 675 subject headings was extracted. The resulting network has 852 nodes—too many to depict in a network layout in letter size. Using the Science of Science tool (Sci2)[8] and the Gephi[9] graph visualization platform, the network was analyzed to identify all subject nodes with an out-degree (i.e., number of linked books) greater than five, and all their associated books. The resulting network has 19 subject nodes and was laid out in a two dimensional space using a force-directed layout (Figure 2).

Subject heading nodes are colored pink and labeled by subject headings; the nodes for the 177 books are green and labeled with book titles. For the 19 subject heading nodes, node and label size increases and color darkens as the out-degree increases from six to 21. For book title nodes, the node and label size and the color are scaled according to the number of unique subject headings associated with a book title in the original network. Node labels are truncated to improve the readability of the graph.

Overall, the network shows that the high-degree subject headings and associated books cover a wide range of modeling approaches developed in diverse disciplines of science. *Science* characterizes many of the books, and its subcategories *Science – Social Aspects* and *Science – Philosophy* play a major role. We also see "Mathematics" and "Mathematical models". Specific areas in mathematical modeling emerge: *System Theory*, *Game Theory*, models of *Evolution* and *Social Networks*. Another set of subject headings describes research areas that inspired

8 http://sci2.cns.iu.edu

9 http://gephi.org

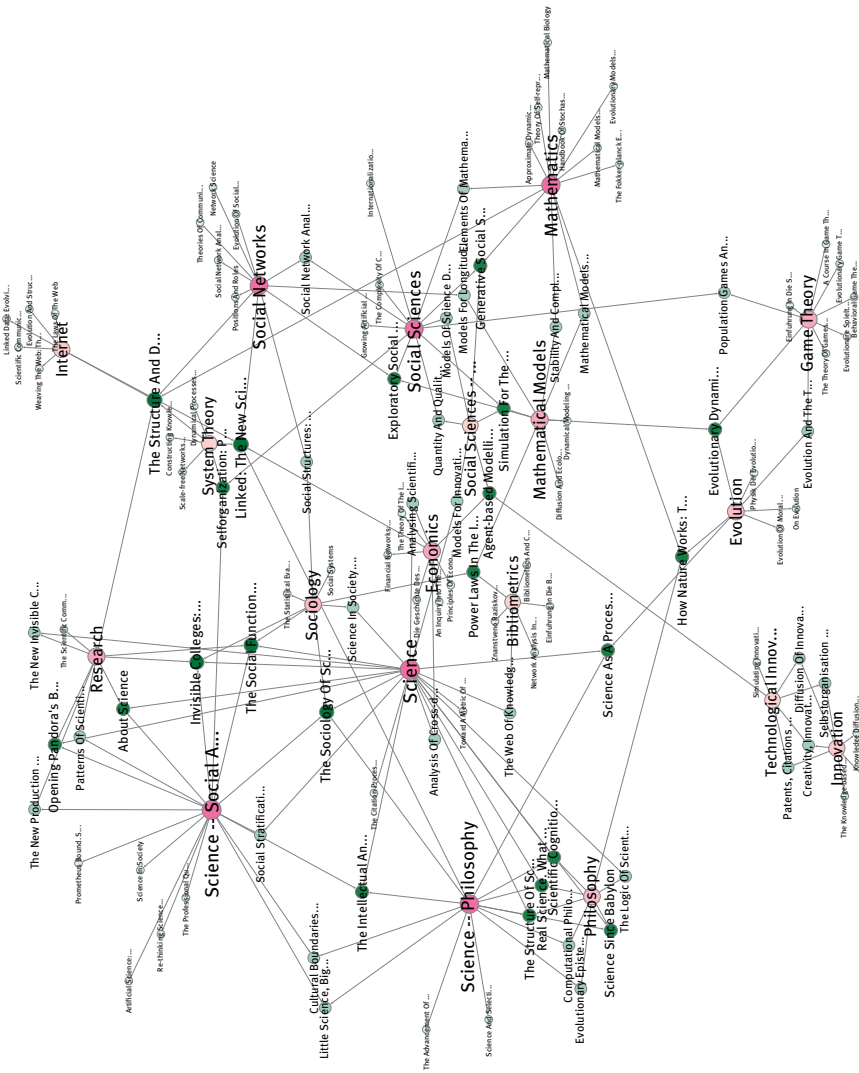


Fig. 2: Bimodal network of high-degree subject heading nodes (in pink) linked to associated book nodes (in green). See website at http://cns.iu.edu/2015-ModSci.html for a high-resolution, searchable pdf file.

new mathematical models of science to answer questions related to the process of knowledge production, e.g., *Innovation*, *Communication*, *Internet*, and *Bibliometrics*. While most books are associated with only one subject heading, some books are associated with many areas. Among them is *The Structure and Dynamics*

of Networks (Newman et al., 2006) which introduces the highly interdisciplinary, emerging area of network science to a broad audience. Usually, books belonging to the same epistemic thread are connected to the same subject headings. For instance, Per Bak's *How Nature Works* (1996) is linked to the subject node *Evolution* which contains other books that discuss evolution from the perspective of physics (physics of self-organization), game theory (evolutionary game theory), or biology. One of them is the German title *Physik der Evolutionsprozesse* (Ebeling et al., 1990)—a linkage that would be difficult to identify using linguistic analysis or citation-based analysis. Those two books belong to one research stream within statistical physics. Some titles do not deal with science specifically, but describe methods that can be applied to describe and model complex phenomena such as the science system itself. Only a close inspection of the content of the books can reveal this similarity, yet subject headings and library classification codes can be used to identify key linkages.

Figure 3 shows the same network using the very same node positions. However, the Blondel community detection[10] algorithm (Blondel et al., 2008) was applied randomly using a resolution parameter of 0.9. The networks modularity was measured to be 0.643. The communities detected in this network represent the major areas of research on models of science discussed in *Modelling Science Dynamics* (Scharnhorst et al., 2012), including, philosophy of science and knowledge (teal), science studies (yellow), innovation and communication in science (pink), economics and social sciences (purple), mathematical models (lime green), bibliometrics and information science (Kelly green), evolution and game theory (light blue), and computer science (blue).

The science studies community encompasses books from science and technology studies, such as the *New Production of Knowledge* by Gibbons et al. (1994), the classics *Invisible Colleges* by Crane (1972) from the sociology of science, as well as *The New Invisible College* by Wagner (2008) from bibliometrics. Also "Science" as general subject heading is put into this community. Note that *The Web of Knowledge: A Festschrift in Honor of Eugene Garfield*, edited by Blaise Cronin and Helen Barsky Atkins (2000) (indicated by a red dotted frame) bridges two major communities relevant to study science: the community of science studies "Science" and the community of "Bibliometrics".

10 The Blondel community detection algorithm partitions a network into communities based on the density of links in a network. A node's membership in a Blondel community is determined by its relationship to other nodes. Nodes are more likely to link to members within their community, than link to those outside of their communities. The algorithm detects and partitions communities based on the relative density of the relationship between nodes in a given network.

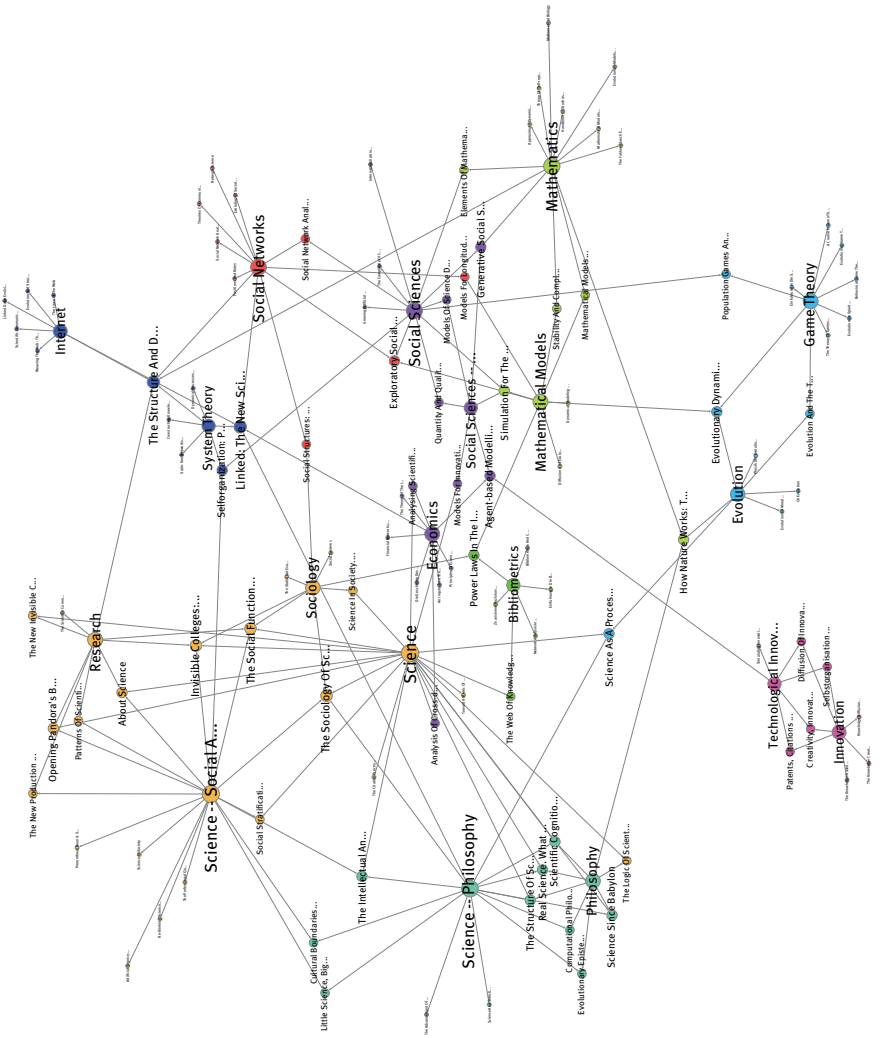
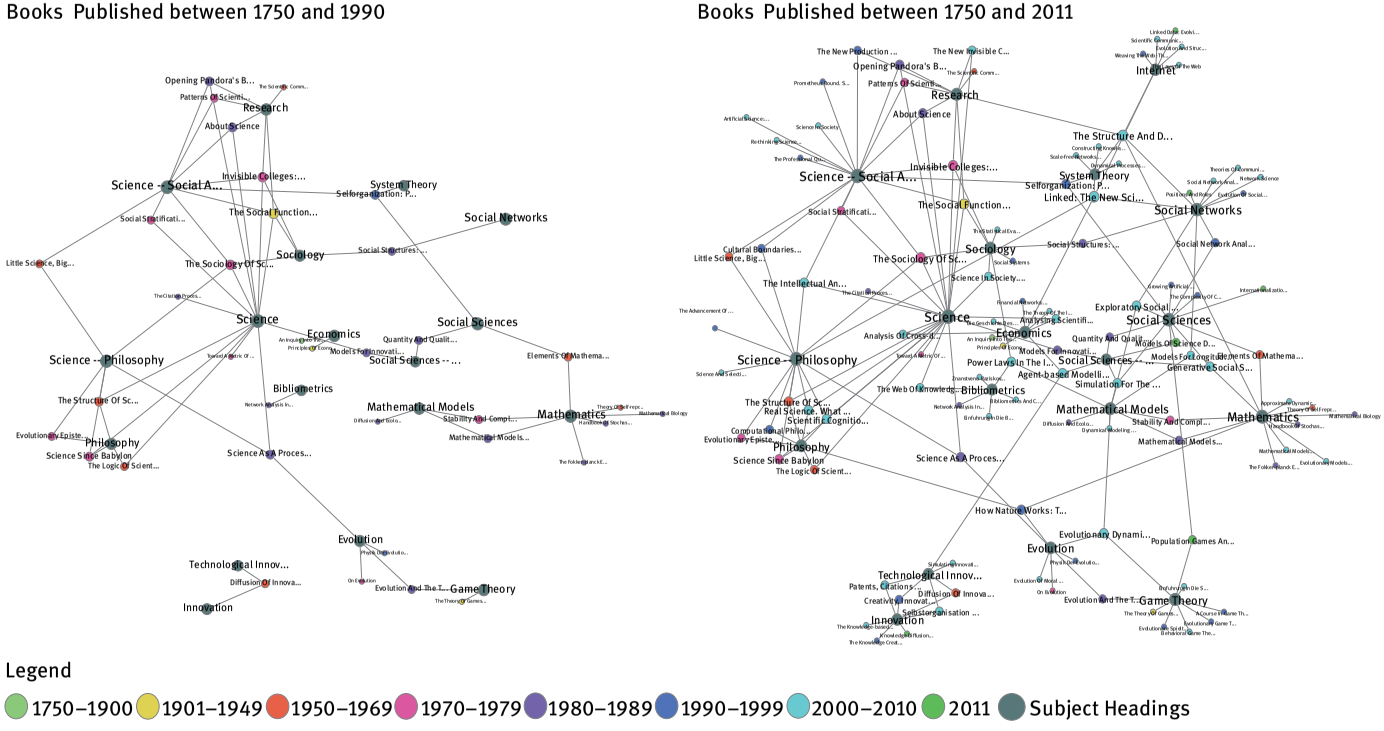


Fig. 3: Bimodal network of high-degree subject heading nodes linked to associated book nodes and colored by Blondel communities. See website at http://cns.iu.edu/2015-ModSci.html for a high-resolution, searchable pdf file.

As in Figure 2, the different subject headings are grouped by *disciplines*, *methods*, and *perspectives*. The community detection algorithm and coloring groups different subject headings, e.g., *Science – Philosophy* and *Philosophy*. It also makes visible how aggregations of subject headings are interlinked, e.g., *Mathematical Models* and *Mathematics* are closely interlinked with *Social Sciences*.



Legend

1750–1900 1901–1949 1950–1969 1970–1979 1980–1989 1990–1999 2000–2010 2011 Subject Headings

Fig. 4: Temporal comparison of networks by book publication date for period between 1990 and 2011. See website at http://cns.iu.edu/2015-ModSci.html for a high-resolution, searchable pdf file.

Figure 4 shows how the topic space of models of science has developed over time. We use the publication date of the different books (first print) and color coded book nodes by binned years. Books published between 1750 and 1990 are given on the left-hand side. 18 of the 19 subject headings are shown—only *Internet* is missing. Several books are not yet published. The full network is given on the right hand side—with book nodes colored by year bins. Early books in yellow and later books in cyan and green can be easily identified.

5 Limitations

A closer examination of *Models of Science Dynamics* (Scharnhorst et al., 2012) reveals some limitations of the present approach. The book is divided into three major parts: The "Foundations" includes two introductory chapters; the "Exemplary Model Types" part introduces three different types of models such as epidemics models, agent-based models, and game theoretic models; the "Exemplary Model Applications" section showcases the application of different models to study collaboration and citation networks. The chapters are written by author teams from different scientific disciplines and they cite different areas of work. Fourteen books are cited in more than one chapter or in the Foreword (FW) or Preface (PF) (Table 5). Among the books listed in Table 3, Kuhn's *Structure of Scientific Revolution* (1962) stands out, followed by Price *Little Science, Big Science* (1963). Although written in the 1960s, both still inspire today's modeling science efforts.

Figures 2–4 present only nine of the listed books as the other five are not connected to the highly interlinked 19 subject headings. For example, the *Atlas of Science* (Börner, 2010) has subject headings: *Classification of sciences – Atlases*, *Science – Atlases*, *Communication in science – Data processing*, *Digital mapping*. Only *Science – xxx* occurs in the network shown in Figures 2–4. However, the subject *Science – Atlas* was not merged under the term Science in the initial subject heading aggregation process and hence the book does not show in the figures.

Subject headings indicate multiple aspects of the topics covered in a work. Complex subject headings may be used to combine multiple topical subjects into one or to combine topical subjects with a specific methodology; temporal period and era; the material, format, and genre; or geographic regions and languages of a work. Many subject heading schemes have a hierarchical structure, e.g., a subject term has parent and child terms, or is a composite of two parent terms with two facets of co-equal status. In other words, there are relationships between subjects, books and classification schemes that are currently not utilized in this initial anal-

Tab. 5: Listing of books that are cited by more than one chapter, the Foreword, or Preface.

Title of the book (authors)	Year	Chapters*
The Theory of Games and Economic Behaviour (Von Neumann, Morgenstern)	1944	2,5
Human Behaviour and the Principle of Least-Effort (Zipf)	1949	1,3
The Structure of Scientific Revolutions (Kuhn)	1962	FW,PF,1,2,3,6
Little Science, Big Science and Beyond (Price)	1963	FW,PF,1,3,4,6
Invisible colleges: Diffusion of knowledge in scientific communities. (Crane)	1972	FW,1,6
The sociology of science: Theoretical and empirical investigations (Merton)	1973	PF,1,6
Matematicheskie modeli v issledovanii nauki (Yablonsikii)	1986	PF,FW
Introduction to informetrics: quantitative methods in library, documentation and information science (Egghe & Rousseau)	1990	FW,2,3
The New Production of Knowledge. The Dynamics of Science and Research in Contemporary Societies. (Gibbons et al.)	1994	1,6
Social network analysis: Methods and applications (Wasserman & Faust)	1994	6,7
Growing artificial societies: social science from the bottom up (Epstein & Axtell)	1996	2,4
Linked: The New Science of Networks (Barabási)	2002	PF,2,6
Evolution and structure of the Internet: A statistical physics approach (Pastor-Satorras & Vespignani)	2004	2,7
Atlas of Science: Visualizing What We Know (Börner)	2010	FW,PF,8

* PF = Preface, FW = Foreword

ysis. A follow-up study could refine links between books, classification schemes, and domains by using both topical and methodological subject headings.

There are also problems connected with the context-richness of subject headings. One problem is the vagueness of compound subject terms. Subjects headings like “Data processing”, “Methodology”, and “Research” can describe many ideas and techniques. However, compound subjects can allow for the collection of thematically related materials for later comparison. More specific methodological subjects, like network analysis, may be used to compare the use of a method or technique across disciplines.

While the bibliographic-bibliometric method proposed and exemplified here benefits from the collective wisdom of indexers, it also comes with its own caveats.

However, the resulting analyses and visualizations can be used to gain a new, more comprehensive understanding of the richness of scientific disciplines, methods, and perspectives as captured in books.

6 Conclusions

The edited book *Models of Science Dynamics* provided a review of major models of science for an expert audience (Scharnhorst et al., 2012). This chapter introduced and exemplified a novel means to construct the topical or concept space in which works on models of science are situated by using key books, library subject headings, and classification codes. Specifically, this chapter *extends* existing methods of bibliometric analysis of classification systems to subject headings, which come from multiple controlled vocabularies. We implemented a method to identify and classify both LC classifications and subject headings within a common framework of scientific domains to facilitate comparative analysis.

Our method, as applied to subject headings, is unique in that it reveals a degree of cross-domain pollination of concepts and method that is not captured with LCC numbers. While LCC numbers reveal the most unique domain associated with a work, our analysis of subject headings reveal the interlocking domains used to create models of science.

The bibliographic-bibliometric analysis of existing models of science provides a first depiction of major *disciplines*, *methods*, and *perspectives*. The study also highlights challenges and opportunities that arise when books, cataloging data, and subject headings are used in delineating and mapping a domain. It is our hope that this study inspires future reviews, exemplifications, and discussions of models of science developed in different scientific disciplines. Future work might expand this bibliographic-bibliometric analysis beyond books, e.g., to journal publications, course content, and/or encyclopedias. It might attempt to generate cross-walks between science, engineering, education, and other classification systems and taxonomies that define and organize different model types. Likely, challenges encountered in the work presented here will persist—document titles and author names are non-unique, the terminology used differs considerably among the different disciplines, and among catalogers.

Most relevant to the present volume, this work depicts the landscape of models of science by identifying key works and visualizing the relationships among these works. Starting with the references in one book on models of science (Scharnhorst et al., 2012), a landscape unfolds as diverse and broad as the table of contents in Bernal's book (Bernal, 1939). However, a comparison of the

headings of Bernal's book and the dominant subject headings in Figure 3 reveals an important difference. The structure of Bernal's book reads like a *what-to-be-modeled* list. Examples are organization (*The existing organization of research in Britain*), scientific practices (*The efficiency of scientific research*), scientific careers (*The training of the scientist*), and globalization (*International science*). In turn, the dominant subject headings form a checklist of necessary dimensions or ingredients for a *good* model of science, a *how-to-model* list. Such a model would need to address the epistemic foundations of science (*Science Philosophy*), its social structure (*Science Social*), its relations to innovations and economic growth (*Innovation*), and aspects of its networked nature (*Systems theory, Social Networks, Internet*). Taken together, these depictions provide science modelers with holistic orientation to begin their work.

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