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A Geohistorical Study of 'The Rise of Modern Science': Mapping Scientific Practice Through Urban Networks, 1500-1900

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Abstract

Using data on the 'career' paths of one thousand 'leading scientists' from 1450 to 1900, what is conventionally called the 'rise of modern science' is mapped as a changing geography of scientific practice in urban networks. Four distinctive networks of scientific practice are identified. A primate network centred on Padua and central and northern Italy in the sixteenth century expands across the Alps to become a polycentric network in the seventeenth century, which in turn dissipates into a weak polycentric network in the eighteenth century. The nineteenth century marks a huge change of scale as a primate network centred on Berlin and dominated by German-speaking universities. These geographies are interpreted as core-producing processes in Wallerstein's modern world-system; the rise of modern scientific practice is central to the development of structures of knowledge that relate to, but do not mirror, material changes in the system.

Keywords Modern science, Space of flows, Scientists, Scientific centres, Scientific practice, Urban, Networks

According to Immanuel Wallerstein (1974, 2004a), the modern world-system emerged in the 'long sixteenth century' (ca. 1450-1650) as a European-based world-economy straddling the Atlantic. Its basic structure encompassed a division of labour that defined core and periphery zones of economic activity. During the long period of its establishment, the core zone moved from Mediterranean Europe to North West Europe reflecting the reorientation of Europe to the rest of the world. It is the processes that create and recreate the core zone that have generated the social changes which have ultimately led to the elimination of all alternative world-systems; by ca. 1900 the modern world-system was effectively global in scope. One of these core processes has been what is conventionally known as the 'rise of modern science'.

As well as core-periphery spatial structures, world-systems analysis recognises structures of knowledge that have also changed in the unfolding of the modern world-system (Wallerstein 1999, 2004a, 2004b). The process that is identified as the 'rise of modern science' links these two structures.[1] In other words, adopting a world-systems analysis approach enables us to integrate the stories of changing science and changing geography through the modern world-system. The relevance of 'science' to social needs emanating from the endless accumulation of capital, the *differentia specifica* of the modern world-system, has encompassed both materialist reproduction (the work of science underpinning technology) and ideological reproduction (the idea of science underpinning progress).[2] This has culminated in science dominating modern structures of knowledge through two successful challenges to 'traditional knowledges': first a secular challenge to religious authority inherited from medieval knowledge structures, and second an empirical challenge to the critical philosophical knowledge that replaced the sacred; by ca. 1900 specialised scientific disciplines had been created in recognisably modern universities (Ben-David and Zloczower 1962; Wallerstein 2004b). This paper brings together these two parts of world-systems thinking, core-periphery and

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[1] The term structure is used here to mean the slowly changing bases of the modern world-system from which processes emanate to constitute the historical system (Wallerstein 1974; Sayer 1992).

[2] According to Wallerstein (2004b, p. 7), 'For very many, the label "scientific" and the label "modern" became virtually synonymous, and for almost everyone the label was meritorious'.

knowledge structures, by mapping the production of modern structures of knowledge through a detailed study of the changing geography of scientific practice in the modern world-system to 1900. We show it is a process located in the core of this world-system but its geography is always more complex than specification as simply core process indicates: sometimes scientific practice lags behind other core processes, at other times it is at the forefront of changes in core location.[3] We draw upon the encyclopaedic researches of Robert Gascoigne (1984, 1987, 1992) for historical data to depict these geographies of science.

In his historical demographic study of 'modern science', Gascoigne (1992) uses biographical data on 12,000 persons who practiced 'science' from the early thirteenth century through to 1900.[4] The pattern of change he presents matches Wallerstein's chronology of core zone changes: there is no growth of scientific activity through the medieval period but from sometime in the late fifteenth century onwards 'science' grows exponentially (Gascoigne 1992, p. 550). Furthermore, during the 'long sixteenth century', Italy initially grows to dominate in scientific activity but then stagnates to be 'overtaken' by England, France and

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[3] Ben-David used a core-periphery model in his classic studies of the rise of modern science (Schott 1993, pp. 475-477); our world-systems analysis differs from his work through setting these structures, and therefore scientific practice as a core-making process, within a historical systems framework (Wallerstein 2004a).

[4] Gascoigne has a very traditional approach to history that is 'Whiggish' in nature: he uses twentieth century categories to describe pre-twentieth century practices in an evolutionary argument. However, we understand that concepts such as 'scientist', and indeed 'science' and therefore 'scientific career', are quite problematic as descriptors for the time-scale of the modern world-system. For instance, Shapin and Thackray (1974, p. 3) have written that '[t]o write the history of any period before *ca* 1870 primarily in terms of such unqualified modern categories is to endanger the enterprise at its inception' with 'teleological assumptions'. However there are intellectual practices throughout the modern world-system that have come to be interpreted as contributing to the rise of what is now understood to be 'modern science'. These are the practices we are concerned with in this study and for which Gascoigne provides relevant information in the form of systematically organised data. Thus while we problematise the modern categories that describe the intellectual practices that are implicated in 'the rise of modern science', we do argue there to have been a process that can be traced through the history of the modern world-system that we will categorise as 'scientific practice'. While these earlier practices are not precisely 'modern science' since they occur in different social contexts, they do represent a lineage of work leading up to modern science. And it is this lineage that we study here: obviously just because 'science' was not socially constructed as a concept until the late nineteenth century, this does not mean that practices that are now viewed as 'scientific' were not undertaken before the modern conceptualizations. We are interested in this lineage of practice, which for ease of presentation we call scientific practice.

Germany, and specifically Holland (Gascoigne 1992, pp. 556-559; Ben-David 1971).[5] Subsequently within northern Europe, it is Germany in particular that contributes most to the spectacular growth of 'modern science' in the later years of Gascoigne's study. In this paper we break down Gascoigne's national geographical categories into the actual urban places in which the science is practised.[6] Further we map specific urban networks of science by focusing on the 'career' paths of one thousand 'scientists' that Gascoigne has identified as 'the most important in the period 1450-1900' (1992, p. 548; Gascoigne 1987). From this source we are able to recreate some of the spatial dynamics that were integral to the practice of science as it grew to become and be central to modernity.

The argument proceeds through three sections. First, we set out the parameters of our study within the context of the rise of historical geographies of science. We argue that our contribution is to bring in particular social theories that augment our understanding of the rise of science as a world-systems process. Second, we introduce the data we use, how we analyse it, and discuss different levels at which our results may be interpreted. Third, we present our findings on the spatial dynamics of the 'career' paths of leading scientists from 1500 to 1900. This highlights the geographies of connections across Europe in 'the rise of modern science'.

Historical Geographies of Science

David Livingstone (2005) has identified a geographical turn in science studies and this has been particularly the case for historical studies of science. In a recent review, Naylor (2005) specifies three such historical geographies of science: the microgeographies of science, the places where scientific activity occurs; the broader contexts in which science exists, defined by scale – these are city, region, national and international contexts; and cartographies of

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[5] For more detail on the latter see Davids (2001).

[6] This is another way in which our study differs from the work of Ben-David; he uses national units of analysis without any systematic investigation of the urban places where science was practised (Ben-David 1971; Schott 1993, pp. 458-462).

science, the geographies within science discourses. Despite a conclusion that identifies a need to go 'beyond place and culture' (Naylor 2005, p. 11), this framework is a very place-orientated conceptualisation of geographies.[7] He does note that there are 'many other ways of thinking geographically about the history of science' including thinking beyond 'fixity' to 'movements and circulations that help sustain […] science', but the latter is conspicuous by its absence from the substance of his review.[8] This is a classic example of the tendency of much of the more humanistic approach in human geography to focus on place at the expense of flows.[9] In this paper we take a more social science approach to our geography and bring flows to centre stage.

A key understanding to derive from more humanistic approaches to the historical study of science is the diversity of roles that practitioners of science have played. Steven Shapin (2006) emphasizes this heterogeneity by showing how the 'man of science' has been cleric, government official, clerk, family tutor, domestic servant, gentleman, medical practitioner as well as university scholar. The meanings of the science being practised obviously varied with the roles being played: thus, according to Harris (2006, p. 346), it is 'anachronistic to speak in terms either of a "scientific community" as a coherent group or of "scientist" as a professional designation during the early modern period'. There may have been no 'scientific community' as Gascoigne purports to measure, but this does not mean there were not collective practices of knowledge production.[10] Shapin's 'man of science' was also a 'man of letters', correspondence was very important: one of the Royal Society's foundation

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[7] We appreciate that the author provides 'only a brief and broad introduction' (p. 12) but it is in such limiting situations, where hard choices of inclusion and exclusion have to be made, that essential thinking is revealed.

[8] Powell (2007) similarly takes a largely place-orientated perspective in his review of geographies of science within and beyond the discipline of geography but points out the potential for future work on movement and circulation.

[9] Humanistic approaches to human geography were a reaction against studies of spatial models that reduced human beings to automatons (e.g. 'economic man'). The critique involved replacing theories of space by meanings of place in which interpretation of people was much more complex and recognisably human. This has carried over into studies of scientific practice through prioritizing place over flows but this is now changing: see Livingstone (2003), who discusses 'Circulation: Movements of Science' as one of three key 'geographical modalities' in his seminal exploration of geographies of science (the other being 'Site: Venues of Science' and 'Region: Cultures of Science').

[10] See footnote 4 above.

committees was the Correspondence Committee (Lux and Cook 1998). It is this communicative aspect of scientific practitioners, the ‘Republic of Letters’, that Harris (2006, pp. 347-348) focuses upon. Lux and Cook (1998) take a similar approach and highlight the problem of focussing on places with small groups, which they term ‘closed circles’. They argue for more attention being given to ‘open networks’: the ‘assumption that all practices are local practices [is] undercutting the sense of a European-wide movement’ in early modern scientific practice (Lux and Cook 1998, p. 201). Thus while respecting heterogeneity amongst scientific practitioners it is important not to throw out the communicative baby with the community bathwater in studying the lineage of modern science.

A key advantage of employing a social science approach to the historical study of science is that it gives access to pertinent social theory. For instance, Harris (2006, p. 354) in his discussion of the Republic of Letters draws upon Jürgen Habermas’s (1989) ideas to understand the overlapping and expanding networks of knowledge in early modern scientific practice as part of the new fabric of urban life that was the establishment of a public sphere. Lux and Cook (1998) provide a particularly creative adaptation of a social theory to historical circumstances. They use Mark Granovetter’s (1973) social network model that salvages the specific importance of weak ties in diffusions of ideas. The argument is that strong ties tend to be inward looking (closed circles) that play little part in passing ideas on. In contrast weak ties are vital as efficient transmitters of ideas; being in between the closed circles, they form the vital links in the circulation of ideas. Lux and Cook show how the replacement of a more informal Paris institution by the new secretive Academy of Sciences in 1666 led to a loss of weak ties through which Paris had linked the southern half of scientific Europe to the north. Properly applied, these studies show social theory can furnish useful tools for the historical study of science.

We employ different areas of social theory from those reported above. As indicated at the start, our study is framed by Wallerstein’s world-systems analysis.[11] We are concerned to describe and analyse one important core-making process: science practice. Our focus is on the creation of social spaces in the core zone of the modern world-system by agents (scientific practitioners) carrying out their (scientific) activities. Such activity reproduces spaces that sustain (scientific) trust between participants. In his general model of the production of social spaces, Manuel Castells (1996) identifies two types of social space: spaces of places and spaces of flows.[12] In the former contiguity facilitates face-to-face interaction creating places of activity that generate trust. A market place is a classic such space; a laboratory is an equivalent scientific space. With spaces of flows trust is based upon indirect contact, distant communication through which trust is built up. Banking networks are a classic case of this form of space (you let your salary be paid to strangers); publication in a peer-reviewed journal is an equivalent example of a space of flows that sustains scientific practice. Of course, these two forms of social spaces do not exist in isolation; they need one another: places are constituted by flows (input, throughput, output); flows are organized through places (nodes).[13] Therefore the research choice is not which space to study but rather which space to use as the starting point of analysis:[14] choosing where to start prioritises one type of space over the other but does not necessarily neglect the space not chosen first. It is in this spirit that we use spaces of flows as the initial social space below. This is to focus on the dynamics before addressing the fixity: to recover historical networks and then to consider nodes in the network.

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[11] Wallerstein employs a critical realist methodology that encompasses two main approaches: intensive research and extensive research (Sayer 1992). The former involves detailed study of the agents/actors who create the processes, whereas extensive research focuses on the broad patterns of (usually) quantitative data. Extensive research is often used as a prelude providing the statistical context for intensive research. This paper is an exercise in extensive social science; patterns of nodes and networks are described but the detailed interpretation of the agents in these places and flows is a further step towards improving understanding of the ‘rise of science’ that is not attempted here.

[12] Castells uses the two spaces to argue that contemporary globalization is characterised by spaces of flows dominating spaces of places as the key social space. We follow Giovanni Arrighi (1994) who shows that such an imbalance is not unique to the present; the concepts can be used as historical categories; see also Taylor (2007).

[13] The limiting cases of a purely fluid space of flows and a purely inert space of places do not exist in social relations; see Taylor (2007).

[14] See John Allen’s (1999) discussion on ‘city networks’ versus ‘networks of cities’.

Whereas spaces of places are observable as relatively neat maps, the study of spaces of flows is far messier: the myriad overlapping networks, chains, circuits and paths have been likened to dealing with a blizzard (Thrift 1999, p. 272). The Republic of Letters referred to above can be interpreted as part of just such a space of flows. In this study we research the ‘career’ paths of a population of scientists and aggregate them to show networks of workplace connections. This is an embodied space of flows that will have been a determinant of parts of the virtual Republic of Letters. The key advantage of dealing with aggregated ‘career’ paths is that it provides a manageable universe of flows to delineate the geohistorical patterns in the ‘rise of modern science’ as a material space of flows.[15]

Social flows are articulated through nodes, in this case the workplaces of scientists. Materialist urban theory that treats towns and cities as places of work can be brought into play at this point. We will use the urban theory of Jane Jacobs (1969) to make some sense of what happens to urban settlements when scientists (a university) come(s) to town. Her argument is that a city is a place within overlapping networks associated with unique internal complexity: a highly diverse urban place is a successful dynamic city. Scientific activity may be important in this process because, in Naylor’s terms, as well as ‘science’ creating ‘spaces and places for its own activities’, it also ‘spatializes the world in a wide variety of ways’ (2005, p. 3). In other words, scientific activity can have influences beyond its own sphere. We use Jacobs’ theory of city complexity to provide a new take on the perennial town versus gown conflict over place.

Data Construction and Analysis

The data for this study come from Gascoigne’s (1987) chronology of the history of science. Part 2 of Gascoigne’s work, entitled ‘The Social Dimension’, provides ‘career’ sketches of one thousand scientists, selected from an earlier more comprehensive list (Gascoigne 1984). Inclusion in the ‘top thousand’ list was based on ‘the degree of importance accorded to each [scientist] in various

[15] Other relevant flows include academic travel. See, for example, Jöns (2008).

biographical dictionaries and encyclopaedias and in histories of the individual sciences' (Gascoigne 1987, p. ix).[16] While inevitably based on some subjective judgement, a comparison of statistical data derived from this source with Gascoigne's (1984) original list and data compiled from the *Dictionary of Scientific Biography* shows a remarkable degree of consistency between the different sources (Gascoigne 1992).

Biographical entries on individual scientists are arranged by country or region (Italy, France, Britain, Germany, Holland, Scandinavia, Switzerland, Eastern Europe, Russia, United States); within each territory, individual 'careers' are placed chronologically by decade of 'career' start. Entries vary in length but generally list workplaces by town or city. Often these refer to universities and other teaching institutions, but other sites of scientific engagement (courts, museums, botanical gardens, observatories etc.) are also listed. For data collection and analysis, we divided the available data into four centuries of major developments in the history of 'modern science' (Fig. 1). In practical terms, this temporal division ensures a large enough number of scientists in each period to enable an analysis of key shifts by workplace rather than nationality of the scientists. More importantly, although centuries are arbitrary time periods, in this case they do relate to different phases in the 'rise of modern science' as indicated by the labels attached to them in Figure 1. Subsequent spatial analyses will confirm the utility of this time frame.[17]

[16] Of course, these sources are notoriously 'Whiggish' in nature (see footnote 4) but nevertheless they do provide relevant information for deriving a sample of relevant individuals who have contributed to the 'rise of modern science'. In this way we employ a 'collective biography' or basic prosopographic approach through aggregating 'career' paths in knowledge production. This is the lineage of modern science described below. Like any empirical study the results are only as good as the data; in this case we treat Gascoigne's massive encyclopaedic work as a reasonable starting point, while recognising that it could be improved. But that is for another research effort; the credibility of the results presented below do strongly suggest that Gascoigne provides a reasonable initial basis for describing the lineage of modern science.

[17] These centuries also broadly fit Wallerstein's (1974, 1980, 1989) chronicling of the early modern world-system: creation centred on the sixteenth century (reorientation of Mediterranean economy), consolidation centred on the seventeenth century (rise of North West Europe especially the Dutch), rivalry centred on the eighteenth century (mercantile struggles), and expansion centred on the nineteenth century (industrial revolution). Note also that Figure 1 contrasts with Riddle's (1993) data on university foundings (Figure 2, p. 55), which, as she points out (p. 55), show no relation to Wallerstein's world-system cycles. Clearly scientific practice and the establishment of

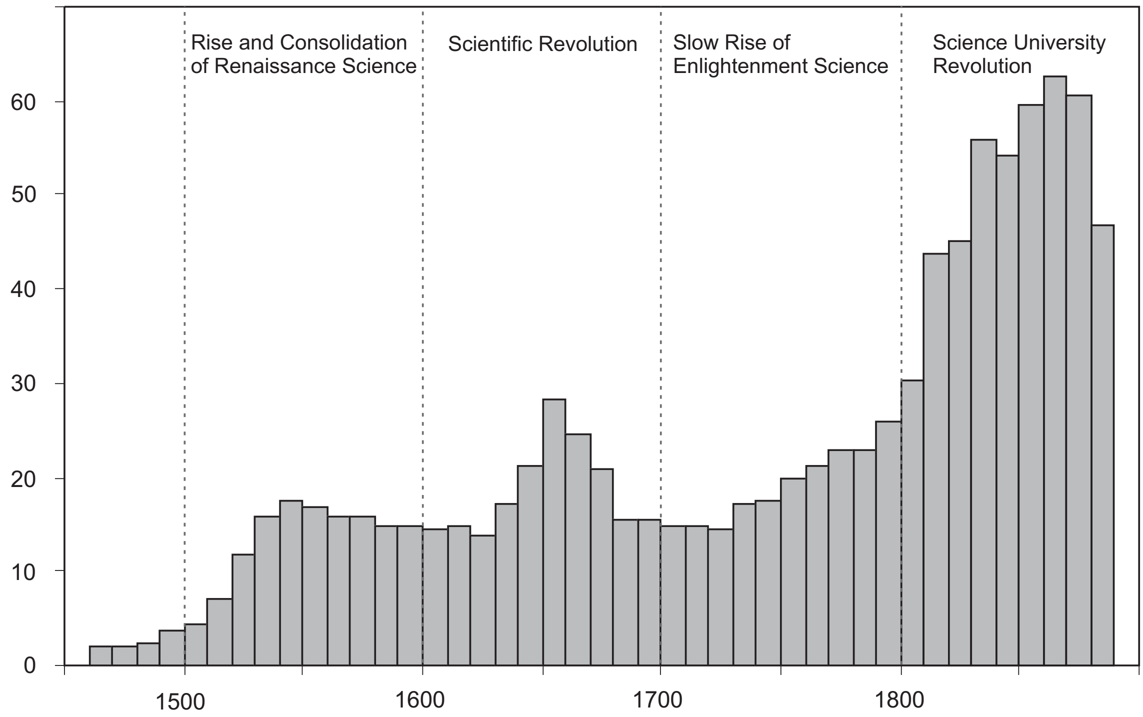

Fig. 1 Growth of the 'scientific community', based on data in Gascoigne (1987, pp. 529-535; amended version of Gascoigne, 1992, p. 551). Note: Number of 'leading scientists' by decade of 'career' start (three-decade moving average)

We initially recorded the 'career' paths of listed scientists in a matrix that arrays scientists (columns) against workplaces (rows). For each century, one such matrix was created: 116 scientists x 61 places in the 16th century; 151 scientists x 85 places in the 17th century; 145 scientists x 88 places in the 18th century; and 422 scientists x 114 places in the 19th century. Each cell of each matrix records presence or absence of a scientist in a particular location during their 'career'. The chronology of 'career' stops is indicated by the sequence of allocated numbers (i.e. 1 for first workplace, 2 for second workplace etc.).[18] In total, information was collected for 834 scientists for whom details of workplaces were available in the source.[19] This basic information allows a crude reconstruction of individual 'career' paths. For the purpose of this study, we then converted each of the scientist x place matrices into a place x place matrix (ranging in size from 61 x 61 places in the 16th century to 114 x 114 places in the 19th century). Each cell in these inter-workplace matrices records, for the

universities are distinctive and separate processes, the latter being particularly influenced by political structures (Riddle 1993). For spatial patterns of university foundations from 1500 to 1800, see Frijhoff (1996, pp. 95-105).

[18] Return to a previous workplace was also listed.

[19] As we focus on the rise of modern science in Europe, information on US-American scientists (predominantly 19th century) was also excluded from the study.

respective century, the number of ‘career’ stops of leading scientists that link two specific locations.

For each of the four analyses two sets of results are presented below. First, for each place we count the number of scientists who spent part of their ‘careers’ at that place. This provides a simple measure of the importance of a place; we will refer to it as the nodality of the place within the overall network. In this way the most important scientific workplaces can be identified for each century. Second, we focus on the dyads, pairs of places, and count the number of scientists whose ‘career’ paths encompassed both locations. In this way we can find the most important links between places. It is the latter that can be used to delineate the space of flows for each century.

Finally, before we present our results it is necessary to say something about interpretation. The findings below can be considered at two levels. First, at a literal level, they show actual patterns of ‘career’ path characteristics over four centuries. This is interesting in its own right but ‘career’ paths in and of themselves are not our prime concern.[20] Second, at an inferential level, the results represent a general patterning of the ‘rise of modern science’. Our conjecture is that our data and analysis indicates more than ‘career’ paths, they are surrogates for much broader processes. Whether this is substantiated depends on the robustness of the data, model and theory underpinning this extensive research. These have each been dealt with above but the proof is in the pudding so to speak. We know of no other mapping study that attempts to recreate a detailed urban geography of the ‘rise of modern science’ but we think our results are in line with what is known about this changing geography.

Geohistories of Scientific Career Paths

The basic geohistory of ‘modern science’ can be gleaned from the workplaces of leading scientists: Figure 2 shows the distribution of places where

[20] A large body of literature on the subject has developed since Eulenburg’s (1908) early study of academic recruitment in Germany. For an explicitly geographical perspective, see for example Meusburger (1990).

Gascoigne's leading scientists spent parts of their 'careers' over four centuries.[21]

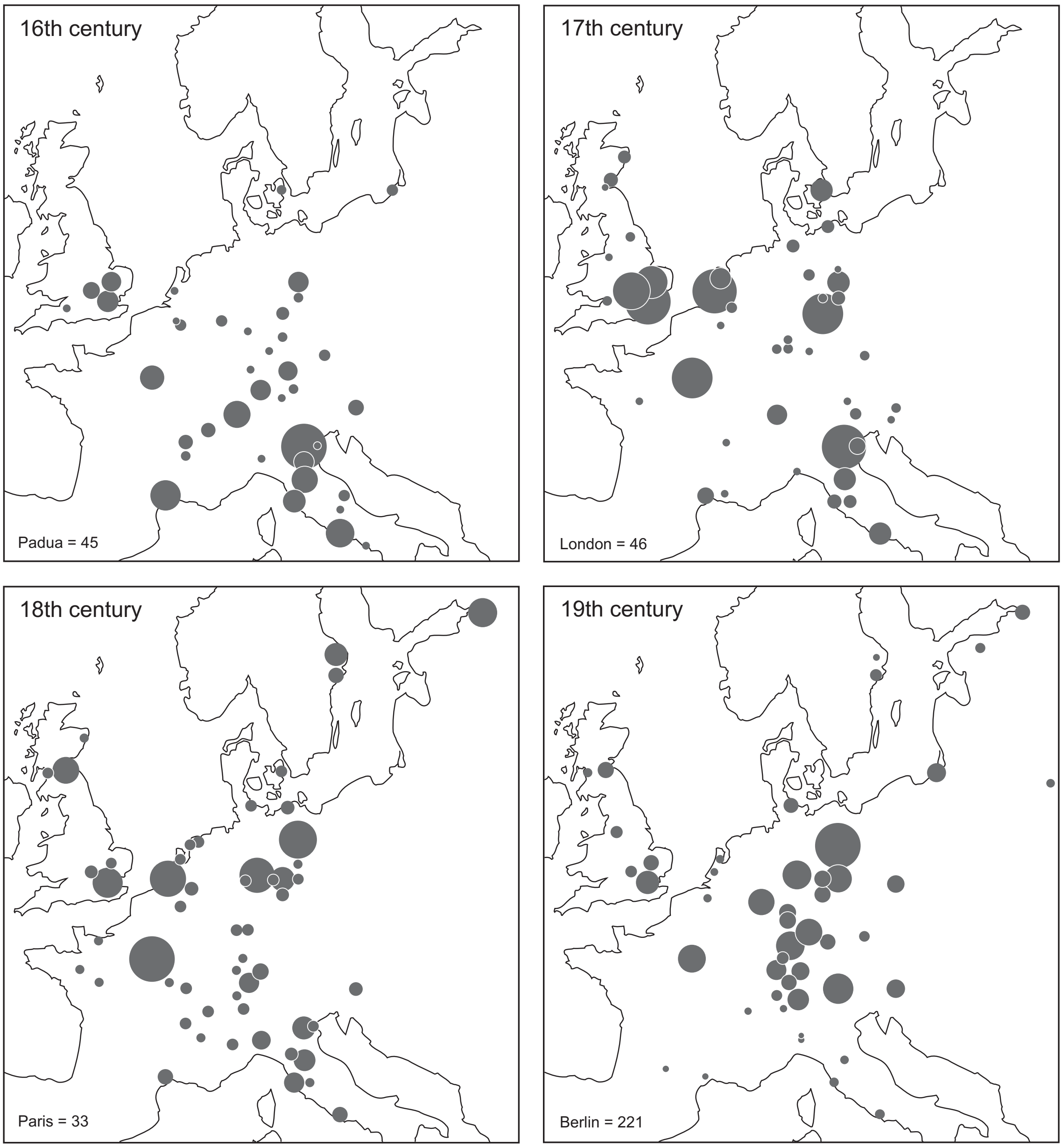

Fig. 2 Workplaces of leading scientists, 16th – 19th centuries. Note: Workplace symbols proportional to place with most 'career' stops in each century; perceptual scaling of symbols; absolute numbers for top places are given in Tables 1-4

[21] One of the most obvious features of these maps is that they each have a wide distribution of scientists across Europe. And yet, during the four centuries they cover, developments in means of transport developed greatly, culminating in railways in the nineteenth century. But the nineteenth century map (Figure 2(d)) has roughly the same spread, with just a little expansion to the east. We know from merchant activities that travel was Europe-wide by the sixteenth century and scientists seem to have covered this same activity space throughout the times of this study.

For each map places are shown proportional to the place with the most ‘career’ stops. The patterns are not surprising but do reinforce our preconceptions of what was happening across Europe in terms of scientific practice. Clearly in the sixteenth century northern and central Italy dominate in a ‘primate’ pattern centred on Padua.[22] Beyond this core region there are a string of places just north and west of the Alps plus Paris, the English Cambridge-London-Oxford triangle and a small German scattering. In the seventeenth century the pattern is very different: Padua continues to dominate in Italy but across the Alps there are four other important centres at London, Leiden, Paris and Jena. This is the only strong polycentric distribution we have uncovered in this research.[23] By the eighteenth century Italian places have declined as scientific centres and Paris now dominates in a weakly polycentric pattern. Finally, in the nineteenth century there is a reversal to a primate pattern, now centred on Berlin with Germany in general dominating places of science.

Table 1 Scientists’ movements through places in the sixteenth century

Places	Number	Proportion of highest	% of total
Padua	45	1.000	13.98%
Montpellier	22	0.489	6.83%
Rome	20	0.444	6.21%
Bologna	18	0.400	5.59%
Basel	18	0.400	5.59%
Paris	15	0.333	4.66%
Pisa	14	0.311	4.35%
London	12	0.267	3.73%
Wittenberg	11	0.244	3.42%
Tübingen	11	0.244	3.42%
Ferrara	11	0.244	3.42%
Cambridge	11	0.244	3.42%
Nuremberg	10	0.222	3.11%
Oxford	8	0.178	2.48%
Vienna	7	0.156	2.17%
Lyons	6	0.133	1.86%
Geneva	6	0.133	1.86%
Jena	5	0.111	1.55%

[22] A primate settlement pattern occurs when one centre dominates – is much larger than – all the other places.
[23] A polycentric settlement pattern is where there are several roughly equal centres i.e. no one place dominates: it is the opposite of a primate distribution.

Table 2 Scientists' movements through places in the seventeenth century

City	Number	Proportion of highest	% of total
London	46	1.000	9.75%
Leiden	44	0.957	9.32%
Padua	44	0.957	9.32%
Jena	38	0.826	8.05%
Paris	38	0.826	8.05%
Oxford	33	0.717	6.99%
Cambridge	26	0.565	5.51%
Bologna	14	0.304	2.97%
Wittenberg	14	0.304	2.97%
Copenhagen	13	0.283	2.75%
Rome	13	0.283	2.75%
Amsterdam	12	0.261	2.54%
Basel	11	0.239	2.33%
Montpellier	8	0.174	1.69%
Venice	8	0.174	1.69%
Leipzig	6	0.130	1.27%
Pisa	6	0.130	1.27%
St. Andrews	6	0.130	1.27%
Aberdeen	5	0.109	1.06%
Florence	5	0.109	1.06%
Hamburg	5	0.109	1.06%
Rostock	5	0.109	1.06%

Table 3 Scientists' movements through places in the eighteenth century

City	Number	Proportion of highest	% of total
Paris	33	1.000	9.54%
Berlin	24	0.727	6.94%
Leiden	22	0.667	6.36%
Göttingen	21	0.636	6.07%
London	16	0.485	4.62%
St. Petersburg	15	0.455	4.34%
Edinburgh	13	0.394	3.76%
Halle	11	0.333	3.18%
Padua	10	0.303	2.89%
Uppsala	10	0.303	2.89%
Bologna	9	0.273	2.60%
Freiburg	8	0.242	2.31%
Pisa	8	0.242	2.31%
Pavia	7	0.212	2.02%
Tübingen	6	0.182	1.73%
Montpellier	5	0.152	1.45%
Rome	5	0.152	1.45%
Stockholm	5	0.152	1.45%

Table 4 Scientists' movements through places in the nineteenth century

Place	Number	Proportion of highest	% of total
Berlin	221	1.000	10.88%
Munich	108	0.489	5.31%
Göttingen	99	0.448	4.87%
Heidelberg	97	0.439	4.77%
Leipzig	94	0.425	4.63%
Paris	93	0.421	4.58%
Würzburg	92	0.416	4.53%
Bonn	84	0.380	4.13%
London	68	0.308	3.35%
Zurich	59	0.267	2.90%
Strasbourg	52	0.235	2.56%
Königsberg	48	0.217	2.36%
Vienna	45	0.204	2.21%
Tübingen	43	0.195	2.12%
Breslau	41	0.186	2.02%
Giessen	41	0.186	2.02%
Halle	40	0.181	1.97%
Jena	39	0.176	1.92%
Marburg	39	0.176	1.92%
Edinburgh	36	0.163	1.77%
Freiburg	36	0.163	1.77%
Cambridge	33	0.149	1.62%
Erlangen	33	0.149	1.62%
St. Petersburg	32	0.145	1.57%
Kiel	31	0.140	1.53%

Part of the statistics from which these maps were drawn are given in Tables 1 to 4 in which the leading places are listed. In Tables 1, 2 and 3, for the sixteenth, seventeenth and eighteenth centuries respectively, the lists of top places include those where at least five leading scientists spent part of their 'career'. Three pieces of information are given for each place: its scientist count, its proportion of the highest count, and its percentage of all scientist 'career' stops for the century. Thus in Table 1 the primacy of Padua is clear having more than twice as many scientific 'career' stops as Montpellier ranked second. Furthermore, Padua has almost 14% of all 322 'career' stops we have recorded in the sixteenth century; this is by far the highest percentage we report for any century. The polycentricity of the seventeenth century is equally clear on Table 2 with three places covered by a range of just two stops and another four places with over half the 'career' stops of the highest. Note that the percentages for overall stops, there were 472, are all below 10%. In the eighteenth century

(Table 3) the growth of scientific ‘career’ stops stalls with only 346 recorded. Paris has the highest, with three other places showing over half of Paris’s relatively low total. Note that Berlin in second place is the highest ranked German place thus far. In this case the low level polycentricity is further shown by the lowest percentages of total stops recorded in this study. Finally, in Table 4 equivalent results for the nineteenth century are shown but with a total of 2032 ‘career’ stops recorded, the cut-off point for listing a place is set at 30. This change of criterion reflects a transformation of scale in the practice of science in Europe in the nineteenth century. The table confirms Berlin’s primacy and Germany’s dominance: twenty of the places listed are German-speaking universities. Berlin also records a percentage of total ‘career’ stops second only to Padua in the sixteenth century. However it is somewhat short of the latter’s percentage reflecting a far broader network of university science places in the nineteenth century.

The previous results show where scientific practices were taking place across the four centuries but do not show actual connections, dyad links between places. We have constructed a set of four maps that illustrate the changing space of flows through which ‘modern science’ has been constructed. The dyads we map are aggregates of ‘career’ links between places. In Figures 3, 4 and 5, for the sixteenth, seventeenth and eighteenth centuries respectively, all dyads with at least two links in scientists’ ‘career’ paths are shown. In Figure 3 sixteenth century European science is shown unmistakably as a network of links centred on Padua. Strongest links are found in Italy and in the English triangle but the latter is relatively isolated – Montpellier is clearly the second node of the network. In Figure 4 there is a clear expansion of the network, not just geographically across the Alps but as a strongly connected polycentric structure. Note that this diagram differentiates the main five centres as listed in Table 3. Although London is ranked first in terms of ‘career’ stops (Table 2) its position in the network is not so marked: the other four leading places all have more links than London, with Padua continuing to have most links overall, and Jena has by far the most strong links. London’s high number of ‘career’ stops (Table 2) is based simply on unusually close links within the English triangle during the scientific revolution. Figure 5 shows the eighteenth century pattern that suggests a dissolution of the previous century's space of flows. Here the network appears to be breaking up into four subnets: northern Italy just surviving, plus a mainly Paris-centred French net, a London-centred British net (including Scottish Enlightenment places and Leiden), and a more dispersed German net. There are only three dyads linking the subnets: Paris-Berlin, Paris-Pavia, and Leiden-Göttingen. This looks very much like the end of a process.

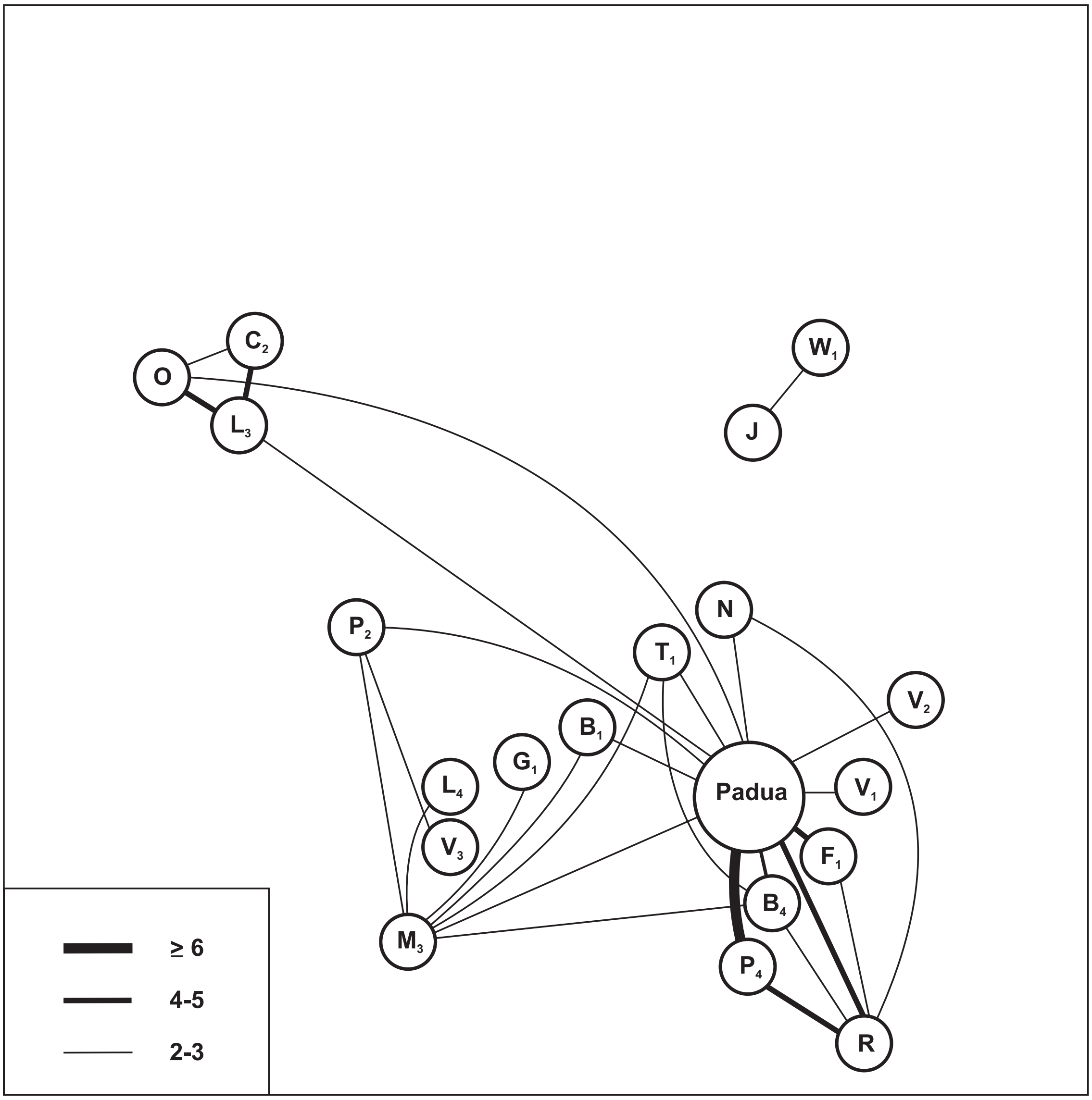

Fig. 3 16th century networks of scientific practice. City codes for Figures 3-6: A_1 Amsterdam, A_2 Avignon, B_1 Basel, B_2 Bath, B_3 Berlin, B_4 Bologna, B_5 Bonn, B_6 Breslau, C_1 Caen, C_2 Cambridge, C_3 Copenhagen, D Dijon, E Edinburgh, F_1 Ferrara, F_2 Florence, F_3 Freiburg, G_1 Geneva, G_2 Giessen, G_3 Glasgow, G_4 Göttingen, H_1 Halle, H_2 Heidelberg, H_3 Helmstedt, J Jena, K_1 Kiel, K_2 Königsberg, L_1 Leiden, L_2 Leipzig, L_3 London, L_4 Lyons, M_1 Marburg, M_2 Modena, M_3 Montpellier, M_4 Munich, N Nuremberg, O Oxford, P_1 Padua, P_2 Paris, P_3 Pavia, P_4 Pisa, R Rome, S_1 St Petersburg, S_2 Stockholm, S_3 Strasbourg, T_1 Tübingen, T_2 Turin, U Uppsala, V_1 Venice, V_2 Vienna, V_3 Vienne, W_1 Wittenberg, W_2 Würzburg, Z Zurich

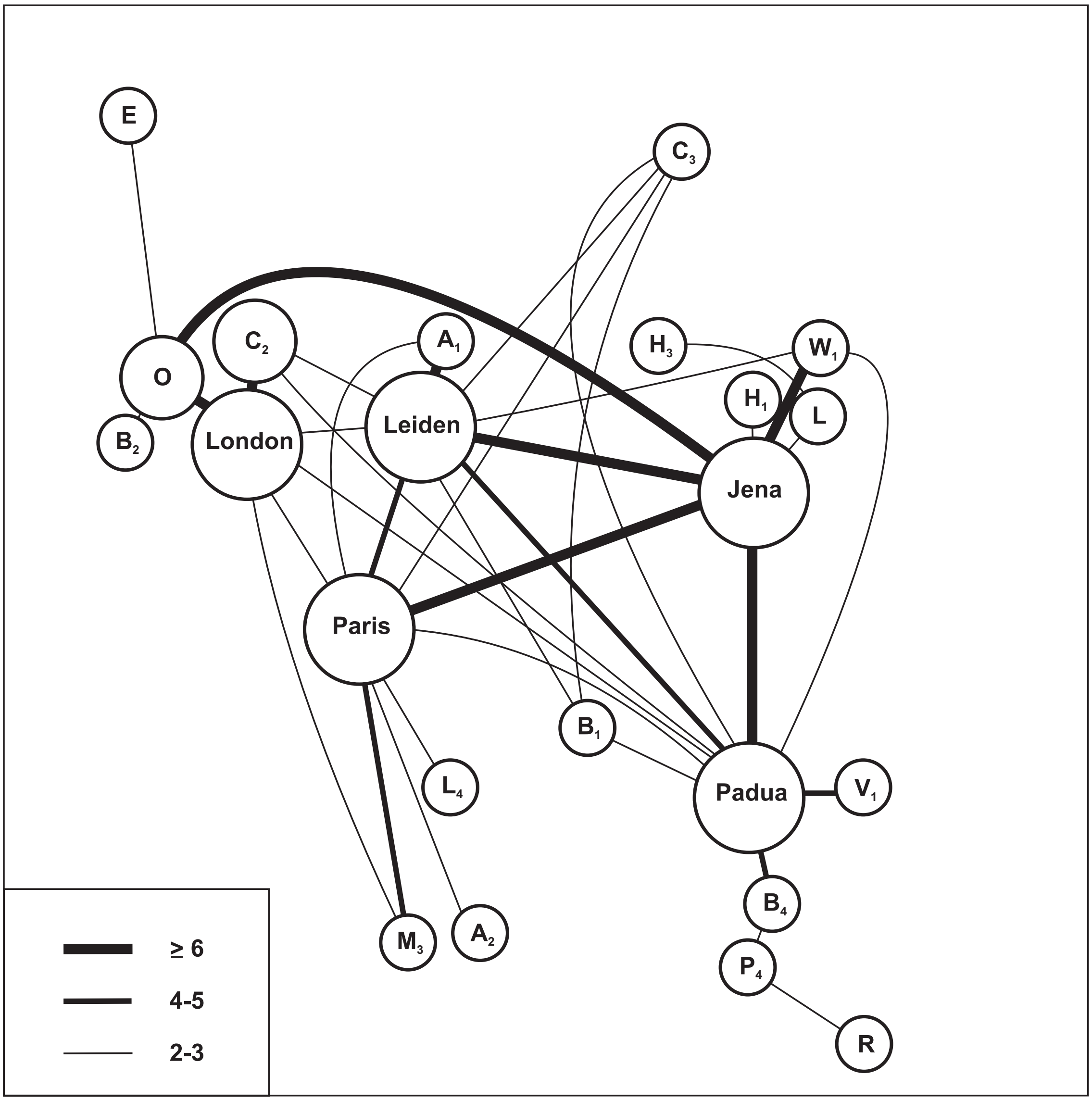

Fig. 4 17th century networks of scientific practice. For city codes, see Fig. 3

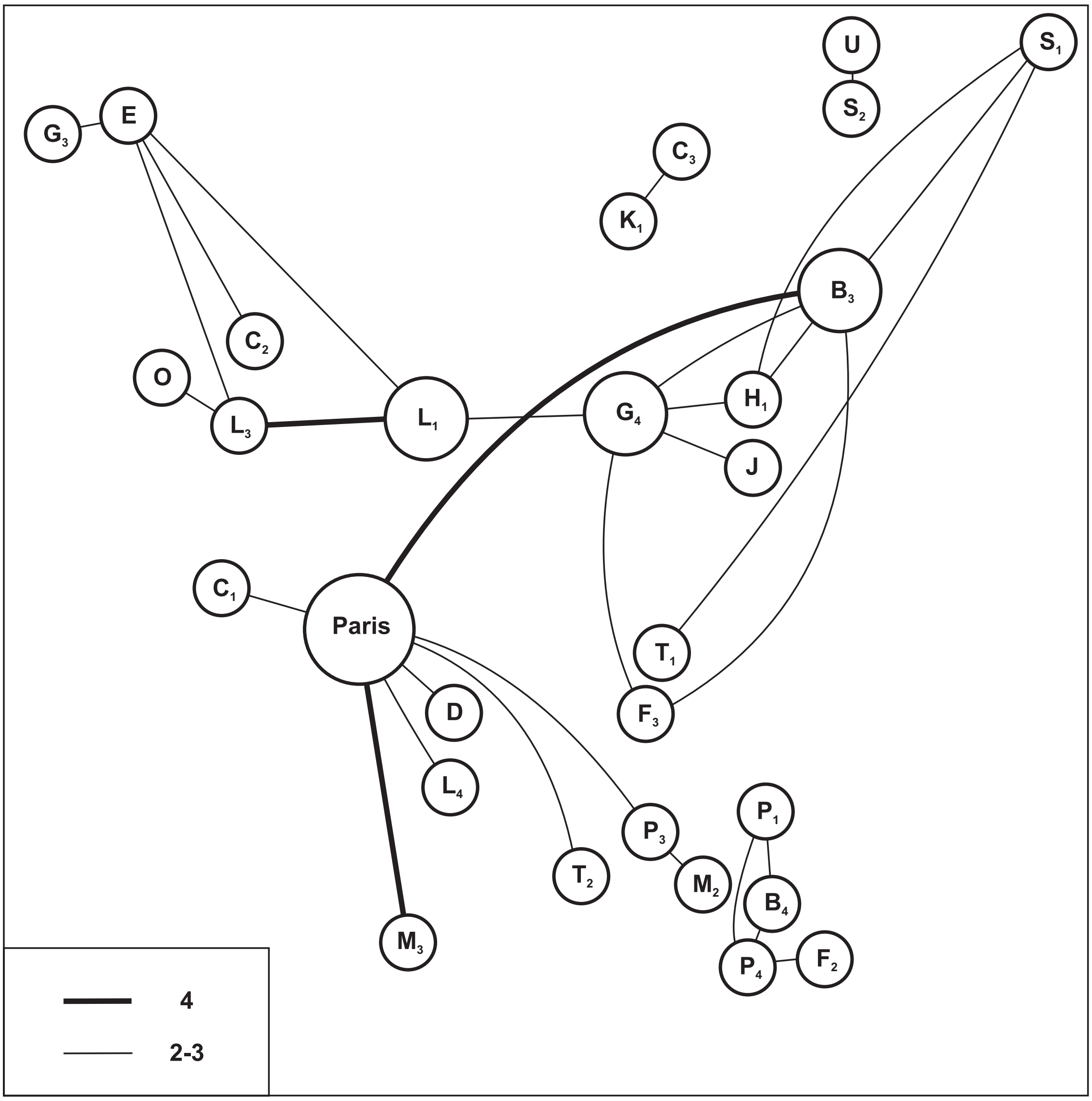

Fig. 5 18th century networks of scientific practice. For city codes, see Fig. 3

The diagram for the nineteenth century cannot use the same dyad size categories because of the scale of change: in Figure 6 all the dyads shown are in categories that were combined together in the largest category (over 6) in the previous three maps. This diagram emphasizes the primacy of Berlin and the dominance of Germany in a network pattern more definitively expressed than in any of the previous analyses. There is not just a change in scale, there is a qualitatively different network: a German-speaking net of universities that almost alone define the great growth of European scientific practice. Outside this major network only one other subnet appears – the English triangle plus Edinburgh as a very minor part of 'modern science' in nineteenth century

Europe. Overall Figure 6 represents the origins of the university-based 'modern science' that dominated worldwide scholarship in the twentieth century.

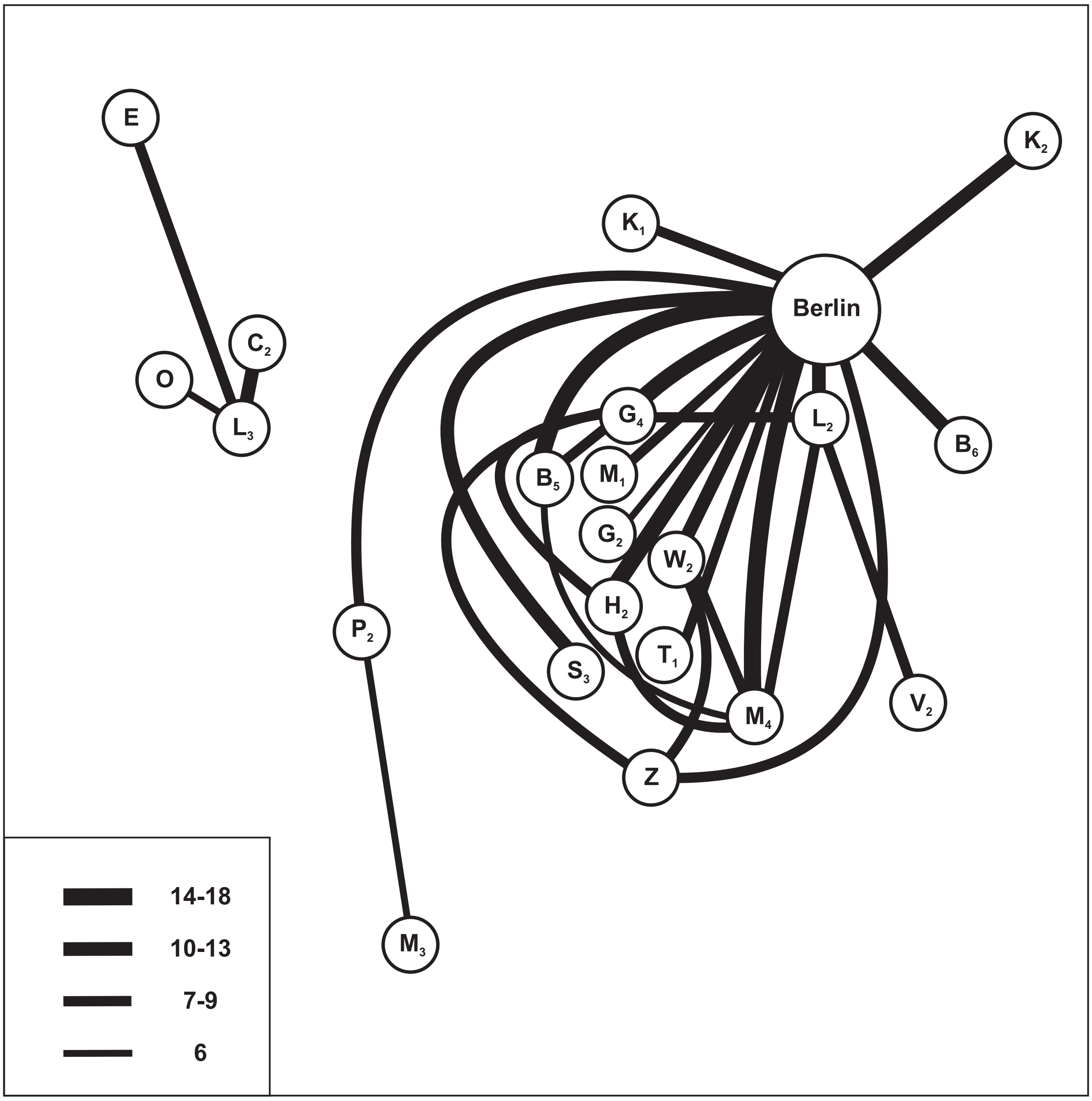

Fig. 6 19th century networks of scientific practice. For city codes, see Fig. 3

A Theoretical Excursion into Town-Gown Conflict

University towns have a special place in the urban theory that is employed in this study. Active nodes in vibrant networks are expected to produce large successful cities (Jacobs 1969; Taylor *et al.* 2008). But consider the following places that feature in the tables and maps above: Cambridge, Erlangen, Giessen, Göttingen, Heidelberg, Helmstedt, Jena, Marburg, Modena, Oxford, Pavia, St Andrews, Tübingen, Uppsala, Vienne, Wittenberg, and Würzburg. They are all small or medium sized urban places[24] that have been on the demographic margins of the great urbanization revolutions that made Europe the most urbanized world region in the modern world-system by the end of the nineteenth century. And yet these places have all been relatively important centres for the development of 'modern science'. The conundrum is, therefore, that since science is so important to modernity and the main demographic feature of modernity has been historically unprecedented high levels of urbanization, why have so many science centres *not* become major cities? There will be particular answers that can be given for every case above but given the quantity of cases, can there be a general explanation?

The first point to make is that there are also some places referred to in previous analyses that are today large cities – Berlin, London and Paris are the obvious examples. But these exceptions prove the rule: they are places that have grown as multi-functional modern capital cities in which science practice has not been an overriding dimension. And that is the point: the 17 science centres listed above have all been dominated by the science workplaces that are universities. In Jacobs' theory of economic expansion through cities the key process is diversification of division of labour to create complex economic entities.[25] The converse of this is the 'company town'. Such settlements might be efficient from the company point of view but their innate economic simplicity lessens opportunities for generating new work. Mill towns remain mill towns. Creating a new capital city is a similar one-function place production process that has created numerous politically-powerful but relatively small places (Abuja, Brazilia, Canberra, etc.): it took Washington, DC nearly two centuries to become a major US city because of its 'company town'[26] start (Abbott 1999). In other words, large clusters of scientists (i.e. universities) condemn their towns to likely never becoming important cities. University towns are company towns; like other 'companies' they thrive through monopolising power in relatively small

[24] All of these urban places have populations under 200,000 today.
[25] Jacobs (1969), see chapter 3 'Valuable Inefficiencies and Impracticalities of Cities'.
[26] Fifer (1981) actually referred to Washington, DC as 'a company town'.

urban places at the expense of the economic expansion of those places.[27] Thus Padua never became a Venice or Genoa, Leiden never became an Amsterdam, Uppsala never became a Stockholm, and Heidelberg and Würzburg never became a Hamburg or Munich. This monopolistic obstacle to economic growth is the essence of the town versus gown conflict.[28]

Conclusion

We have presented an extensive social science analysis of the 'rise of modern science' and briefly revealed one local economic effect of the rise. Starting with a northern Italian Renaissance centre of scientific practice based on Padua in the sixteenth century, the net expanded across the Alps to produce a Europe-wide polycentric network in which the scientific revolution blossomed. This integrated net was dissipated to a large degree in the eighteenth century Enlightenment resulting in a disjointed network loosely centred on Paris. It was all change in the nineteenth century with the German invention of the modern university harnessing scientific research and totally dominating advanced scientific practice. Taking the story forward we can say that the Berlin-centred net expanded across the Atlantic to produce a worldwide polycentric science network in the twentieth century. If the model is extrapolated it suggests that in the current century this successful net's organization will dissipate; we might argue that this is happening as scientific research leaves the university for new corporate masters in another qualitative change in the nature of scientific practice (Wallerstein 2004b).

We began this paper setting out a world-systems frame that interweaves spatial core-periphery structures with knowledge structures and we conclude with a

[27] Our study ends in 1900, but it can be noted that in several cases, in the twentieth century, 'town' has been able to fight back successfully against 'gown' turning, for example, Oxford into a major motor manufacturer and Cambridge into a high tech centre in the recent economic climate where universities are keen to show they are economic assets rather than obstacles: spin-offs are demanded in return for high levels of state support. But historically universities have been severe obstacles to economic growth: that is why so many centres of science practice in our geohistory are small places.

[28] For an orthodox discussion of the town-gown conflict, see Brockliss (2000).

comment on what this research has confirmed about this approach. The ‘rise of modern science’ can be interpreted as an archetypal core-making process that has worked its way through the history of the modern world-system to become central to what ‘modern’ is. But it has a particular geography and this is not necessarily congruent with other core-making processes: there is no simple, spatially coherent bundle of core processes. The latter would imply a rather uniform core-zone of social practices and that, of course, has never been the case. The interesting divergence of the ‘modern science’ process from other core-making is to be found in the relative unimportance of Britain during the period of its hegemonic cycle (late eighteenth century through the nineteenth century).[29] Britain was predominant in many things during its hegemony but not in ‘science’. This relates to our interpretation of the town-gown conundrum: it was not in Oxford and Cambridge that new practical technologies were created, rather the great cities of northern Britain such as Manchester, Birmingham and Glasgow were the vibrant cities underpinning British hegemony. Structures of knowledge are integral to the reproduction of the modern world-system in their own right, they do not simply mirror leading material and technological processes (Wallerstein 2004a).

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[29] Hegemonic cycles constitute the historical frame of Wallerstein’s (1984) modern world-system and are constituted by the rise, consolidation and fall of a power possessing dominant economic, cultural and political power (i.e. state hegemony). Wallerstein identifies three such cycles: Britain’s hegemony occurs after the Dutch and before American hegemony.

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