Flora, Cosmos, Salvatio: Pre-modern Academic Institutions and the Spread of Ideas

David de la Croix* Rossana Scebba† Chiara Zanardello‡

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Abstract

While having good ideas is not uncommon, their spread and evolution require a community. In premodern Europe (1084-1793), approximately 200 universities and 150 academies of sciences gathered thousands of scholars, shaping an extensive network of intellectual exchange. By reconstructing inter-personal connections through institutional affiliations, we demonstrate how the European academic landscape facilitated the diffusion of ideas and led cities to develop – examples include botanic gardens, astronomical observatories, and Protestantism. Counterfactual simulations reveal that both universities and academies played crucial roles, with academies being particularly effective in connecting distant parts of the network. Moreover, we show that idea diffusion through the network remains remarkably resilient, even after the removal of key regions such as England or France. In Europe, ideas gain significance being effectively channelled by powerful institutions.

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*IRES/LIDAM, UCLouvain & CEPR, Paris.
†IRES/LIDAM, UCLouvain & Research Unit of Early Modern History, KU Leuven.
‡IRES/LIDAM, UCLouvain.

1 Introduction

In Europe, during the Middle Ages and Early Modern period, more than one hundred thousand scholars were actively engaged in the production, dissemination, and development of various forms of knowledge. During their lifetime, it was not uncommon for some of them to have powerful ideas. Crucially, these scholars did not operate in isolation. Two key institutions facilitated their interaction: universities and academies. These institutions organized teaching and research within self-governed communities of scholars (Rashdall 1895; McClellan 1985). From the halls of medieval universities like the University of Paris and Bologna's *Alma mater*, to the lively debates in academies like the Royal Society much later, formal higher education institutions made it possible for scholars from diverse origins to engage in intellectual exchange. Not only these institutions employed scholars, but they also convened them in the sane physical spaces, thereby stimulating interaction. This intellectual exchange was further enhanced by the use of a common language, Latin, and, during the Middle Ages, the unifying authority of the Catholic Church.

In this paper, we measure how significant ideas spread through the academic affiliation network.[1] Specifically, we provide a quantitative analysis that models the diffusion of ideas through an evolving network of scholars with documented affiliations to formal institutions, based on data from the *Repertorium Eruditorum Totius Europae* project (RETE). As Becker et al. (2024) do for the pre-WWII period, connections between scholars are based on their overlapping presence at the same academic institutions. To simulate the transmission of ideas, we combine an epidemiological approach with the network structure (Banerjee et al. 2013; Koher et al. 2016; Fogli and Veldkamp 2021; Zamani et al. 2023). Our approach fits within the class of network diffusion models, such as the one formalized in Bramoullé and Genicot (2024). Importantly, we take the network as given, focusing on the dynamics of diffusion rather than on the mechanisms of network formation.

Our network is dynamic and spans from 1084 to 1793. This timeframe begins with the establishment of jurist Irnerius's (c. 1050 - after 1125) school of jurisprudence in Bologna, a forerunner of the Alma Mater, and concludes with the French Convention. The entities that constitute the graph, or the *nodes* of the network, are premodern scholars. A connection, or an *edge* in the network, is established between any pair of scholars who share at least one year of concurrent affiliation with the same institution and work within a broadly similar field. Following the view that ideas spread through networks like infectious diseases, we hypothesize that scholars can share their inventions to peers with a certain probability.

1. See Borgatti and Halgin (2011) for a survey of papers using affiliation networks.

At any given point in time, we can compute various measures of exposure to the simulated idea spreading through the network, capturing it at the scholar level, the institution level, and the city level. In what we refer to as "empirical assessments," we contrast the predicted outcomes of our model of knowledge spread via the affiliation network with actual Europe-wide trends, to evaluate the model's ability to account for observed patterns. By modeling the diffusion of key ideas, we aim to understand their potential long-term impacts on the European development, tracing influences that originated in the distant past.[2]

Our analysis begins with the development of botany. Leonhart Fuchs (1501 Wemding - 1566 Tübingen), a professor at the universities of Tübingen and Ingolstadt, established botany as a discipline independent of medicine. Through careful observation of nature, he updated the knowledge of plants and published a comprehensive herbal–a book detailing the medicinal uses of plants, complete with new descriptions and realistic illustrations. We label this paradigm shift as "Botanical Realism." Fuchs' work sparked widespread interest in botany across Europe, as evidenced by the rise of botanic gardens. To assess whether the diffusion pattern suggested by the academic affiliation network aligns with historical outcomes, we calculate the exposure of European cities to Fuchs' Botanical Realism over time and analyze its correlation with the establishment of botanic gardens. Using a proportional hazard model (Cox), we demonstrate that the likelihood for a city to see the creation of a botanic garden is positively correlated with its exposure to Botanical Realism.

The second empirical assessment focuses on the astronomical revolution that occurred during the Scientific Revolution all over Europe. We selected Johannes Regiomontanus (1436 Königsberg - 1476 Rome) as the pioneer of modern trigonometric tables and formulas later used by Copernicus, Kepler, and Galileo to effectively reform both mathematics and astronomy. We refer to this innovation as "Mathematical Astronomy." Regiomontanus was professor at the University of Vienna first and then also in Bratislava, Padua, and Rome. We assess the outreach of his advances in Mathematical Astronomy investigating the correlation with the creation of astronomical observatories. Specifically, using another proportional hazard model, we show that the likelihood for a city to see the creation of an astronomical observatory is positively correlated with its exposure to Mathematical Astronomy.

In both proportional hazard models, we account for the Euclidean distance from the idea's birthplace, thereby controlling for alternative diffusion pathways consistent with a gravity model. Consequently, our measure of exposure remains correlated with outcomes

2. Academia was not the only factor driving Europe's early economic rise but we focus on propositional knowledge generated within academia, particularly during the Scientific Revolution. We also keep in mind presence and the importance of practical knowledge developed and disseminated through self-managed institutions such as guilds and vocational schools (Mokyr 2002; De la Croix, Doepke, and Mokyr 2018).

even beyond these other channels. This is particularly striking in a world where books play a crucial role and the printing press facilitates the spread of ideas. It underscores the enduring importance of interpersonal connections in knowledge transmission, reinforcing the findings of Atkin, Chen, and Popov (2022) on the significance of face-to-face interactions for knowledge flows in the Silicon Valley today.

The third empirical assessment examines a less direct relation between ideas and outcomes, and covers a case of a backlash against an idea. Scholasticism, pioneered by Petrus Lombardus (c. 1100 Lumellogno - 1160 Paris), a professor in Paris, was the dominant approach to philosophy and theology in the Middle Ages. This framework used logical reasoning to explore theological questions and subsequently spread to other universities. Over time, however, it became increasingly detached from the practical concerns of believers, declining into abstract debates, a decline often cited in historical literature (Chaunu 2014; Barrett 2023). This detachment may have set the stage for the rise of Protestantism, which emerged as a reaction to Scholasticism, emphasizing the importance of scripture over intellectualized theological debate (Chaunu 2014). To test this hypothesis, we simulate the diffusion of Scholasticism through the affiliation network and measure exposure in 1508, just before Martin Luther's academic career began, to minimize potential counfounders. From the exposure to Scholasticism across universities in 1508 we infer the exposure of nearby cities. Using a linear probability model, we assess whether cities with higher exposure to Scholasticism were more likely to embrace Protestantism using the dataset and the control variables of Rubin (2014). The results show a strong correlation between exposure to Scholasticism and the likelihood of becoming Protestant.

Having demonstrated the model's effectiveness by comparing its predictions with real-world outcomes, we turn to exploring counterfactual scenarios. In this analysis, we compare observed outcomes with the hypothetical scenarios that would have emerged under alternative conditions. These conditions include: assigning the invention of a given idea to a different scholar within the network, removing affiliations to academies or to institutions situated in a specific geographical area, and excluding scholars belonging to the Jesuits community. By examining these counterfactuals, we aim to assess the network features that are most critical for idea diffusion.

It is important to emphasize that our focus on counterfactual scenarios is primarily methodological. We employ them as tools to gain a deeper understanding of the academic network's intrinsic properties rather than to definitively predict what might have occurred in these hypothetical situations. This approach aligns with the spirit of classic works like Fogel (1964)'s seminal study on the impact of railroads on American economic development, which emphasized the importance of counterfactual reasoning for historical analysis.

In the first counterfactual experiment, we attribute the intellectual origin of a particular idea to different figures from the same historical period and field, exploring whether the idea would spread differently under these alternative scenarios. This approach helps to pinpoint the conditions under which an idea might fail to propagate. One key finding is that the European academic network is so interconnected that, in most cases, ideas reach the entire network within two centuries, although the speed of diffusion and the specific pathways ideas take can vary significantly.

The second counterfactual analysis concerns the relative role of academies vs universities. Most academies were developed in the seventeenth century (the most well known one being the Royal Society, the French Académie des Sciences, and the German Leopoldina), but there were some forerunners in the century before (Cimento, Lincei, Mersenne). Compared to universities, they had a more international reach by appointing long distance scholars. Some respected scholars were members of as many as 20 academies (Carl Linnaeus, Joseph Banks, Leonhard Euler, etc.), which enhanced the circulation of ideas laying down ulterior spreading channels. To evaluate the importance of academies, we construct a counterfactual network without them. We simulate the spread of the same ideas in both the benchmark network and the counterfactual network. We look at the implied exposition to various ideas by city at the end of the period. In all cases considered, academies proved a strong multiplier effects. They allowed ideas developed in remote universities to reach all of Europe. They also proved useful to save ideas threatened by the closure of universities during wars (such as the Thirty Year war).

Beyond the influence of wars and academies, these simulations highlight the serendipitous nature of knowledge transmission. At times, an idea follows a remarkably narrow path, where sheer luck determines its survival.

The third counterfactual experiment draws inspiration from numerous country-specific analyses that emphasize the importance of particular nations. For example, during the Industrial Revolution, England applied scientific advancements developed by continental Europe (Kindleberger 1973). To explore this, we construct counterfactual affiliation networks by systematically removing all institutions based in specific countries. Specifically, we exclude institutions from the British Isles, France, the Italian Peninsula, and the Iberian Peninsula. However, since the two ideas under consideration originated in the Holy Roman Empire, we do not simulate a scenario without it. By comparing the diffusion of key ideas–Botanic Realism and Mathematical Astronomy–across the baseline network and these counterfactual networks, we evaluate the resulting city-level exposure to these ideas by the end of the period. Our findings reveal that some regionsof Europe were essential for the spread of these ideas.

Before delving further into the specifics of our approach, it is important to acknowledge that institutional overlap, while insightful, captures only a fragment of the multifaceted reality of knowledge dissemination in the premodern period. Our study primarily focuses on scholarly interactions within formal institutional settings during the medieval and premodern periods. These exchanges occurred through in-person interactions as well as institutionally-driven epistolary communication, as practiced in some academies. We emphasize the structured environment of these institutions, which facilitated scholarly interaction and fostered intellectual exchange. For instance, academy correspondence was directed to all members through official channels rather than through private, intentional communication. Beyond formal communication, these institutions also provided spaces for direct intellectual engagement among individuals.[3] A striking example of this dynamic is the relationship between the abovementioned Regiomontanus and Polish astronomer Martinus Bylica de Ilkusz, who met at the University of Padua in 1463. They formed a long-lasting intellectual bond–with Bylica amending manuscripts of Regiomontanus–which mirrored that of their mentors, respectively Georg Peuerbach and Martinus Król (Domonkos 1968), and underscores how institutional settings fostered scholarly connections also across generations.

While our model prioritizes scholar-to-scholar interactions within institutions, we recognize that, in the realm of in-person intellectual exchanges, student-teacher relationships, as well as student associations (such as *nationes*, *bursae*, fraternities and others) also played a part in the dissemination of ideas (see Koschnick (2023) on teacher-student interactions in Oxford and Cambridge). However, incorporating students into our analysis, based on the RETE project, would pose some significant challenges. First, RETE focuses primarily on scholars affiliated with institutions, limiting systematic identification and tracing of student networks.[4] Second, even if we were to extend our analysis beyond RETE, reconstructing comprehensive student attendance records from the medieval and early modern periods is a highly complex task, not only due to incomplete or fragmentary data but also because students were more transitory members of university communities compared to professors. Third, expanding our database to include students may disproportionately capture those who later became scholars (as opposed to those who pursued careers in the clergy, gov-

3. Aggregation centers were crucial for intellectual exchange in the medieval and premodern world. As shown by Brunt and García-Peñalosa (2022), cities played a similar role in fostering knowledge diffusion by concentrating individuals and increasing opportunities for encounters and idea transmission.

4. The *Repertorium Eruditorum Totius Europae* project primarily focuses on individuals who represent the "upper tail" of talent and knowledge distribution within premodern European society–those who likely achieved a high level of recognized scholarship.

ernment service, medicine, or trade), leading to a non-representative sample and potential survival bias. Lastly, while our study includes both universities and academies as hubs of knowledge and intellectual exchange, there is a structural difference: universities included a student body, whereas early modern academies typically did not. Incorporating students into our study would thus create an inconsistency by comparing scholars alone in academies with a mix of students and scholars in universities.

Other avenues, such as reading habits, undoubtedly contributed to knowledge dissemination, quantifying their impact remains challenging. Citations could offer some insights to what was being read and discussed in the academic community (Zhao and Strotmann 2015), yet they would fail to provide a complete picture of reading patterns.[5] While citations can reflect "positive" engagement with prior work, including critical remarks, they fail to capture instances where scholars deliberately avoid acknowledging influential ideas. Put simply, not all works that were read were cited, and this very occurrence further underscores the limitations of citation analysis in reconstructing the full spectrum of intellectual interaction. Our study, therefore, focuses on traceable, institutionally-mediated pathways through which ideas spread. Unlike in biological contagion, 'infection' in the context of idea diffusion does not imply endorsement or adoption. As Banerjee et al. (2013) highlight in their study on microfinance diffusion, individuals may receive or transmit information without endorsing it. For this reason, we prefer to speak of exposure rather than infection.

This distinction also informs our methodological approach. In the spirit of an intent-to-treat (ITT) framework, we focus not on actual compliance with ideas, but on the potential for exposure. By observing whether scholars were present in the same location at the same time–specifically, in universities or academies, which typically had a limited number of scholars–we can infer exposure to ideas, regardless of whether these ideas were ultimately adopted (i.e., compliance). This approach contrasts with much of the existing literature on the diffusion of knowledge, which relies on measures such as the actual content of publications, correspondence, citations, translations, or co-authorship, all of which inherently assume compliance (Goyal, Van Der Leij, and Moraga-González 2006; Donker 2024; Abramitzky and Sin 2014; Hallmann, Hanlon, and Rosenberger 2022; Roller 2023). In randomized controlled trials, ITT is generally preferred for primary analysis because it avoids the biases that arise from excluding non-compliant participants and preserves the benefits of randomization. In ITT analysis, estimate of treatment effect is generally conservative (Gupta 2011). We apply this same principle to trace the diffusion of ideas.

5. Moreover, in premodern texts, citations did not follow standardized formats like those used today, making it difficult to systematically trace them across different works.

Another advantage of our approach is that we know were the gaps are in our affiliation network. Gaps occur when some universities are not well covered by the sources we used, leading us to miss some of their professors. In contrast, in correspondence network, it is impossible to know whether letters are missing–or how many. Gaps, in that case, are impossible to assess.

The paper is organized as follows. Section 2 presents the methodology, including the construction of the database and how it is mapped into an affiliation network. It also presents the epidemiological model to simulate the diffusion of ideas. Section 3 presents the three empirical assessments, based on flora, cosmos and *salvatio* (Scholasticism). The counterfactual experiments are detailed in Section 4. Section 5 concludes.

2 Methodology

We now present our methodology, starting with the constitution of the database of professors, followed by the definition of the temporal network and the epidemiological model used to describe how ideas flow.

2.1 79555 scholars

The comprehensive database of scholars we compiled and utilized comprises information on 79,555 individuals spanning the period 1000 - 1800. The data were manually collected from 662 distinct sources. Unlike other studies that rely on ex-post recognition of scholars–such as that derived from Wikipedia/Wikidata, see Laouenan et al. (2022) and Serafinelli and Tabellini (2022) – our selection is based on membership lists or secondary sources related to key higher education institutions. These institutions fall into three categories: universities (referenced in Frijhoff (1996), see also De la Croix et al. (2024)), scientific academies (as cataloged in McClellan (1985), and further discussed in Zanardello (2024)), and various other institutions with links to universities, including Italian Renaissance academies mentioned in The British Library (2021), and other higher education entities that conferred academic degrees.

Medieval universities primarily focused on four disciplines: theology, law, arts and humanities, and medicine. The faculty of arts provided foundational education to grammar school pupils, many of whom became teachers themselves, contributing to rising literacy rates among the general population. Some students progressed to higher faculties, preparing for professions in other fields. The faculty of medicine trained medical practitioners, the faculty of laws produced future administrators with specialized knowledge in canon or civil law, and the faculty of theology educated teachers for episcopal schools, where ordinary parish priests were instructed (Pedersen 1992). Academies, emerging later in the 17th and 18th centuries, were created to foster new areas of research not traditionally covered by universities (McClellan 1985; Applebaum 2003). These ranged from informal groups of amateur naturalists or local historians to prominent official societies that gathered leading scholars, published journals, and formed networks of corresponding members, known collectively as the Republic of Letters (Mokyr 2016).

To compile the list of scholars from each academy and university, we mostly relied on secondary sources, primarily books detailing the history of these institutions and their members based on primary records. For universities, our aim was to include scholars involved in teaching, covering a range of positions from royal chairs in France to fellowships in England. Further details on the inclusion criteria for university scholars can be found in De la Croix et al. (2024), while global statistics are available in De la Croix (2021) and various issues of the *Repertorium Eruditorum Totius Europae*. For academies, this process was generally straightforward since comprehensive membership lists are often available. Our data on academies have already been utilized in works such as Blasutto and De la Croix (2023) for Italian academies, De la Croix and Goñi (2024) for analyzing father-son pairs across academies and universities, and Zanardello (2024) for evaluating the impact of different fields of study within academies. These lists encompass several membership categories, including ordinary, corresponding, and honorary members. Corresponding members, though not present at academy meetings, contributed from a distance. Honorary members often included local dignitaries like bishops, wealthy merchants, and governors, who supported and protected the academies. To prevent skewing our results due to the inclusion of these sometimes prominent figures, we excluded anyone holding honorary membership or those clearly not scholars or intellectuals (e.g., Napoleon, who was elected to the Académie des Sciences in 1797).

The resulting database can be accessed at https://shiny-lidam.sipr.ucl.ac.be/scholars/.

Additionally, we leverage data from VIAF and Wikipedia entries associated to each person in the database, when available, to provide a unique measure for individual quality (Curtis and De la Croix 2023). This variable aims at reflecting a scholar's influence and recognition, is then combined using Principal Component Analysis to create a single "human capital index" score for each individual. Later in the paper, we will refer to this measure and employ it in our analysis.

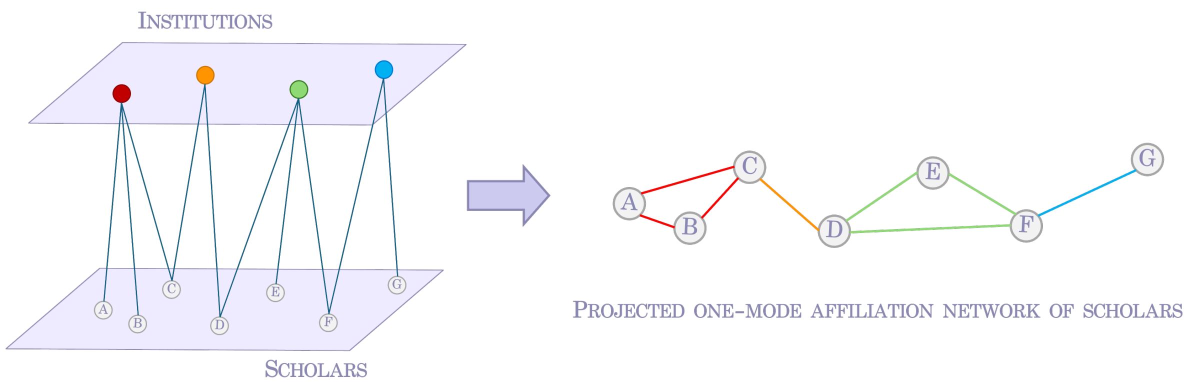


Figure 1: Intuitive representation of network projection: from a bipartite or two-mode graph to the one-mone affiliation network of scholars.

2.2 Definition of the affiliation network $\mathbb{G}$

We now look at the data on scholars and their affiliation to institutions using the lens of network theory, a powerful tool to study the spread of information over time and space, among other subjects (Jackson 2008; Goyal 2023). We model the affiliation network as a graph, where *nodes* represent scholars and *edges* denote their shared presence at the same institution during overlapping years. This network is derived from an initial bipartite representation, consisting of two types of nodes: scholars and institutions. In the bipartite version, edges connect scholars to the institutions they were affiliated with. Since our focus is on scholar-to-scholar interactions, we project this bipartite graph onto a single-mode network of scholars, where an edge between two nodes represents their concurrent affiliation with the same institution, as shown in Figure 1.[6] Premodern universities were small compared to universities of today. It is thus reasonable to assume that all the professors knew each other. Appendix A presents some descriptive statistics for the 10 cities with the highest number of scholars in 1793, differentiating by type of institution (university vs academy). On average, cities with a university do not have more than 60 professors. On the other hand, cities with an academy host a higher number of scholars on average, reaching 80 in Halle and Paris, and 126 in London. Nevertheless, the average number of scholars for academies is much more volatile, reflecting a more flexible structure and a higher presence of corresponding members.

Our analysis spans from the foundation of a new school of jurisprudence, which would later become the University of Bologna, in $\underline{t} = 1084$, to the French Convention in $\bar{t} = 1793$ which led to the abrupt closure of all universities and academies on the territory of the new

6. A complementary approach consists in using a network of institutions only, see De la Croix and Morault (2025).

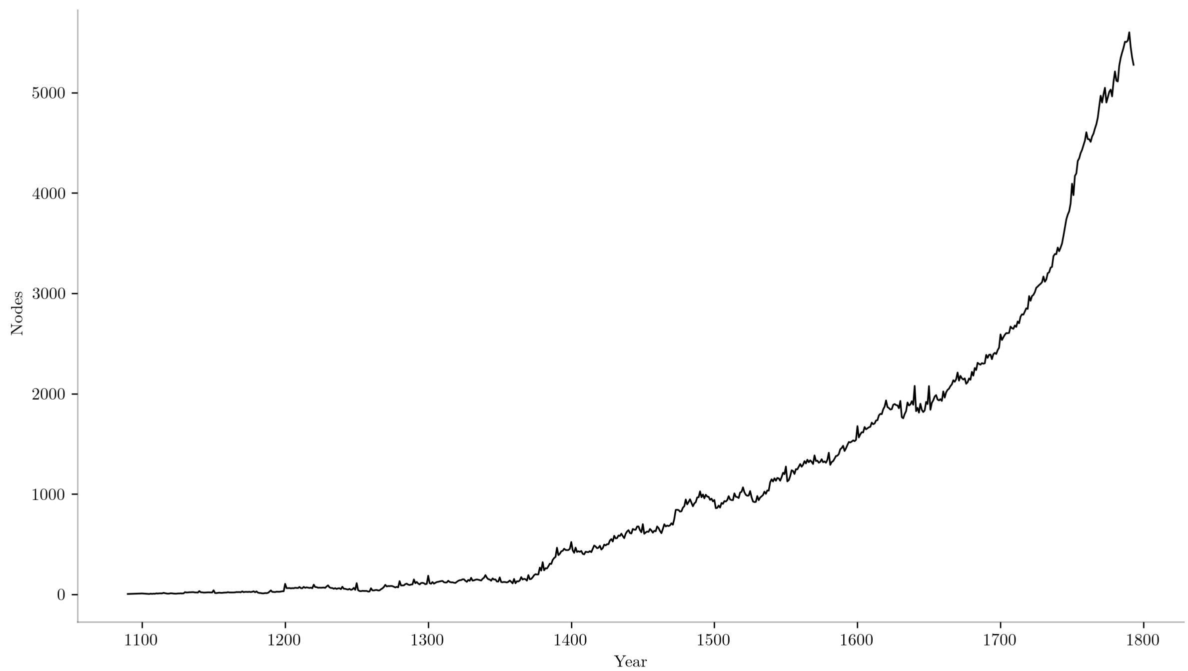
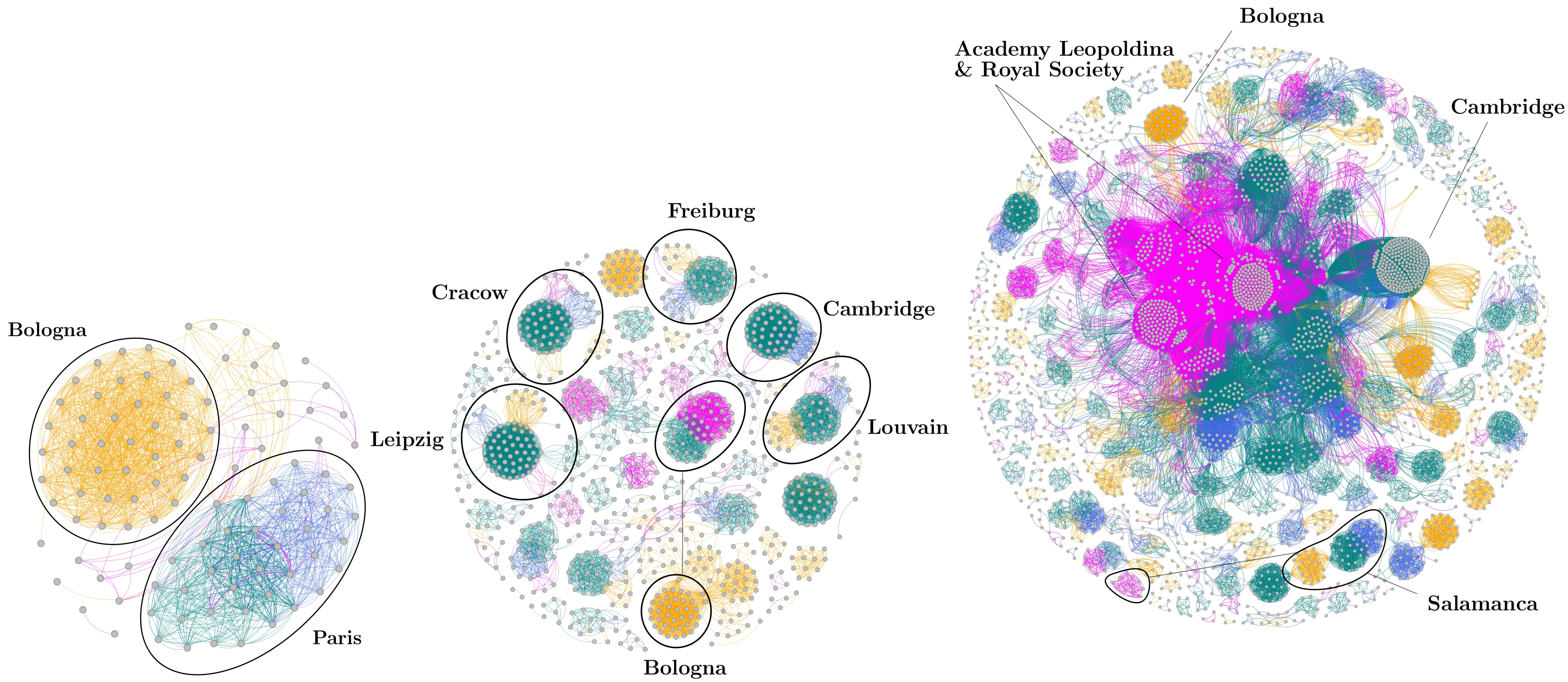


Figure 2: Number of active scholars in the network, 1084-1793.

Republic. During this timeframe, the network's nodes (scholars) and edges (connections) exist only within specific periods defined by the duration of each scholar's activity and their affiliations with institutions.

More formally, given two scholars i_s and i_v, the link between i_s and i_v lasts as long as i_s and i_v share an overlapping affiliation period in a common institution. This implies that the collection of edges is dynamic over time: edges serve as channels for the spread of ideas, appearing and disappearing only during the active life of scholars. In contrast, nodes (scholars) exist in the network as long as they are active, i.e. affiliated with one or more institutions as in our main database. Figure 2 shows the evolution of the number of active scholars over time, consisting of an overall exponential growth, in particular after 1650, with the creation of academies.

The active period of each scholar is defined from the start of their academic career until retirement or death. Activity begins in the earliest known year of affiliation with a formal educational institution, when available. For university professors, this is the year they began teaching, while for academy members, it is the year they were elected as members of the academy. If the exact affiliation date is unavailable, we infer the first year of affiliation from approximate dates. In more extreme cases, we use the earliest available date among: 30 years after the birth year, the year of death, the institution's closing date, or 1793, which marks the end of our study period. This approach aims to provide a conservative estimate



(a) 1200 (b) 1508 (c) 1730

Figure 3: Snapshots of the affiliation network in 1200, 1508 and 1730. Edge colors broadly denote the disciplines: theology (blue), law (orange), humanities (teal), and sciences (magenta). Isolate nodes not represented.

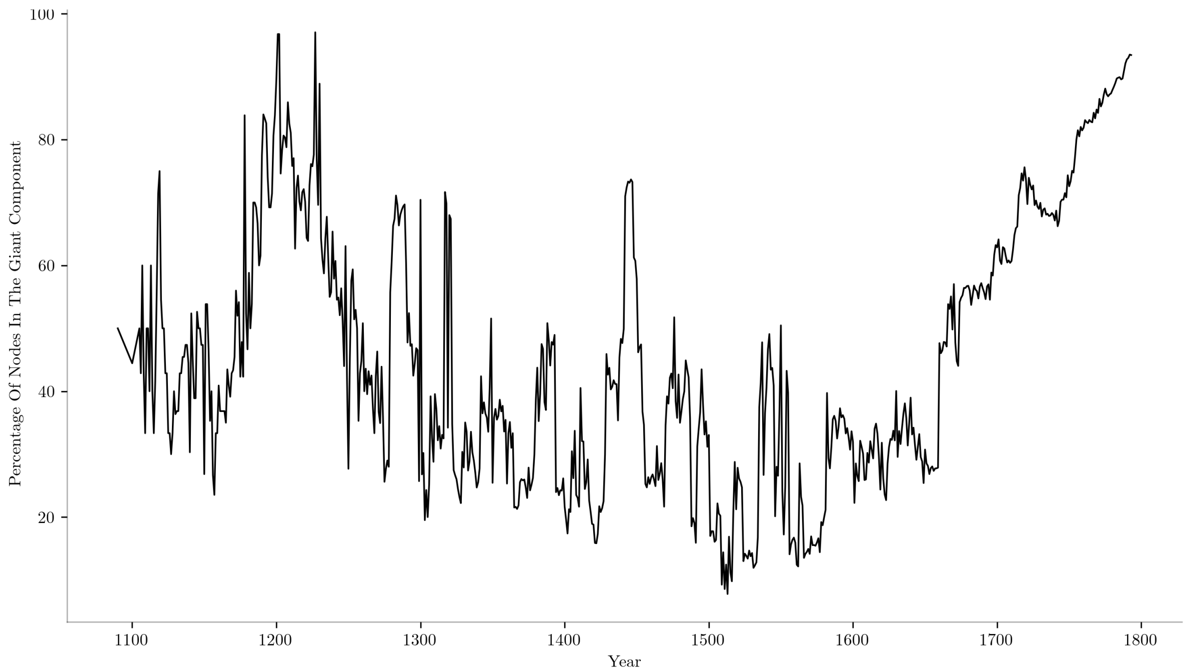


Figure 4: Percentage of active scholars in the giant or connected component over time, 1084-1793.

of each scholar's active period.

Scholars remain active until they leave the institution, if this date is available. For university professors it is the year their teaching ends. For members of academies it is usually the death year, or in some rare case, the year the member was expelled. When there is no precise information about the end of their activity, we infer it in two different ways for university professors and academicians. For university professors without a precise end affiliation date, we assume it is equal to the approximate affiliation date when available. Otherwise, if these pieces of information are unknown, we assume that a university professor will teach in that university for eight years.[7] Hence, we take the earliest date between the beginning date (after adding eight years) and the year of death. For academicians without a precise end date of their affiliations, we also assume it from more approximate dates if available. When not possible, for these scholars, we assume a lifelong affiliation,[8] so we take the year of death when there is no more precise information. Otherwise, when we do not know the year of death either, we assume they stay in the academy only one year, imposing the end affiliation date equal to the beginning date.

7. Eight years being the median of the affiliation years in the sample of university professors for which we know the precise beginning and end affiliation dates.

8. Academies usually grant a lifelong affiliation.

Table 1: Network statistics for the affiliation network, 1200-1700

Year	1200	1300	1400	1500	1600	1700
Total active scholars	105	186	520	941	1677	2591
Avg. degree	28.057	13.753	29.596	24.642	34.202	47.306
SD degree	14.209	8.957	24.382	17.724	60.674	68.598
Giant component	94	131	113	311	536	1629
Giant %	89.5	70.4	21.7	33	32	62.9
Second-largest component	7	17	100	141	206	51
Clustering coefficient	0.897	0.904	0.921	0.902	0.882	0.891
Avg. distance (giant)	2.16	3.56	1.92	4.02	4.74	4.24
SD distance	1.01	1.8	0.81	1.86	2.14	1.84

The affiliation network reveals several important characteristics, visualized in Figure 3. Before the rise of academies, the network at any given time typically consisted of a series of mostly disconnected clusters, each representing a single university. These clusters in turn comprise *cliques* (fully connected clusters) of scholars operating in the same field at the same university. Occasionally, cliques overlapped, highlighting scholars active in multiple fields. Over time, as scholar mobility increased, occasional links began to form among different university clusters, creating pathways between otherwise separate regions of the network. With the emergence of academies, however, connections between scholars multiplied significantly. Academies often appointed foreign members, serving as bridges between previously isolated universities clusters, as shown in Figure 3. From 1650s to the end of the timeframe, the cluster- and clique-based appearance of the early network transformed into a densely interconnected web of connections, and this is directly attributable to the academies.

This effect is also evident in the percentage of nodes connected to the main network, known as the "giant component"–the largest connected subgraph in which any two nodes are reachable from one another– in Figure 4. At the beginning, the affiliation network is almost fully or entirely connected, like around 1200, because it was made up of few institutions and few scholars. From the 14th century onwards, the connectedness of the graph followed an overall decreasing pattern, but with the advent of academies, the percentage of nodes in the giant component increased from 40% in 1650 to 90% by 1793.

In Table 1, we report network statistics at the beginning of each century, between 1200 and 1700, following Goyal, Van Der Leij, and Moraga-González (2006), to assess whether our network exhibits properties of an emerging small world. The graph consistently displays a high clustering coefficient (above 0.88 in all periods), well above the levels expected in a random graph with similar size and density, where clustering would typically approximate to the average degree divided by the number of nodes–and hence close to zero in sparse networks of this scale. At the same time, average path lengths (or distances) within the giant component remain low–between 2.2 and 4.7–and stable over time, even as the number of scholars increases significantly. While the network is highly fragmented in earlier centuries, with the giant component capturing as little as 21.7% of scholars in 1400, its expansion to over 60% by 1700 reflects a growing integration of academic communities across institutions. In other words, in the earlier centuries, the affiliation network resembles an archipelago of small "islands" (i.e. universities) which are internally well connected (as shown by the very high clustering coefficients) but connected to each other only through the occasional mobility of scholars. Over time, particularly by 1700, these isolated islands begin to form bridges–thanks to multiple simultaneous affiliations, partly due to the breakthrough of academies. The result is an increasingly interconnected network, where the size of the giant component grows to nearly two-thirds of all scholars, while clustering remains high and path lengths stay short. The size of the second-largest component further underlines this aspect: it increases up to 1600 but drastically decreases in 1700, thanks also to the arrival of scientific academies. This shift marks the emergence of a small-world structure out of what was once a fragmented archipelago.

The affiliation network serves as the underlying structure on which we will simulate the spread of ideas. Each idea is assumed to originate in a specific year and from an inventor, who can transmit it to their neighbors at each time step, but under certain conditions. Each idea belongs to a broad field that reflect the main disciplines of premodern times, and can spread only among scholars active within the associated field. Our assumption is that if a scholar is working on science[9] they are presumed to engage productively with peers in medicine or applied science.[10] One may argue that in the past there were all-around scholars, capable to engage in discussions with scientists even if primarily philosophers and vice-versa. Still, we decide to assign specific fields to each idea, but we acknowledge that this may possibly lead to an underestimation of the speed for the ideas' diffusion.

2.3 Epidemiological model

Following the view that social networks diffuse information like infectious diseases (Fogli and Veldkamp 2021; Banerjee et al. 2013), we start from an epidemiological approach. There is a fixed number of nodes, N, each representing a scholar. Time is discrete, with $t \in \{\underline{t}, \dots, \overline{t}\}$,

9. Within science, there is mathematics, logic, physics, chemistry, biology, astronomy, Earth science, geography, and botany.

10. Within applied science, we classify engineering, architecture, and agronomy.

$\underline{t}$ and $\bar{t}$ being the start and end date of our analysis. At each date, a node can be susceptible or infectious.[11] A contact between two nodes appear as a undirected link in the network at a given time. Interactions are represented by an adjacency matrix $A_t = [a_{sv}]_t$ of dimension $N \times N$, each element a_{sv} taking value 1 if scholar s and v are connected at time t, and zero otherwise. Connections will depend on whether s and v are at the same time in the same institution working in the same field (more on this later). We represent a temporal network $\mathbb{G}$ by a set of adjacency matrices A_t.

The state of the world is described at each date by a vector $I_t = [i_s]_t$ of length N. We only have binary entries in I_t, with $i_s = 1$ if scholar s is infected, and $i_s = 0$ otherwise. Initially, there is no idea and nobody is infected. At some date t_0 an initial "inventor" has an idea. We thus have $[i_s]_t = 0$ for all $t < t_0$, and $[i_{s^\star}]_{t_0} = 1$. $s^\star$ is the inventor.

Following the binary nature of the state vector, we use Boolean arithmetic, i.e. element-wise addition and scalar multiplication are replaced by the logical "or" and "and", respectively (Koher et al. 2016). Dynamics are then represented by:

$$I_{t+1} = A_t I_t + I_t \tag{1}$$

To understand this formula, consider the s scholar. If they are alive at period t, their infection status at $t+1$ is given by $\sum_v a_{sv} i_v$. With Boolean arithmetics, this term is equal to 1 if there is at least one v such that $a_{sv} = 1$ (s has met v) and $i_v = 1$ (v is infected). If, instead, s is either unborn or dead at time t, $a_{sv} = 0 \; \forall v$, and their infection status does not change.[12]

We also assume that once contaminated by an idea, a scholar cannot forget it. Hence the "recovered" state of the epidemiological model is not relevant here.

So far we have assumed that ideas are transmitted upon contact with probability 1. If instead, there is a transmission probability $\alpha \in [0, 1]$,[13] we define a stochastic operator $\Omega^d(A)$ (following Koher et al. (2016)) which acts element-wise on the adjacency matrix: for $a_{sv} = 0$, we have $\Omega^d(a_{sv}) = 0$; for $a_{sv} = 1$, we have $\Omega^d(a_{sv}) = 1$ with probability α and $\Omega^d(a_{sv}) = 0$ with probability $1 - \alpha$. Each potential transmission is evaluated independently on each

11. Here, our model closely relates to Banerjee et al. (2013), since infection does not equate adoption of the idea.

12. While the model could in principle track how many times s has been exposed to infected neighbors, as suggested by Bramoullé and Genicot (2024), we adopt a simplified binary-state process: infection occurs upon the first effective contact. Subsequent contacts with infected peers do not accumulate and have no further effect on the "intensity" of infection.

13. Rather than assuming automatic transmission, we model a probabilistic approach to idea diffusion, reflecting the uncertainty and selectivity observed in historical intellectual exchanges–a logic similar to the stochastic imitation dynamics in Brunt and García-Peñalosa (2022)

edge: a susceptible scholar becomes infected through contact with an infected neighbor with probability α, based on an independent draw.

Dynamics of the state vector I are now represented by:

$$I_{t+1}^d = \Omega^d(A_t) I_t^d + I_t^d \tag{2}$$

where d is an index of simulations (draws). Since each 1 in A_t independently survives with probability α, the expected value of the stochastic contact matrices is:

$$\mathbb{E}[\Omega^d(A_t)] = \alpha A_t.$$

Such a specification increases the computational effort and allows for interactions between topological effects (those coming from the structure of the network) and probabilistic effects.[14]

We now define three different levels of exposure. These levels are expected levels, given the stochastic nature of the simulations.

Expected scholar s exposure $[\bar{i}_s]_t \in [0,1]$ is obtained by averaging individual exposure over the D simulations:

$$[\bar{i}_s]_t = \frac{1}{D} \sum_{d=1}^{D} [i_s^d]_t$$

Expected institution k exposure $S_t^k \geq 0$ is obtained as an average over individuals s belonging to set of members $V(k,t)$, at time t, weighting individual exposure by quality q_s:

$$S_t^k = \sum_s \underbrace{q_s}_{\text{quality}} \left(\underbrace{I(s \in V(k,t))}_{\text{membership}} \; \underbrace{[\bar{i}_s]_{t'}}_{\text{exposure}} \right) \tag{3}$$

The quality variable q_s is derived from footprints left in the libraries, as described above in Section 2.1. It is a comprehensive measure of human capital (see De la Croix et al. (2024) and Curtis and De la Croix (2023) for more details).

Accounting for institutional exposure being influenced by the publication output of scholars implies that better scholars, with higher quality, contribute more to the institution's exposure compared to scholars with lower q_s. Consequently, if a scholar did not publish anything over their lifetime, resulting in a zero quality index, they will not contribute to the

14. In the main text, Section 3, we show the stochastic case with a transmission probability $\alpha = 0.3$, but the results are confirmed also in the deterministic case with $\alpha = 1$ (Appendix E).

institution's exposure.

The measure of exposure S_t^k will be used in the proportional hazard models of Sections 3.2 and 3.3 to assess how exposure at a certain date is correlated with the emergence of botanic gardens or observatories.

It is also useful to define an exposure measure at the institution level which takes into account a window of time (instead of a point in time above), which will be used in Section 3.4. We opted for a window of 30 years, one academic generation: the average age at appointment for university professors is 31 years, and their average age at death is 63; meanwhile, academicians begin their careers at an average age of 38 and typically pass away at 67 (Zanardello 2024). This is the time an idea could survive the passing of its author, for example through its influence on teaching material and/or the culture of the institution. Accordingly, we define

$$\tilde{S}_t^k = \sum_s \underbrace{q_s}_{\text{quality}} \left(\frac{1}{30} \sum_{t'=t-30}^{t} \underbrace{I(s \in V(k,t'))}_{\text{membership}} \underbrace{[\bar{i}_s]_{t'}}_{\text{exposure}} \right). \tag{4}$$

Finally, **Expected city c exposure** $S_t^c \geq 0$ is obtained by averaging over nearby institutions, weighting by inverse distance:

$$S_t^c = \sum_k w_{ck} \tilde{S}_t^k \tag{5}$$

The weights w_{ck} are derived from the inverse distance between all the institutions in our database and the cities in our samples (precise details about these cities data are provided in each experiment). Considering the inverse distance means that the further a city is from an exposed institution, the lower the influence that reaches the urban center. An institution fully influences cities within 10 kilometers, essentially the city hosting that institution. Beyond 10 km, the influence power decreases linearly, up to 1000 km. After this threshold, we assume that the institution's influence loses all its power, reaching a weight of zero, and thus it cannot influence any city beyond 1000 km.

3 Three empirical assessments

The aim of this section is to simulate the diffusion of groundbreaking ideas, predict which cities in Europe will be more exposed to them, and confront these results to measurable outcomes. While no model can be definitively validated, such exercises help to build support for the model's relevance. We will simulate three distinct ideas onto our network of scholars, each "invented" at different times and encompassing different fields. Subsection 3.1 outlines the selection process of these ideas and their inventors, who serve as the initial sources from which the ideas begin to spread. In addition, we explain the importance of establishing the starting date for the diffusion process. Section 3.2, Section 3.3, and Section 3.4 provide details for each idea and its corresponding inventor, visualize how these ideas spread across Europe, and simulate the probability of various measurable outcomes, which we also described in details. All the results presented in Section 3 consider a transmission probability $\alpha = 0.3$, however, Appendix E shows that our findings also hold in the deterministic case with $\alpha = 1$.

3.1 Ideas, inventors and exposed scholars

In this paper, we simulate the spread of ideas originating from inventors, i.e., scholars who developed a new idea at a specific point in time. Inventors can propagate their ideas to their peers, who, once exposed, can further propagate them to others. Upon being exposed to the idea, scholars can pass it along to their own neighbors without needing to maintain an enduring direct link with the original inventor. In our context, an inventor is a scholar recognized for a groundbreaking idea, as reported in one of the major historical encyclopedias. We use English (2005) for ideas spread before 1500 C.E., and Applebaum (2003) for ideas diffused after the invention of the printing press (circa 1450s) until the French Revolution. From these sources, we identify some significant ideas that changed the course of history, each in its own way, prioritizing those for which related historical outcomes are available to validate our model's predictions. For each idea, we pinpoint the inventor, as detailed in Section 3.2, Section 3.3, and Section 3.4.

We will simulate the spread of three ideas–two originating from the Scientific Revolution and one from the Middle Ages–and compare the resulting exposures to observed outcomes. For the Scientific Revolution, we rely on Applebaum (2003)'s encyclopedia to identify ideas, focusing on the earliest ones for which corresponding European-level outcome data is available. The earliest idea mentioned in astronomy is attributed to Regiomontanus, whose work, published in 1496 but developed since 1450, formalized Ptolemaic astronomy to make it accessible for future research in the field, we will refer to it as 'Mathematical Astronomy'. A corresponding outcome for this idea could be the establishment of astronomical observatories, for which we have European-level data. In botany, the earliest idea referenced by Applebaum is 'Botanic Realism', foundational to the herbarium published by Fuchs in 1542. Exposure to this idea can be linked to the creation of botanical gardens, another outcome for which data is available at the European level.

For the Middle Ages, we identified significant ideas emerging from academia using the index in English (2005)'s encyclopedia. These include alchemy, anatomy (including Practical Surgery), astrology, computus, Corpus iuris civilis (civil law), economic thought and justice, cartography, humanism, music, optics, political theory and treatises, punctuation, and the Scholastic method. Since the selected ideas above are both scientific in nature, we chose one from a different field for balance: theology. Scholasticism, a method of learning that emphasized rigorous logical reasoning and dialectical analysis to reconcile faith with reason, is particularly significant. It goes back to Lombardus. It cultivated a systematic approach to inquiry, which profoundly influenced the development of scientific and philosophical rationalism. At the same time, Scholasticism provoked theological reactions, particularly among those who prioritized revealed truths through scripture (e.g., Protestantism) over logic and deduction. In turn, the relative outcome we use in this empirical assessment is the probability to become Protestant for European urban centers.

A key challenge common to all three ideas is determining when the scholar first developed the concept. To define this moment, we collect two types of dates for each idea, when available: (i) the publication date, which refers to when the scholar first published a work on the topic, and (ii) the inception date, which is the year when the scholar first conceived the idea and likely began discussing it with colleagues. We identify the inception date manually, by reviewing biographical information and related historical context. To illustrate why distinguishing between inception and publication dates is important, consider the case of Nicolaus Copernicus (1473 Toruń - 1543 Frombork) and his heliocentric theory. His book, *De revolutionibus orbium coelestium*, was published posthumously, which highlights a key issue for our analysis: if we relied solely on the publication date, we would fail to capture the period when ideas were actively being developed and discussed. According to Copernicus's biography (Applebaum (2003), pp. 254-255), he began formulating his heliocentric ideas in the 1510s. By 1514, he had already written a manuscript, and by 1539, the book was nearly complete. However, he hesitated to finalize and publish it. It was only after his pupil and friend Georg J. Rheticus (1514 Feldkirch - 1574 Kaschau) published a summary of his work that Copernicus completed it, just months before his death in 1543. The publication process began before his death but was concluded afterward.

In our model, ideas spread through interactions among scholars, and these interactions can only occur when scholars are alive. Therefore, using the inception date rather than the publication date allows us to better capture the dynamics of idea dissemination through the scholarly network, as it reflects the period when discussions and exchanges of the idea were possible. Our preferred date is therefore the inception date, though we rely on the publication date when the inception date is unavailable.

Overall, ideas are more likely to spread if certain conditions are met: (a) scholars have long lifespans, which allows them more time to spread their ideas; (b) there is a high density of scholars at a given institution, creating more opportunities for intellectual exchange; and (c) scholars move between institutions, which facilitates the dissemination of ideas across different scholarly communities. However, the spread of each idea may vary significantly depending on specific factors, including the centrality of the inventor within their peer network, their affiliations with large institutions, and the timing of the idea's inception.

Before moving ahead, some clarifications on the terminology used throughout this study is necessary. First, the term 'inventor' is used as a shorthand to refer to the main proponent or originator of a particular idea. In many cases, these individuals were not inventors in the traditional sense, but rather key figures who developed, articulated, or popularized a concept. Secondly, the term 'idea' is also somewhat reductive. Under the umbrella of 'ideas', we include a range of intellectual contributions, such as theses, paradigms, and methodological approaches. Each of these types of contributions can vary significantly in scope, complexity, and influence. Thus, while we use 'inventor' and 'idea' for simplicity, it is important to recognize the nuance behind these terms.

3.2 Botanical Realism and botanic gardens

In Europe, natural history traces its roots back to ancient Greek philosophers such as Aristotle, Theophrastus, and Dioscorides. During the Scientific Revolution, botany underwent major advancements, transitioning from a primarily descriptive field into a more systematic and experimental science. By the 16^{th} and 17^{th} centuries, botany started encompassing not only the identification and classification of plants species, but also the growing field of plant physiology, investigating the properties and functions of plants life. This marked a shift in botanical practices, expanding beyond the descriptive and illustrative focus of ancient authors (Applebaum 2003), towards a more empirical approach that we will refer to as "Botanical Realism". Before 1650, botany was considered merely a complement to medical studies, but it became an independent field of study during the Scientific Revolution. Universities renown for their medical faculties began offering innovative botany lectures, where students were taken directly to gardens to observe plant species first-hand. These universities were also the first to establish their own botanic gardens to support further research and development in botany. Following this trend, private citizens and local lords also recognized the importance of botanical studies and funded the creation of such gardens (Applebaum 2003).

One key figure in this transformation was Leonhart Fuchs, a German physician and botanist. He is best known for his book *De historia stirpium commentarii insignes*, which translates to "Notable commentaries on the history of plants". Printed in Basel in 1542, one year before Nicolaus Copernicus' *De revolutionibus orbium coelestium* and Andreas Vesalius' *De humani corporis fabrica*, this work laid the foundation for modern botany. Fuchs not only provided ideal visual representations of 511 plant species, but he also included his own critical observations on their uses and characteristics, highlighting differences from ancient texts (Applebaum 2003).

Fuchs was based in Tübingen for the majority of his life, were he was teaching medicine and botany at the local university between 1535 and 1566 (Conrad 1960). Before he had also been professor at the university of Ingolstadt from 1522 to 1533 (Schwinges and Hesse 2019). Despite his fame, he was not at all a mobile scholar and declined prestigious teaching offers from Denmark and Italy (Applebaum 2003).

In this first empirical assessment, we examine the potential correlation between exposure to Botanical Realism and the establishment of botanic gardens. We calculate exposure to original botanical ideas in the following way. The diffusion of the idea begins with Leonhart Fuchs and spreads to his colleagues at the University of Tübingen, extending further through mobile scholars—those who are affiliated with multiple institutions throughout their lifetimes. Using our epidemiological approach, we average the D simulation outcomes to model how these ideas spread across European institutions between 1500 and 1800 (remember each simulation will differ, because there is a probability of transmission less than one). In this period, in Europe there are two main types of higher educational institutions: universities and academies.[15]

We use the sample of cities that hosted a university between 1600 and 1800 as recorded in our database (De la Croix 2021), resulting in a total of 185 university cities.[16] For this first experiment, we also gathered information on the existence and founding dates of European botanic gardens. Our starting point was the first annual report of the Montreal Botanic Garden (1886), which lists the botanic gardens open worldwide in 1885. From this,we selected only European gardens and determined their founding dates using AI-assisted tools, which were then manually verified through sample checks. We then matched this sample of botanic gardens with our university cities, assuming that a city without a botanic garden was not listed in the first annual report by Montreal Botanic Garden (1886). Figure 13

15. Universities are traditional higher educational institutions created from the 12^{th}-13^{th} century, while academies are created later and had a broader outreach thanks to their corresponding members.

16. Of these, 182 cities had universities that remained operational after 1600, while the cities of Budapest, Palencia, and Bratislava hosted universities prior to 1600 but did not survive beyond that period.

(in Appendix B.2) illustrates this sample of cities along with their exposure to Botanical Realism in 1600, 1700, and 1800.

In what follows, we analyze the probability ("risk") each university city has to see the creation of a botanic garden. Specifically, we are interested is analyzing whether this probability is affected by the exposure to Botanical Realism in the institutions of the city. We accordingly estimate a Cox proportional hazard model. Following the Cox model, the "risk" $h(t)$ to get a botanic garden of a city with fixed characteristics x and time varying characteristics $y(t)$ changes with the survival time t according to

$$h(t) = h_0(t) \exp(x\beta + y(t)\gamma) \tag{6}$$

where $h_0(t)$ is the baseline hazard. As time invariant regressors x, we use initial population in 1500 and the Euclidean distance from Tübingen. In a simple gravity model of diffusion, the distance from Tübingen captures the general effect of the invention, and its spread through other ways than via our affiliation network. The regressor of interest is the time-varying exposure $y(t)$. This exposure counts the number of botanists, physicians, and scientists[17] exposed to Botanical Realism at time t. The exposure used here refers to S_t^k in equation (3), and it is varying every year. Bear in mind that the institutional exposure takes into account also publication output of its scholars, discounted by the number of individual affiliations.

We consider the time frame 1500-1793. The first botanic garden is observed in 1520 in Pavia, Fuchs' invention takes place in 1542 and the affiliation data run through 1793. Some cities never saw the establishment of a botanic garden during this period. These cities are assumed to have one beyond the censoring data cutoff of 1793, according to the construction of the Cox model. However, the fact that only 59 out of 185 cities experienced the creation of a botanic garden before 1793 limits the implementation of our Cox model. Specifically, we cannot stratify the fitting routine by city, as too many cities have no event. To address this issue, we cluster the standard errors at the city level. To compute the "risk" of getting a botanic garden, we simulate the cumulative hazard function using the estimated vector of parameters $\hat{\beta}$. In turn, the probability to see the creation of a garden is just the inverse of the computed survival. Here, the estimator used to compute the baseline hazard is the Nelson-Aalen estimator, which sums the hazards over the cities still at risk. Using t_i to indicate the different years in which a garden was created, we obtain the expected number

17. These scholars work in fields such as medicine, botany, mathematics, physics, chemistry, astronomy, and applied sciences like agronomy and engineering.

of events as follows:

$$E(g_i) = \sum_{j:t_j > t_i} \hat{h}_0(t_i) \exp(x\hat{\beta} + y(t)\hat{\gamma}) \tag{7}$$

where g_i is the number of events at a specific time t_i and the sum only considers cities still at risk at that specific time t_i (i.e., cities without a botanic garden at t_i). We replace the expected number of events $E(g_i)$ with the actual number of gardens created and we obtain the estimate of the baseline hazard $\hat{h}_0(t_i)$.

By construction, the Cox model assumes time to be continuous, meaning that each botanic garden should have been created one at a time, with no years in which multiple cities saw the establishment of a garden simultaneously. However, in our sample there are six instances of two botanic gardens being created in the same year–occurrences known in the literature as"ties" or "tied events". To handle this in the likelihood calculation and to better clarify the order of events, we use the "Efron" method. This method assumes the tied events occurred in small groups and evenly distributes the "risk" across cities within the same group. While this is an approximation, it efficiently computes the partial likelihood.To ensure robustness, we apply the 'exact' method, which computes partial likelihoods by systematically evaluating all combinations of tied events. The exact method is the most accurate but is less flexible (since it does not allow for validation tests) and more computationally demanding. Still, it produces results very similar to the Efron method.

Before interpreting the results, we first verify that the proportional hazards assumption holds. This assumption requires that the hazard ratios for the exposure and other covariates remain constant over time. One test for proportionality calculates the scaled Schoenfeld residuals for each covariate and correlates them with time. The assumption is validated if the correlation is statistically insignificant (Schoenfeld 1982). In our preferred specification, presented in Column (3) of Table 2, we compute the correlation between the hazard ratios (i.e., scaled Schoenfeld residuals) and time, both individually for each variable and jointly at the global level. The individual hazard ratio of '(ihs) Exposure to Botanical Realism' shows no correlation with time. Additionally, the global correlation for Column (3) has a p-value of 0.48, indicating that the joint correlation between the hazard ratios and time is not significantly different from zero. We plot this correlation in Figure 15a in the Appendix.

Having tested for the suitability of the Cox Proportional Hazard Model, we can now interpret the results presented in Table 2. For a sound interpretation, we focus on the hazard ratios, which are computed by exponentiating the coefficients (similar to interpreting

Table 2: Cox Proportional Hazards Model – Botanical Realism and Botanic Gardens

	Risk of creating a Botanic Garden		
	(1)	(2)	(3)
(ihs) Exposure	0.363***	0.292***	0.249**
Botanical Realism S_t^k	(0.077)	(0.092)	(0.098)
(ihs) City population		0.256***	0.308***
in 1500		(0.081)	(0.088)
(ihs) Distance to Tübingen			-0.226***
(gravity model)			(0.062)
Observations	54,390	54,390	54,390
Log Likelihood	-297.050	-294.296	-292.307
Score (Logrank) Test	15.856***	21.237***	26.085***

Note: *p<0.1; **p< 0.05; ***p<0.01
Robust standard errors in parenthesis.
For 16 university cities without population data in Buringh (2021) we assume it at zero. All the variables are transformed in inverse hyperbolic sine.

odds ratios in logistic regression). In Column (1), the hazard ratio of 'Exposure to Botanical Realism' is 1.44 ($exp^{0.363}$), implying that a city with an exposure of 1 to Botanical Realism has a 44% higher probability of having a botanic garden compared to a city with 0 exposure. In Column (3), the hazard ratio for exposure to Botanical Realism is 1.28 ($\exp^{0.249}$), meaning that cities more exposed to Botanic Realism have a 28% higher probability of hosting a botanic garden. Our variable of interest 'Exposure to Botanical Realism' remains significant across Specifications (1)-(3), even when we control for all the other possible routes an idea could follow to diffuse, captured by the distance to Tübingen.

Fully grasping the size of these coefficients is challenging due to the variation in exposure over time. To address this, Figure 5 plots the probability of a city having a botanic garden for different levels of constant exposure over time. This figure represents an 'average city', with an average population in 1500 ((ihs) Population in 1500 $\mu = 2.8$), located at an average distance from Tübingen (i.e., (ihs) Distance to Tübingen $\mu = 7.04$). The Figure shows that if a city maintains full exposure (i.e., a maximum exposure of 6.00), over the entire 294-years period, it will follow the dot-dashed line and get a garden with 100% probability just before 1550. In contrast, for cities with lower exposure levels, such as 0.27 (dashed line, representing the mean of exposure), 1 (dotted line) and 0 (solid line), a 100% probability of hosting a garden is never reached. For cities with an exposure of 1, the probability of having a garden

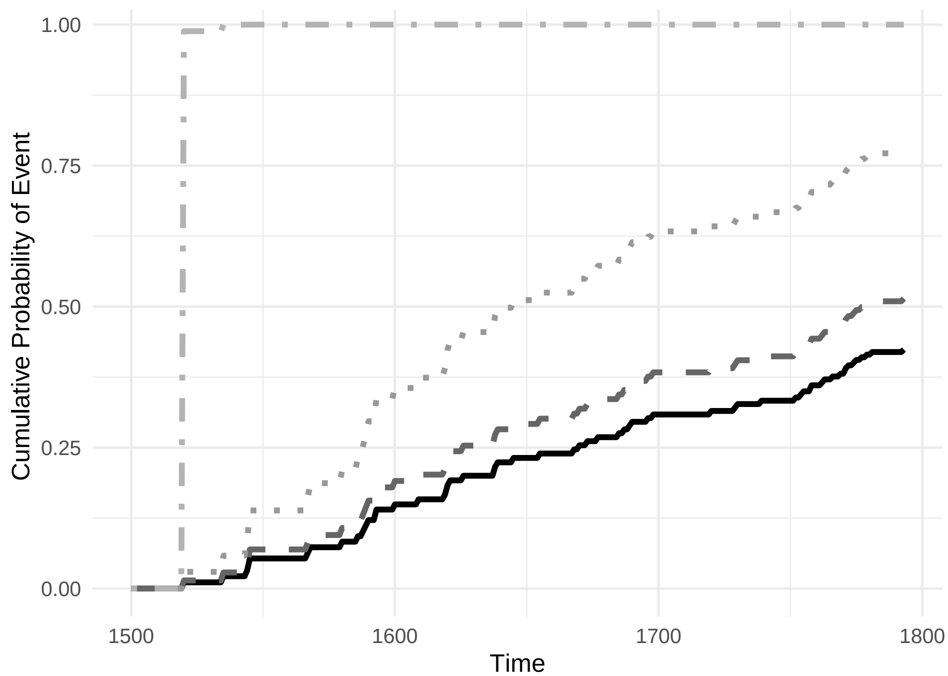


Figure 5: Probability of getting a Botanic Garden by time for different exposure to Botanical Realism levels: dot-dashed line considers a constant exposure of 6.00 (max exposure), the dotted line a constant exposure of 1, the dashed line a constant exposure of 0.27 (mean exposure), and the solid line a constant null exposure.

reaches over 75% only towards the end of the period, around 1793. Conversely, cities with an average exposure of 0.27 will have more than a 50% chance of getting a garden, following the dashed line. The solid line, representing no exposure (0), serves as a baseline, showing that an average city will have about a 40% probability of getting a garden by 1793. Overall, these results demonstrate that being exposed to Botanical Realism exponentially increases the probability to get a garden for an average city: from 40% probability, it jumps to 50% at the mean level of exposure and reaches 75% with a constant exposure of 1.

3.3 Mathematical Astronomy and astronomical observatories

The 15th and 16th centuries witnessed a growing interest in experimental science and increasing dissatisfaction with the explanations offered by ancient astronomical authorities, such as Claudius Ptolemy (c. 100 - c.170 Alexandria). Similar to the approach seen in Botanical Realism, this paradigm shift led mathematicians and astronomers to question the accuracy of Ptolemy's models and sought to refine them through observations and mathematical analysis. This era marked the beginning of the astronomical revolution, characterized by advances in trigonometry, new geometric formulas, and the adoption of decimal calculations in astronomy. The focus shifted from simply explaining the observed motions of celestial bodies to understanding the underlying physical mechanisms that caused them.

A key figure in this astronomical revolution was Regiomontanus, pseudonym of Johannes Müller. His mastery of Greek and mathematics enabled him to study the original works of Ptolemy and other ancient thinkers. At the University of Vienna, around 1454, he and his mentor, Georg Peurbach (1423 Peuerbach - 1461 Vienna) began collaborating on *Theoricæ novæ planetarum, id est septem errantium siderum nec non octavi seu firmament.* This seminal work introduced new methods for solving plane and spherical trigonometry problems, including the use of sine and tangent functions. Regiomontanus also created extensive trigonometric tables with values calculated to decimal units, which remained influential for centuries. As such, he can be considered a pioneer of Mathematical Astronomy. While trigonometry had been used in astronomy and other sciences, Regiomontanus's contributions greatly enhanced its understanding and application. His work, alongside Peurbach's, laid the groundwork for later revolutionary astronomers such as Copernicus, Kepler, and Galileo (Applebaum 2003).

After Peurbach's death, Regiomontanus moved to Northern Italy, then to Hungary in 1467. Later in life, he settled in Nuremberg, drawn by its status as a free city and its central location. There, he established a workshop and printing press, dedicating himself to the dissemination of scientific knowledge. In 1472, he published *Theoricæ novæ planetarum*, his collaboration with Peurbach. In 1475, Pope Sixtus IV invited him to Rome to work on calendar reform, but Regiomontanus died shortly after, at the age of 41.

In the second empirical assessment, we examine the correlation between exposure to Mathematical Astronomy and the creation of astronomical observatories: advances in trigonometric methods foster for more appropriate places, buildings, and instruments to handle more precise astronomical observations, crucial for determining the dates of equinoxes, solstices, and other celestial events. Regiomontanus himself opened an instrument shop specialised in building and printing works related to Mathematical Astronomy (Applebaum 2003).

The computation of exposure to Mathematical Astronomy will follow the same methodology as for Botanical Realism. The idea will spread from Regiomontanus, who shared it with his colleagues in Vienna, Bratislava, Padua, and Rome and will reach other institutions through mobile scholars. After averaging the simulation outcomes, we calculate the S_t^k yearly exposure of each institution to Mathematical Astronomy over time between 1500 and 1793. Only scientists are considered exposed–scholars working in fields such as mathematics, logic, physics, chemistry, biology, astronomy, geography, and botany. As before, we account for the quality of their publications, and we discount it for the number of active affiliations. Finally, we obtain the institutional exposure to Mathematical Astronomy.

In this experiment, we examine the creation of observatories in the same 185 universities cities defined in Section 3.2. We collected the names and foundation dates of observatories from "The Greenwich List of Observatories" compiled by Howse (1986). As we did for the botanic gardens, we only considered observatories in the European continent, assuming that a location did not have an observatory if it was not listed in our source.

We estimate the probability of each university city obtaining an observatory using a Cox Model similar to the one used for Botanical Realism. The technical details, including equations 6 and 7, remain the same. The only difference lies in the covariates included: instead of the distance from Tübingen, we introduce the distance from Vienna to capture the broader influence of Mathematical Astronomy. We focus on the same period, 1500-1793, since the first observatory was established in Kassel in 1560, and Regiomontanus' ideas spread starting in 1454 and ends in 1793, the established end point of our timeframe. 52 cities in the sample that saw the creation of an observatory before the censoring date 1793, while the remaining cities never saw one. However, the Cox Model assumes by construction that these cities will eventually have an observatory after 1793. As with the botanic garden model in Section 3.2, we address this issue clustering the standard errors at the city level; otherwise, the maximization does not converge to a finite likelihood.

Again, we encounter "tied events" in the establishment of observatories. Specifically, there are ten years in which two observatories were constructed simultaneously, and one year (1790) when three observatories were created at the same time. We proceed as in Section 3.2: the main results are computed with the more parsimonious "Efron" method, and we confirm the results with "exact" method.

We validate the suitability of the Cox Proportional Hazard Model as before, following Schoenfeld (1982). Looking at Column (1) we find that the correlation between 'Exposure to Mathematical Astronomy' and time is slightly significant at 10%. On the other hand, in our preferred specification, Column (3), both the individual and joint correlation of all the covariates with time are not statistically different than zero. Overall, there is no correlation with the global p-value being at 0.16. We are confident in validating the proportionality assumption, especially after analysing the Plot 15b of the joint correlation in Appendix C.

For the interpretation of the results we need to consider the hazard ratios as in the case of Botanical Realism. The hazard ratio of 'Exposure to Mathematical Astronomy' from Column (1) is 1.41 ($exp^{0.344}$), indicating that a city with an exposure of 1 to Mathematical

Table 3: Cox Proportional Hazards Model Results – Mathematical Astronomy and astronomical observatories

	Risk of creating an Observatory		
	(1)	(2)	(3)
(ihs) Exposure to Mathematical Astronomy S_t^k	0.344***	0.314***	0.316***
	(0.041)	(0.050)	(0.052)
(ihs) City Population in 1500		0.145*	0.142*
		(0.081)	(0.085)
(ihs) Distance to Vienna (gravity model)			-0.160***
			(0.050)
Observations	54,390	54,390	54,390
Log Likelihood	-254.978	-254.139	-253.212
Score (Logrank) Test	45.470***	47.738***	50.136***

Note: *p<0.1; **p< 0.05; ***p<0.01
Robust standard errors in parenthesis.
For 16 university cities without population data in Buringh (2021) we assume it at zero. All the variables are transformed in inverse hyperbolic sine.

Astronomy has 41% higher probability to get an observatory compared to a city with 0 exposure. Again, like in Subsection 3.2. controlling for possible different routes via which Mathematical Astronomy might have diffused does not undermine the relevance of our main variables of interest. This is shown in Column (3), where we consider also initial population and distance to Vienna: cities more exposed to the innovation of Mathematical Astronomy have 37% more probability to create an observatory–the hazard ratio being 1.37 ($exp^{0.316}$). Figure 6 plots the probability of getting an observatory for different level of constant exposure, which allows for a more straightforward baseline and for a better interpretation of the size of the coefficients. We took an 'average city' with an average population in 1500 ((ihs) Population in 1500 $\mu = 2.8$) and at an average distance from Vienna ((ihs) Distance to Vienna $\mu = 7.38$). The Figure shows that a city that will never be exposed to Mathematical Astronomy will have a probability of approx. 31% to see the creation of an observatory at the end of our timeframe, in 1793. This can be considered as the baseline to see how an increase in the exposure to Mathematical Astronomy impact the likelihood to get an observatory: already with a constant average exposure of 0.4 (i.e., mean exposure), a city will have almost 45% chances to see an observatory, and this probability jumps to almost 65% with a constant exposure of 1. Finally, in the extreme case when a city always has the maximum level of exposure to Mathematical Astronomy, it will have a 100% probability to have an Observatory after 1560, the creation year of the first observatory in our sample.

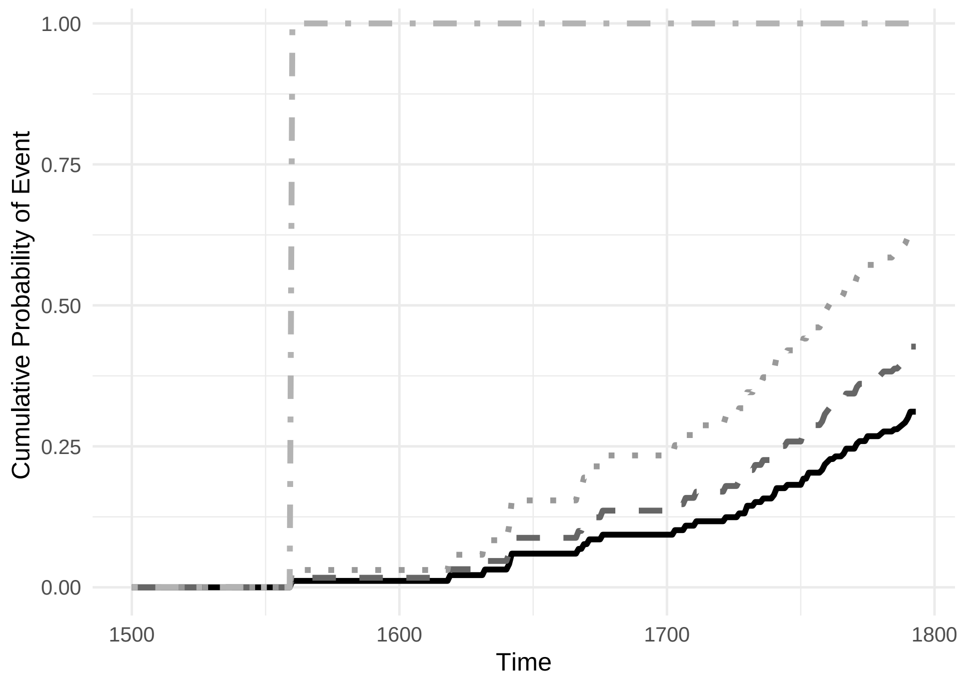


Figure 6: Probability of getting an Observatory by time for different exposure to Mathematical Astronomy levels: dot-dashed line considers a constant exposure of 7.8 (max exposure), the dotted line a constant exposure of 1, the dashed line a constant exposure of 0.4 (mean exposure), and the solid line a constant null exposure.

3.4 Scholasticism and Protestantism

Scholastic theology is a way to approach theological questions using logical analysis and systematic reasoning, influenced by ancient Greek philosophers. It is more a paradigm than a single "idea". Petrus Lombardus is often recognized as an early proponent and influential figure in the scholastic tradition. According to Genet (2019) and Herbermann (1913) he taught at what will become the university of Paris from 1145 to his death in 1160. Mazzetti (1847) also sees him at the University of Bologna around the year 1150.

The main work of Petrus Lombardus is the *Sentences*. Completed around the middle of the 12th century, the *Sentences* contains key theological topics such as the nature of God, creation, the Trinity, grace, and sacraments. The *Sentences* served as a foundational text for theological education in medieval universities and was the starting point for many later scholastic theologians, including Thomas Aquinas, Bonaventure, and Duns Scotus, who wrote extensive commentaries on it. To fix ideas, a good example of reasoning using the tools of scholastic theology is the second proof of the existence of God by Aquinas as reported by

Copleston (1993). Remark that it does not rely much on the scriptures, but rather on a kind of mathematical/logical argumentation:

1. In the world, we can see that things are caused.
2. But it is not possible for something to be the cause of itself because this would entail that it exists prior to itself, which is a contradiction.
3. If that by which it is caused is itself caused, then it too must have a cause.
4. But this cannot be an infinitely long chain, so, there must be a cause which is not itself caused by anything further.
5. This everyone understands to be God.

Martin Luther (1483 Eisleben - 1546 Eisleben), the 16th-century German monk and theologian who sparked the Protestant Reformation, was trained in the scholastic tradition and initially engaged with its methods and ideas. However, as grappled with his own spiritual struggles, Luther became increasingly critical of certain aspects of scholastic theology, particularly its emphasis on human reason. One of Luther's main objections to scholastic theology was its perceived reliance on human reason and philosophical speculation, which he believed obscured the central message of the Gospel. He wrote an entire *Disputatio contra scholasticam theologiam* (1517), with some shocking statements, such as "No syllogistic form is valid when applied to divine terms", and again "[...] the whole Aristotle is to theology as darkness is to light" (respectively, theses 47 and 50).

Luther emphasized the doctrine of *sola scriptura* (Scripture alone), arguing that true theological knowledge could only be derived from the Bible and not from human tradition or speculative philosophy. Several key grievances against the Catholic Church contributed to the rise of Protestantism, including the aspiration to change traditional practices and teachings based on Scholasticism that they believed were not supported by the Bible. The historian Chaunu (2014) defends the idea that Scholasticism, and especially nominalism (this very logical theology ridiculed by Erasmus and Rabelais), has made theology unintelligible therefore provoking a surge of disgust. The theologian Barrett (2023) argues that it was the degeneration of Scholasticism in the later middle ages that was a significant catalyst for the Reformation.[18]

To assess the possible correlation between the exposition to Scholasticism and the rise of Protestant we propose the following experiment. First, we feed the idea of Scholasticism to

18. We acknowledge that this view is not shared by all theologians. For example, for Cross (2024), there is a vast continuity between Luther and late Scholasticism.

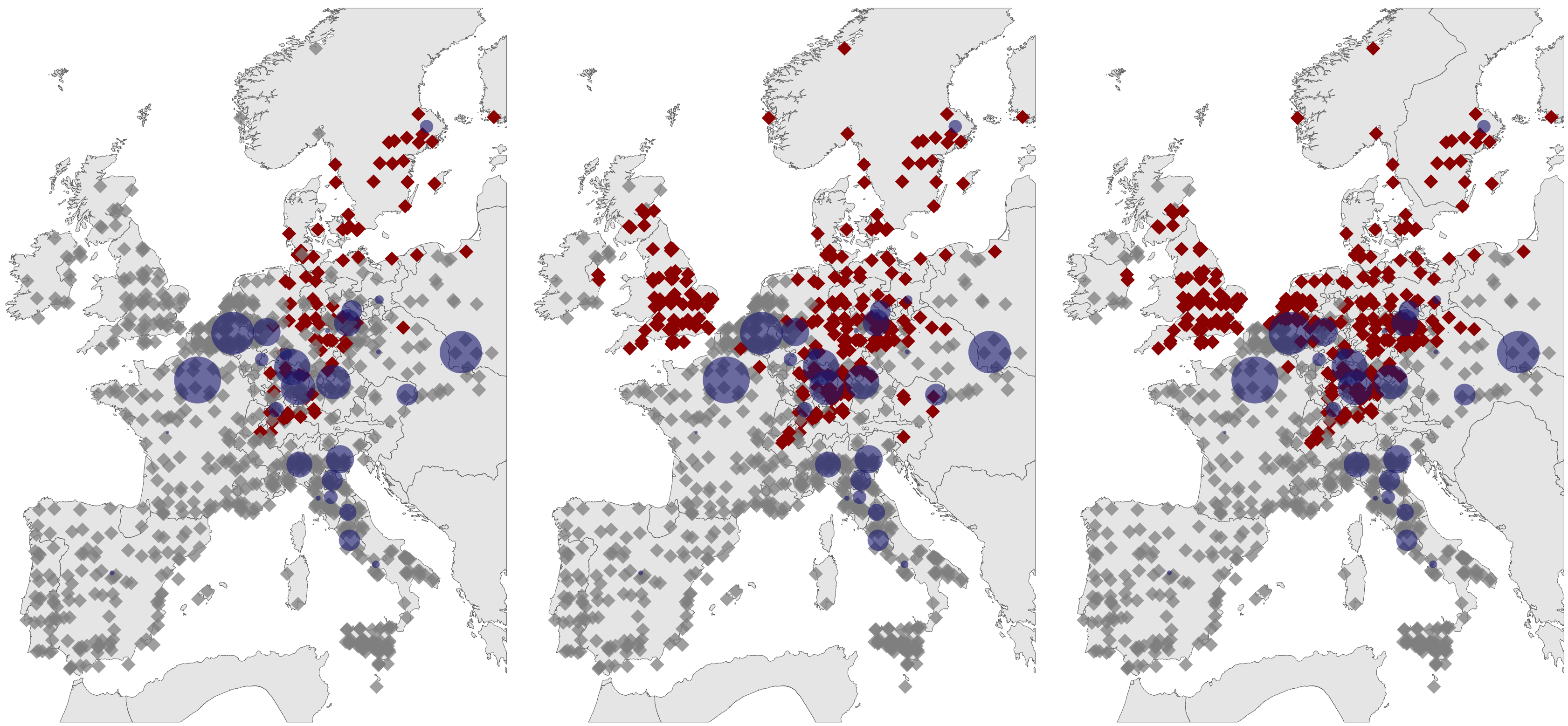
Petrus Lombardus. The idea will then spread to his colleagues in Paris, and then beyond, thanks to the mobility of scholars.

Second, we simulate the spread of this idea in Europe, using the epidemiological approach described in Section 2.3 and all the temporary networks built from our data.

Third, averaging the outcomes of many simulations, we compute the $\tilde{S}_t^k$ exposure of each university to Scholasticism in 1508, the year Luther started teaching at the University of Wittenberg. Exposure is measured by counting the number of theologians exposed to Scholasticism in the last 30 years, by university. Each theologian is weighted by the importance of his publication output. Then, we annualize this exposure dividing by the 30 years over which we counted the active theologians. From here, we obtain the exposure to Scholasticism of each university in the network, which refers to Equation (4).[19] Figure 7 represents this level of exposure. We can go further and compute the exposure to this paradigm for European cities even if they do not host any university, as in Equation (5). We do this by computing the distance between each city in our sample and each university in our network, and summing up universities' exposure at the city level weighted by the inverse of distance, w_{ck}.

The sample of cities used to compute exposure is taken from Rubin (2014), which provides a database of over 800 European cities and classifies them as Catholic or Protestant based on the dominant religion in three different years: 1530, 1560, and 1600. For this paper, we use the same classification, detailed in Appendix A of Rubin (2014). Figure 7 illustrates the sample of cities and the spread of Protestantism. Cities that remained Catholic are shown in grey, while those that became Protestant are marked in red, for the respective years. The blue bubbles represent universities' exposure in 1508, as described earlier. The figure already suggests a possible positive correlation between exposure to Scholasticism and a city's likelihood of rejecting its principles in favor of Protestantism. However, it is important to note that in Italy, institutional exposure to Scholasticism was weaker compared to Northern Europe. This is because scholastic ideas were primarily discussed in monasteries and convents, rather than within universities. In Spain, the scholastic paradigm developed later, mainly in the 16th century, emerging from the works of Francisco de Vitoria. Regarding England, we acknowledge the limitations of our current database of scholars. This version struggles with accurately classifying English scholars by field, making it difficult to distinguish theologians from other professors. We are currently addressing this issue improving data from Oxford, which was the primary center, while Cambridge remained relatively smaller at the time.

19. It is important to notice a distinctive trait between this 'static' exposure and the 'yearly' exposures used in the previous two empirical assessments.



(a) Protestant cities in 1530 (b) Protestant cities in 1560 (c) Protestant cities in 1600

Figure 7: Blue bubbles represent the exposure to Scholasticism 30 years prior 1508, $\alpha = 0.3$ and $D = 10,000$. Protestant cities are the red diamonds, and Catholic cities are the grey diamonds.

We employ a linear probability model to better estimate the correlation between exposure to Scholasticism and the likelihood that a city became Protestant in 1530, 1560, and 1600. For this experiment, we cannot use a Cox proportional hazard model because in some European regions, such as England and Scotland, the shift towards Protestantism was a top-down decision implying that all the cities became Protestant on the same day. This would create too many 'ties', violating the assumption of time being continuos of the Cox model. For this reason, we simply employ a linear probability model. Column (1)-(3) in Table 4 show the results. The key variable of interest is *Exposure to Scholasticism* S^c_{1508}, whose estimated coefficient is consistently positive and statistically significant in 1560 and 1600. Columns (1)-(3) show the variable of interest without fixed effects. Here, we only control for the presence of universities in 1500 to show that *Exposure to Scholasticism* S^c_{1508} is not directly substituted by the simple presence of a university. This means that although a city has a university, it must also be exposed to Scholasticism either directly from the university of the city itself or indirectly, being close enough to other exposed cities. In Appendix D, we include additional controls and fixed effects in the Table 11.

Using the estimated coefficient in Table 11 Columns (1)-(3), we can assess the magnitude of the relationship between a city's exposure to Scholasticism and its likelihood of adopting Protestantism. Given Heidelberg's position as the most exposed place to Scholasticism, we can estimate how the probability of becoming Protestant might have changed for other cities in our sample, had they experienced a similar degree of exposure. For example, considering Barcelona in Spain, which is in the lowest quartile of the exposure distribution, we find that its probability of becoming Protestant would have increased by 11% in 1530, by approximately 32% in 1560 and by 43% in 1600. Looking at a city in the second quartile, such as Copenhagen in Denmark, the increase in probability would be 8% in 1530, 25% in 1560, and 33.5% in 1600. For Bologna in Italy, which falls in the middle of the third quartile, the increase would have been about 4% in 1530, approximately 13% in 1560, and 18% in 1600. In contrast, a city in the same quartile as Heidelberg, like Leuven in Belgium, which has a difference in exposure of only 20.7 absolute points compared to Heidelberg, would have a much lower increase in probability: around 2% in 1530, approximately 6% in 1560, and 8.3% in 1600.

In Column (4)-(6) we show how the correlation between the *Exposure to Scholasticism* S^c_{1508} and the probability to become protestant does not change much when we control for the *Exposure to Practical Surgery* PS^c_{1508}. This is particularly interesting because the exposure to Practical Surgery is capturing an orthogonal effect with respect to the exposure to Scholasticism. We compute the exposure to Practical Surgery in a very similar way than Scholasticism, the only difference is the starting point. The 'inventor' of Practical Surgery is Guy de Chauliac (c. 1300, Chauliac — 1368, Avignon), who was the most prominent physicist and surgeon in the Middle Ages. His most famous work *"Chirurgia Magna"*, published in 1363, was the first to detail various surgical procedures which were mostly treated by charlatans before him. It remained the main reference for Practical Surgery until well into the 17^{th} century (The Editors of Encyclopaedia Britannica 2024).

The orthogonal relationship between Scholasticism and Practical Surgery is already clear looking at the Figure 16 (Appendix D): Practical Surgery was much more prominent in Southern Europe, spreading independently with respect to Scholasticism. Additionally, in the simple linear probability model showed in Columns (4)-(6) of Table 4, *Exposure to Practical Surgery* PS^c_{1508} always has a negative sign and is always highly significant. We interpret these results as an indication of robustness: controlling for both the simple presence of a university and the exposure to a strand of thought orthogonal to Scholasticism, we still see a positive and significant correlation between the latter and the probability for the city to become protestant. This reinforce our initial hypothesis of a "disgust" effect initiated by the exposure to Scholasticism.

Table 4: Linear Probability Model - Exposure to Scholasticism in 1508 and cities' probability to become protestant in 1530, 1560, and 1600

	Protestant in			Protestant in		
	1530 (1)	1560 (2)	1600 (3)	1530 (4)	1560 (5)	1600 (6)
Exposure to Scholasticism S^c_{1508}	0.001* (0.001)	0.003** (0.001)	0.004*** (0.001)	0.002*** (0.001)	0.005*** (0.001)	0.007*** (0.001)
Presence of university in 1500	-0.036 (0.027)	-0.077 (0.052)	-0.142*** (0.054)	-0.026 (0.026)	-0.043 (0.044)	-0.092** (0.044)
Exposure to Practical Surgery PS^c_{1508}				-0.001** (0.001)	-0.004** (0.001)	-0.005*** (0.001)
Observations	867	867	867	867	867	867
Adjusted R^2	0.022	0.059	0.098	0.035	0.141	0.260
Log Likelihood	-198.38	-505.74	-523.72	-192.20	-465.73	-437.44

Notes: Robust SE clustered by territory in parentheses.
A constant term is included in all regressions.

4 Counterfactual experiments

In this section, we identify the features of the academic network that are more conducive to spreading ideas. We perform two kinds of experiment. One consists in assigning the authorship of an idea to fictitious inventors, in order to track whether the idea would spread differently in these alternative realities. The second experiment consists in removing some parts of the network to assess their importance in spreading ideas. We first exclude academies from the network, which were more innovative and more connected institutions than traditional universities. We also remove institutions from certain geographical areas (the British Isles, the Italian Peninsula, Iberia, and France) to assess the historical importance of each region in fostering scientific progress. This removal alters the network by eliminating edges representing affiliations to these institutions, thereby disconnecting scholars solely affiliated with them. Finally, we remove the Jesuits from the network, which are an important component with their c. 6000 scholars and c. 50 higher education institutions.

4.1 Placebo inventors of Botanical Realism

To better understand how the structure of a network influences the speed at which ideas spread, we conduct a series of counterfactual experiments using Fuchs' Botanical Realism as a case study. In these experiments, we imagine that it was not Fuchs who introduced the new paradigm of Botanical Realism, but another contemporary scientist from a different region of Europe. We simulate the diffusion of this paradigm, still originating in 1542, but emerging in various alternative locations: in Salamanca with Juan Aguilera (1507-1560), in Zaragoza with Gaspard Lax de Sarenina (1487-1560), in Oxford with John Warner (c. 1500-1565), in Louvain with Jeremius Dryvere (1504-1554), in Wittenberg with Andreas Goldschmidt (1513-1559), in Cracow with Mikołaj Mleczko Wieliczki (1490-1559), in Rostock with Jacob Bording (1511-1560), in Montpellier with Antoine Saporta (1507-1573), in Padua with Girolamo Donzellini (1513-1587), in the Royal College of France with Oronce Fine (1494-1555), in Pisa with Realdo Colombo (1510-1559), and in Leipzig with Georg Joachim Porris (1514-1574). These counterfactual simulations allow us to explore how regional networks and academic hubs would have shaped the spread and influence of Botanical Realism across Europe.

While it is speculative to say whether each of these twelve individuals could have invented Botanical Realism, many of them were indeed prominent scholars in fields that could have contributed to the development of a more empirical approach to botany. However, the emergence of a paradigm like Botanical Realism depended on a combination of factors–

intellectual, cultural, and scientific–beyond the work of individual scholars. Below, a closer look at the potential of each of the individuals:

- Juan Aguilera was professor of medicine and sciences at the University of Salamanca from 1538 to 1560 (Vidal y Díaz et al. 1869; Esperabé de Arteaga et al. 1917): as he had a background in natural philosophy or medicine, he could have contributed to a more empirical study of plants, as Salamanca was a leading university with a strong focus on scientific inquiry during the Renaissance.
- Gaspard Lax de Sarenina was professor of sciences at the University of Zaragoza from 1521 to 1560 (Catalán 1924): Known for his work in mathematics and philosophy, Lax might not have had direct expertise in botany, but scholars in these fields often contributed to broader scientific shifts.
- John Warner taught medicine at the University of Oxford from 1520 to 1554 (Gunther 1937) and was a member of the Royal College of Physicians (1561): he might have had access to Renaissance humanist ideas, but Oxford was more conservative at the time, and Warner would need a strong inclination toward natural science to spearhead Botanical Realism.
- Jeremius Dryvere taught medicine at the University of Louvain from 1522 to 1554 (Lamberts and Roegiers 1990): Louvain was a center of scientific learning, and someone like Dryvere could have contributed to botanical studies.
- Andreas Goldschmidt taught medicine at the University of Königsberg from 1550 to 1559 (Schwinges and Hesse 2019): As a scholar trained in Wittenberg, where humanism and scientific inquiry were encouraged, Goldschmidt could have been part of the intellectual currents that led to developments like Botanical Realism.
- Mikołaj Mleczko Wieliczki was professor of medicine at the University of Cracow from 1512 to 1552 (Uniwersytet Jagielloński 2019): Cracow had a strong tradition in astronomy and natural sciences, and a scholar like Wieliczki could have contributed to the empirical study of nature.
- Jacob Bording was professor of medicine at the University of Rostock from 1549 to 1556 and at the University of Copenhagen from 1556 to 1560 (Slottved 1978): as a prominent physician, Bording would likely have been interested in botany as it related to medicine, which was a key motivator for many early botanists.
- Antoine Saporta was professor of medicine at the University of Montpellier from 1531 to 1573 (Dulieu 1979): Montpellier was a leading medical school, and Saporta, as a physician, would have had a strong interest in medicinal plants. He could have been well-positioned to develop a more scientific approach to botany.

- Girolamo Donzellini taught medicine at the University of Padua from 1541 to 1543 (Facciolati 1757): The University of Padua was a hub of medical and scientific learning, so Donzellini, with his interest in medicine, might have had the right environment to develop Botanical Realism.
- Oronce Fine taught sciences at the Royal College in Paris from 1530 to 1555 (Collège de France 2018) : Although primarily a mathematician and cartographer, Fine was part of a broader Renaissance movement that emphasized empirical study, and he could have contributed to a more systematic approach to botany.
- Realdo Colombo taught medicine at the universities of Padua (1538–1544), Pisa (1544–1548) and Roma (1548–1559), see Del Negro (2015): he was a noted anatomist, and his empirical methods in anatomy could have translated well into botany, particularly in the detailed study of plant structures.
- Georg Joachim Porris taught sciences at the universities of Wittenberg (1537–1542), Leipzig (1542–1551) and Vienna (1554–1555), see Schwinges and Hesse (2019) and Aschbach (1865). Also known as Rheticus, Porris was an astronomer and mathematician. While not a botanist, his scientific mindset might have inclined him toward an empirical approach in natural studies if he had turned his attention to plants.

Many of these scholars came from strong intellectual backgrounds and were part of the broader Renaissance shift toward empiricism and direct observation. Several, particularly those with medical training (e.g., Saporta, Colombo, Bording), had practical reasons to study plants carefully and could have contributed to a scientific approach to botany.[20]

Figure 8 illustrates the percentage of individuals in medicine and sciences who were exposed to the idea across the twelve simulated scenarios. This simulation offers valuable insights into the diffusion process. Notably, in three cases, the idea fails to spread. In Salamanca, where Juan Aguilera (professor from 1538 to 1560) lacked other mobile peers for meaningful intellectual exchange, the idea does not take hold. A similar pattern is observed with Wieliczki in Cracow (professor from 1513 to 1552) and with Lax in Zaragoza (professor from 1521 to his death in 1560) where limited interaction with other scientists stifles the spread of the concept. In these locations, few scholars traveled to other universities, reducing the likelihood of transmitting the new paradigm to other academic hubs.

In nine other cases, we observe that by the end of the period, nearly all relevant schol-

20. That said, Botanical Realism required not just empirical skills but also an interest in plants themselves, which admittedly some of these figures might not have shared. Fuchs' success came from a combination of his medical background, interest in plants, access to talented illustrators, and the specific intellectual environment in Germany at the time.

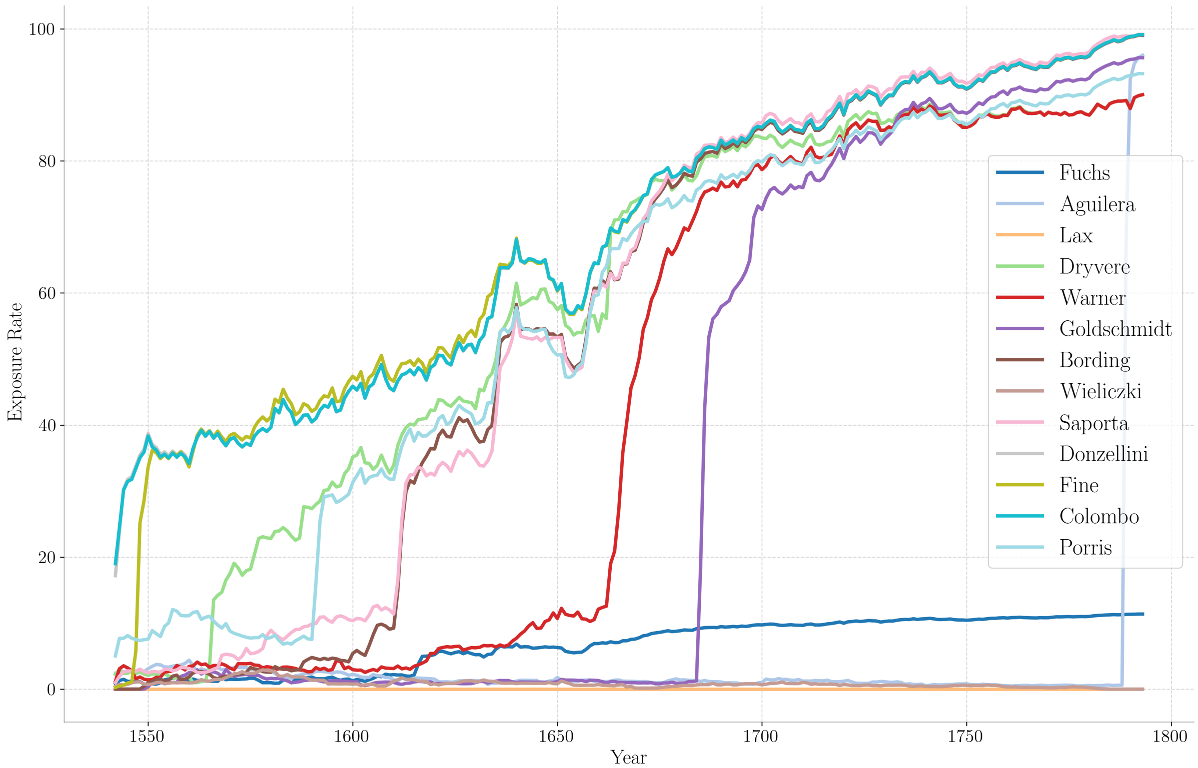


Figure 8: Exposure rates of active scholars in the network from 1084 to 1793, considering different hypothesized proponents of Botanical Realism.

ars had encountered the idea. It is important to note that these results are averaged over 1,000 simulations, meaning a consistently high rate of diffusion across all simulations. This reflects how effectively the European intellectual network functioned to disseminate ideas. Regardless of their point of origin, ideas eventually spread throughout Europe in the long run. For instance, Warner's idea remained localized in Oxford for some time, reaching Cambridge and Gresham College by 1650, before spreading further. Similarly, Saporta's concept, originating in Montpellier, reached Basel, Lincei, and Toulouse by 1600, and continued to propagate across Europe afterward. After two centuries, both Bording's and Saporta's ideas had spread at a similar rate to various locations. This demonstrates that, despite differences in individual pathways and speed of diffusion, the overall outcome was the same: the widespread diffusion of ideas across Europe.

The likelihood of an idea spreading depends on how well-connected its inventor is, typically measured by degree centrality—the number of edges a node has. However, degree centrality (and other centrality measures) does not fully capture the dynamics of idea diffusion, which unfolds over time rather than at a single moment. A high degree centrality does not necessarily equate to greater reach. To illustrate this, we report the degree centrality of each placebo inventor in 1542 (i.e., the number of colleagues in the same field) and in 1550, when the inventor was unconnected in 1542.

If Fine (2) or Colombo (19) had been the originators, the idea would have already spread to 50% of the academic population by the second half of 1600. The next fastest spread would have occurred with Dryvere (8) and Porris (22), followed by Saporta (6) and Bording (2 in 1550). For Warner (10), the spread would occur significantly later, only accelerating after the establishment of the first major academies, with a sharp increase around 1660. If Goldschmidt (0, 3 in 1550) had been the inventor, the idea would have struggled to survive initially, only gaining rapid traction around 1680. Interestingly, had Aguilera (8) been the inventor, the idea would have remained confined to Salamanca, persisting without spreading elsewhere until the end of the 18th century, when we observe a sudden spike. This shift coincides with scientists from the Spanish university beginning to affiliate with more international academies. These simulations demonstrate how academic institutions can play a crucial role in preserving ideas that might otherwise remain obscure due to their development in less influential locations.

In two cases (Wieliczki (3) in Cracow, and Lax (0) in Zaragoza), the idea fails to spread. This confirms that the diffusion process generated by our model is non-ergodic: the success of an idea remains dependent on its initial conditions – specifically, the network position of its inventor. This implies that the distribution of successful ideas does not converge to a single stationary form, i.e. even as time progresses, the expected success of an idea remains contingent on the initial conditions. It also implies that outcomes across different realizations of the process do not average out over time (in an ergodic process, averaging over time should yield the same result as averaging over different realizations of the process, see Peters (2019), including a history of the idea of ergodicity).

The case of Fuchs (4) is particularly interesting, as the diffusion of his herbal plateaus at 10%, unlike the other simulations where ideas either reach full exposure or fade out entirely. This reflects the fact that, in roughly 90% of the simulations, Fuchs' idea dies out quickly, keeping exposure at zero. In the other 10%, Fuchs' idea spreads successfully, reaching high levels of adoption after a century. This outcome suggests that the spread of Fuchs' herbal hinges on a fragile initial phase, where its survival occurs with a probability of about one tenth.

To understand the European academic network, we can examine the transmission of ideas through the case of Fuchs' Botanical Realism. Figure 9 highlights the key individuals and institutions involved. This idea originated at the University of Tübingen, where it thrived for over a century due to the steady presence of scholars in science and medicine. However, the Thirty Years' War disrupted this continuity when the university was effectively closed, particularly between 1628 and 1634, during its occupation by Imperial (Catholic) forces of the Holy Roman Empire.

Despite this disruption, the idea spread to other institutions through Tübingen scholars who secured positions elsewhere. Jakob Degen taught briefly in Strasbourg (Berger-Levrault 1890), while Michael Mästlin held a temporary post in Heidelberg (Drüll 2002). However, these transfers did not result in sustained knowledge transmission: Strasbourg was too small to establish permanent positions in the sciences, and Heidelberg faced the same wartime challenges as Tübingen. Nevertheless, in Strasbourg, the physician Kasper Maliński may have encountered Fuchs' ideas. His subsequent move to the University of Zamość (Kedzoria 2021) could have carried the concept further.

At Zamość, the mathematician Adrien Van Roomen (also known as Romanus) might have engaged with the idea. Near the end of his life, Romanus became a member of the Accademia dei Lincei, where he potentially reintroduced the concept. Through the Lincei, an informal academy with prominent members such as Galileo and Kepler, the idea could have spread internationally.

Adrien Van Roomen is thus necessary for the survival of the idea. He is a key player according to Zenou (2016)'s definition, which was developed in the context of criminal networks: "the key player who is the agent that should be targeted by the planner so that, once removed, she will generate the highest level of reduction in total activity", (p. 1403). This hypothetical trajectory highlights three key features of European academia in the sixteenth and seventeenth centuries. First, the dense network of connections ensured that ideas could survive even amid significant disruptions, such as the Thirty Years' War. Marginal institutions, like the University of Zamość, played a crucial role in this resilience. Second, early informal academies, such as the Lincei, were vital for preserving and disseminating ideas across borders. Third, the European academic network is strongly path-dependent and non-ergodic as described in (David 1985): is shaped by more or less random historical events "rather than systematic forces" [p.332].

4.2 Removing components of the network

As explained above, we simulate the spread of ideas in a network stripped of certain components. This allows to better understand the role of each of these components. Formally, it amounts to rewrite Equation (1) as

$$I_{t+1}^B = B_t I_t^B + I_t^B \tag{8}$$

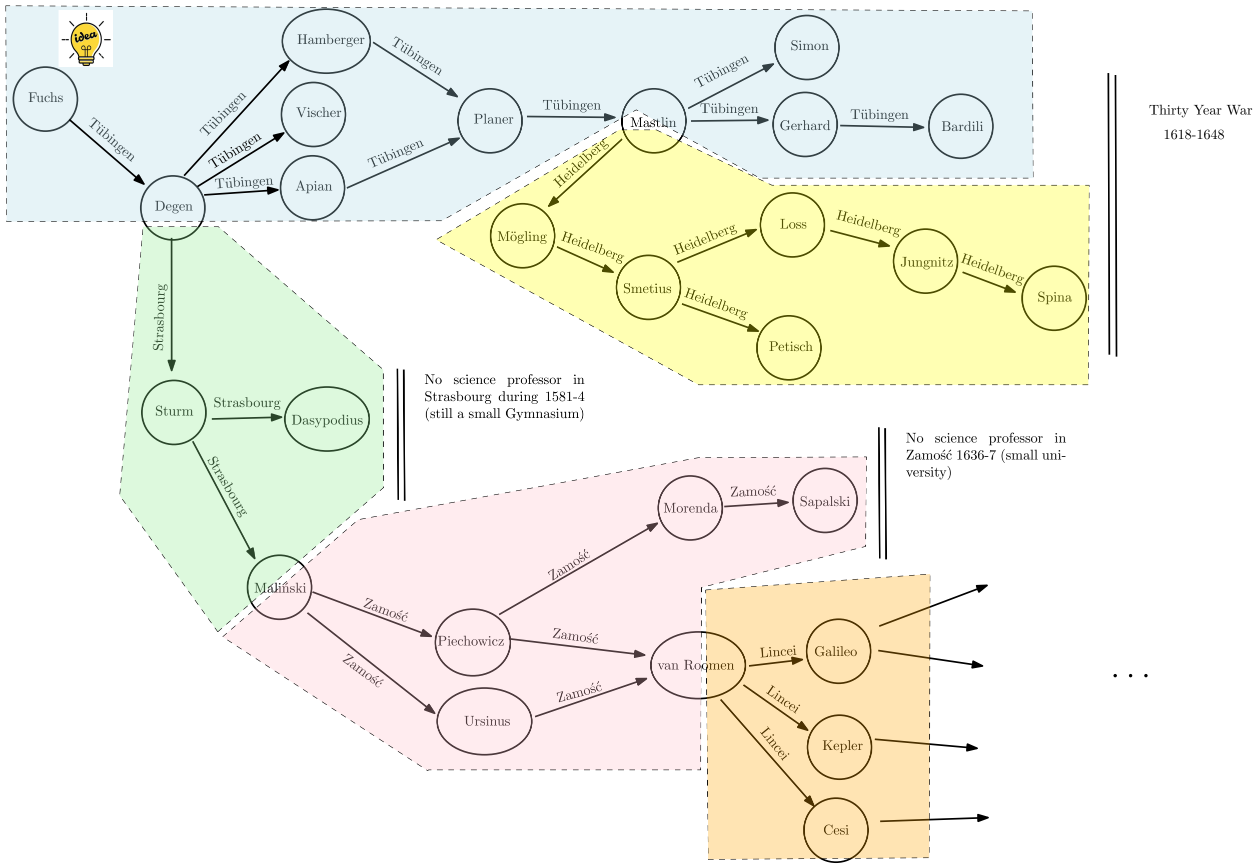


Figure 9: Botanical Realism path

where the new affiliation matrix $B \leq A$ in the Hadamard order (that is, every entry of B_t is less than or equal to the corresponding entry of A_t). Then it is obvious to show that $I_t^B \leq I_t$ $\forall t$, assuming the same initial condition $I_0 = I_0^B$. Indeed, in the new dynamics, there will be fewer exposed persons at every time step, since fewer connections reduce the opportunities for the ideas to spread. This follows from the fact that matrix multiplication with a reduced adjacency matrix B_t leads to a weakly lower infection count at every step.

In the stochastic version, as $\mathbb{E}[\Omega^d(B_t)] = \alpha B_t$, we have $\mathbb{E}[\Omega^d(B_t)] < \mathbb{E}[\Omega^d(A_t)]$ in the Hadamard order, and $\mathbb{E}[I_t^B] \leq \mathbb{E}[I_t]$, $\forall t$. This means that, with an infinite number of simulations D, the world with B (fewer contacts) will still have fewer exposures than the world with A, even in the presence of stochastic transmission. But this statement is no longer strictly true in every realization. If we simulate the process many times, the law of large numbers implies that the average outcome of these simulations should converge to the expectation. The required number of simulations D may however be very large, because of strong non linear effects coming from the topology of the network.

First, we let Botanical Realism and Mathematical Astronomy spread over the affiliation network as if academies never emerged. This analysis allows to assess whether academies were key for the diffusion of the ideas of the Scientific Revolution (McClellan 1985; Pedersen 1992). To measure diffusion, we use Equation (5) which computes the exposure of any European city to an idea. We use the set of cities in Buringh (2021) excluding those in the Ottoman Empire and in Russia. This leaves us with 1,916 cities. We report quartiles of the distribution of exposure across this set of cities relative to the benchmark.

In reporting the results, we distinguish between two roles of academies. First, they contribute directly to the exposure of nearby cities to ideas – for example, when Greenwich benefits from the presence of the Royal Society in London. Second, they facilitate the diffusion of ideas within the affiliation network by bridging university communities – for instance, when Greenwich benefits from scholars at Oxford and Cambridge, whose intellectual development and connectivity have been enhanced by the Royal Society. In Table 5, the line "No direct effect" gives the exposure relative to the benchmark when the direct effect is shut down. Practically, we keep the vector of the individual exposures I_t^d from the benchmark but we remove academies exposure $\tilde{S}_t^k$ from the computation of city exposure S_t^c. The line "No ACAD at all" is based on an alternative affiliation matrix where all the edges stemming from academies are removed, and the various measures of exposures are computed with this matrix.

The following insights can be drawn from Table 5. In 1600, very few academies are around. The Ricovrati in Padua was just created (in 1599), but was mostly literary at that time. The same holds for the Accademia della Crusca (founded 1583 to rule the Italian language). Some other Italian academies founded during the Renaissance still operate, such as the Gelati in Bologna, and the Insensati in Perugia (The British Library 2021). The Lincei, already mentioned above for its role in relation with Romanus and Botanical Realism, will be founded in 1603 (Gabrieli 1989). Accordingly, academies do not influence exposure to Botanical Realism, as both lines remain at 100. However, academies already play a role in spreading Mathematical Astronomy as the median exposure drops to 77. The indirect effect is small, as removing it lead to a further drop in the median to 76. Even at this early stage, when academies are few and primarily informal, they contribute to the dissemination of ideas.

By 1650, academies begin to influence Botanical Realism, both as part of the network (due to figures like Romanus) and directly. By this time, both Botanical Realism and Mathematical Astronomy have reached nearly all cities. From 1700 onward, academies become increasingly significant. For Botanical Realism, academies are essential, as indicated by the second row in each scenario dropping to zero, highlighting their necessity within the

Table 5: Summary Statistics of cities' exposures distributions to ideas when [1] academies have no direct effect on cities but are still present in the network [2] academies have no effect at all.

	Min	Q1	Median	Q3	Max
Botanical Realism					
No direct effect in 1600	100	100	100	100	100
No ACAD at all in 1600	92	100	100	100	101
No direct effect in 1650	47	59	65	78	100
No ACAD at all in 1650	47	59	65	78	100
No direct effect in 1700	24	35	40	44	100
No ACAD at all in 1700	0	0	0	0	0
No direct effect in 1750	10	25	29	34	100
No ACAD at all in 1750	0	0	0	0	0
No direct effect in 1793	0	11	15	19	100
No ACAD at all in 1793	0	0	0	0	0
Mathematical Astronomy					
No direct effect in 1600	4	76	78	83	100
No ACAD at all in 1600	3	73	77	81	99
No direct effect in 1650	32	42	48	62	100
No ACAD at all in 1650	32	42	48	62	100
No direct effect in 1700	18	26	36	44	100
No ACAD at all in 1700	0	1	5	15	32
No direct effect in 1750	0	20	26	31	63
No ACAD at all in 1750	0	3	7	16	57
No direct effect in 1793	0	10	12	16	100
No ACAD at all in 1793	0	4	5	7	24

network. In contrast, while Mathematical Astronomy does not depend strictly on academies for its survival, they play a crucial role in amplifying the extent of exposure. By 1793, the absence of academies would lead to a dramatic reduction in exposure to Mathematical Astronomy.

In addition to analyzing the role of academies, our tool can also be used to analyze the role of specific regions or nations. The literature has examined the contributions of each nation to the rise of science and knowledge in Europe. Each country possessed unique characteristics that, when combined, created a fertile environment for the intellectual and scientific transformations that ultimately led to the development of modernity. Italy laid the foundations with the Renaissance and early scientific methods (Applebaum 2003); England drove empiricism and practical applications (Mokyr 2011); France spearheaded Enlightenment thinking and institutional science (Ferris, Stella, and Yon 2010); Spain advanced economic theory and natural law; the Holy Roman Empire advanced theoretical frameworks in mathematics and astronomy; etc.

Table 6: Summary Statistics of cities' exposures distributions to ideas in five counterfactual networks relative to benchmark in 1793 (= 100)

	Min	Q1	Median	Q3	Max
Botanical Realism					
No Italian Peninsula	0	0	0	0	0
No British Isles	15	75	88	89	90
No France	11	53	65	81	84
No Iberic Peninsula	0	95	95	95	95
No Holy Roman Empire	0	0	0	0	0
Mathematical Astronomy					
No Italian Peninsula	0	0	0	0	0
No British Isles	15	82	97	99	100
No France	14	65	78	96	100
No Iberic Peninsula	0	100	100	100	101
No Holy Roman Empire	9	92	96	99	100

Practically, we use our model to study the importance of each nation in spreading and keeping alive each idea separately. To have a grasp on how nations are key for an idea, we construct five counterfactual networks, removing institutions belonging to specific geographical areas: one without the Italian peninsula, one without the British Isles, one without France[21], one without the Iberian peninsula, and one without the Holy Roman Empire (as defined in

21. We exclude from France cities which became French towards the end of the period: Strasbourg (1681), Molsheim (1648), Nancy (1766), Pont-a-Mousson (1766), Nice (1860), Perpignan (1659), Arras (1659), Douai (1667).

Stelter, De la Croix, and Myrskylä (2021). We then simulate the spread of Botanical Realism and Mathematical Astronomy in these five networks, in addition to the benchmark model.

Results are presented in Table 6. Each number represents a summary statistics of the exposure S^c_{1793} of the cities distributions relative to its exposure in the benchmark (= 100). Without the Italian Peninsula, the idea would not have survived neither for Botanical Realism nor for Mathematical Astronomy. For example, for the latter, the universities of Rome and Bologna served as critical hubs, allowing scholars previously exposed to the Mathematical Astronomy in Vienna or Bratislava to continue disseminating it among their colleagues. Additionally, only the 'Holy Roman Empire' looks necessary for Botanical Realism but not as much for Mathematical Astronomy. For the rest, no region of Europe was necessary for the idea to spread. For example, the British Isles are not needed neither for Botanical Realism nor for Mathematical Astronomy to be known in the rest of Europe. Even if Britain had a key role in the propagation and implementation of useful knowledge (Hallmann, Hanlon, and Rosenberger (2022) show that British inventors worked in technologies that were more central within the innovation network), it is not case as far as our example of propositional knowledge is concerned.

The same reasoning holds for the other regions: the spread of the idea across Europe is not significantly hindered by the absence of France, as for the Iberian Peninsula, its contribution to the spread of the idea appears particularly limited or even negligible for the rest of Europe.

Overall, this analysis underscores the resilience of the European network of academies and universities. Even when some parts are removed, the network remains sufficiently dense to sustain the circulation of ideas.

Finally, we focus on the role of Jesuits, and present the simulation results when Jesuits are removed from the network. The Society of Jesus, founded in 1540 by Ignatius of Loyola, was a highly influential religious order in the Catholic Church. Its members underwent rigorous training, including years of spiritual exercise and intellectual formation. To counter Protestantism, Jesuits rapidly established an extensive network of schools, colleges, and universities across Europe (Grendler 2019) and beyond. In the RETE database, we count 52 Jesuit institutions among the 211 universities and colleges of some renown, and more than 6400 scholars (Jesuit priests)–approximately 8% of all recorded scholars between 1000 and 1800, a figure that rises to 10.9% when considering only the period following the Jesuit order's foundation. Known for their high academic standards, Jesuits taught humanities, sciences, philosophy, and theology. They were also prolific authors: in terms of publications, 5.6% of all VIAF titles associated with RETE scholars have a Jesuit author (6.2% if considering the period following the order's establishment). Their growing influence led to political tensions and subsequently expulsions from several countries: Portugal (1759), France (1764), Spain (1767), and Naples (1767). In 1773, under pressure from European rulers, Pope Clement XIV suppressed the order, though it survived in Russia and Prussia (and later in the USA, when Georgetown University was founded in Washington DC).

Table 7: Summary Statistics of cities' exposures distributions to ideas in the counterfactual network without the Jesuits relative to benchmark in 1750 (= 100)

	Min	Q1	Median	Q3	Max
Botanical Realism					
No direct effect	0	93	97	98	100
No Jesuits at all	0	90	93	94	97
Mathematical Astronomy					
No direct effect	40	91	95	97	100
No Jesuits at all	40	91	95	97	100

Table 7 presents the results or the year 1750 (a few years before the dissolution of the order). When we remove all Jesuit nodes from the network and simulate the spread of Mathematical Astronomy, we observe few differences, except in peripheral regions largely neglected by non-Jesuit institutions (such as Sicily, Andalusia, Romania). This is somewhat surprising, given the widely recognized contributions of Jesuits to science—particularly astronomy—as evidenced by the many lunar craters named after Jesuit astronomers and all the observatories they built (Udías 2003). One possible explanation for their limited role in the broader diffusion of Mathematical Astronomy is that they operated within a relatively isolated network, separate from the rest of academia.

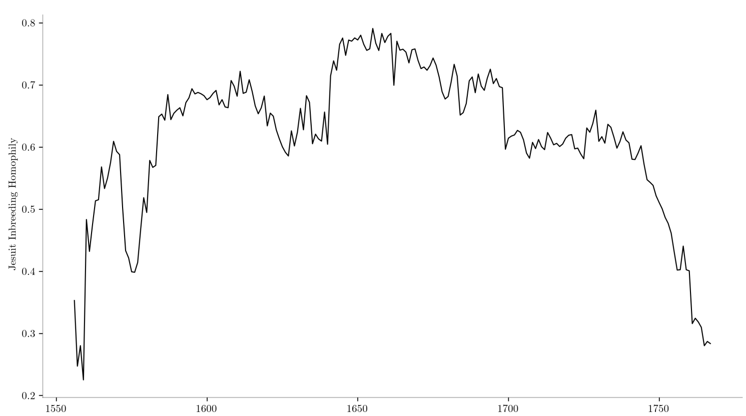


Figure 10: Jesuit inbreeding homophily over time

To test this hypothesis, we examine whether Jesuit nodes are densely connected internally while remaining weakly connected to the rest of the network. We define two groups of nodes: Jesuits and non-Jesuits. To quantify Jesuit insularity, we compute the Coleman (1958) inbreeding homophily index, which ranges from -1 (no internal Jesuit connections) to 0 (connections similar to a random network) to 1 (complete inbreeding). Following Currarini, Jackson, and Pin (2009), we define IH as follows:

$$IH_{Jesuits,t} = \frac{H_{Jesuits,t} - \omega_{Jesuits,t}}{1 - \omega_{Jesuits,t}}$$

where $H_{Jesuits,t}$ is the fraction of edges entailing only Jesuits at time t, and $\omega_{Jesuits,t}$ is the relative fraction of Jesuits in the scholar population any given point in time t.

Figure 10 plots $IH_{Jesuits,t}$ over time, considering the period of the order's existence, from 1556 to 1767. For most of the timeframe, the index remains between 0.6 and 0.8, indicating a high degree of inbreeding. Jesuit universities were typically closed to non-Jesuit professors, and Jesuit scholars rarely taught outside them. However, the index is slightly lower at the beginning, when the Jesuits were establishing their university network, and at the end, preceding their gradual dissolution.

The Appendix F provides additional statistics on the Jesuits' position and connectivity in the network, including their number, density, conductance, and decompositions by field.

5 Conclusions

In 1798, Thomas Malthus (1766 Westcott - 1834 Bath), a fellow at the University of Cambridge since 1793, published a treatise on population and development (Malthus 1807). He developed the idea that population growth tends to outpace food production, leading to inevitable constraints to development. In 1818, Malthus became a Fellow of the Royal Society. Malthus' view had an immense influence on political economy in the following decades. Still today his ideas are modelled and debated (André and Platteau 1998; Ashraf and Galor 2011). Around the same years, Hung Liang-Chi (1744 - 1809), a high official of the Chinese imperial administration, developed similar ideas. The ideas were particularly relevant for understanding Chinese dynamics in the 19th century. Still, Hung Liang-Chi was completely forgotten and only rediscovered in the 20th century (Silberman 1960).

How can we understand the differences in the fates of these two ideas? The approach we developed in this paper can be applied to comprehend Malthus' success. Malthus was integrated in the broad European academic network where his ideas could spread. Hung Liang-Chi, on the contrary, belonged to an administration, where ideas are developed by individuals but not subject to broad dissemination and discussion.

This study examined how academic networks in the premodern era influenced the spread of ideas. Using dynamic network models and counterfactual experiments, we showed that features like the emergence of academies and the connections they created across regions helped ideas spread more widely. By examining the diffusion of groundbreaking ideas and paradigm shifts as Botanical Realism, Mathematical Astronomy, and Scholasticism, we validate the role of higher-education institutions in European development.

The counterfactual experiments revealed the nuanced importance of academies: not only do they act as hubs of direct idea dissemination, but they also enhance the connectivity of the broader network, bridging universities communities. Without academies, the diffusion of ideas born in universities settings would have been significantly slower. Our approach also provided insights into regional contributions to scientific progress, highlighting the resilience of the European network of academies and universities, which remained sufficiently dense to sustain the circulation of ideas even when certain parts were removed.

While our results are robust, the analysis is limited by the assumption that the affiliation network is exogenous, and determined by the data we observe. This is of course a limitation of our approach, as the affiliation network results from location choices of individuals, and is thus endogenous to the rise in prominence of some of its members. Perhaps other scholars joined Tübingen precisely *because* they wanted to learn from Fuchs. Although this endogeneity bias might be of minor importance, an extension of the analysis would thus consider exogenous changes in the network and their effect (a popular source of exogenous changes in network is through the unexpected death of some nodes, as in Benzell and Cooke (2021)).

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A Descriptive Statistics

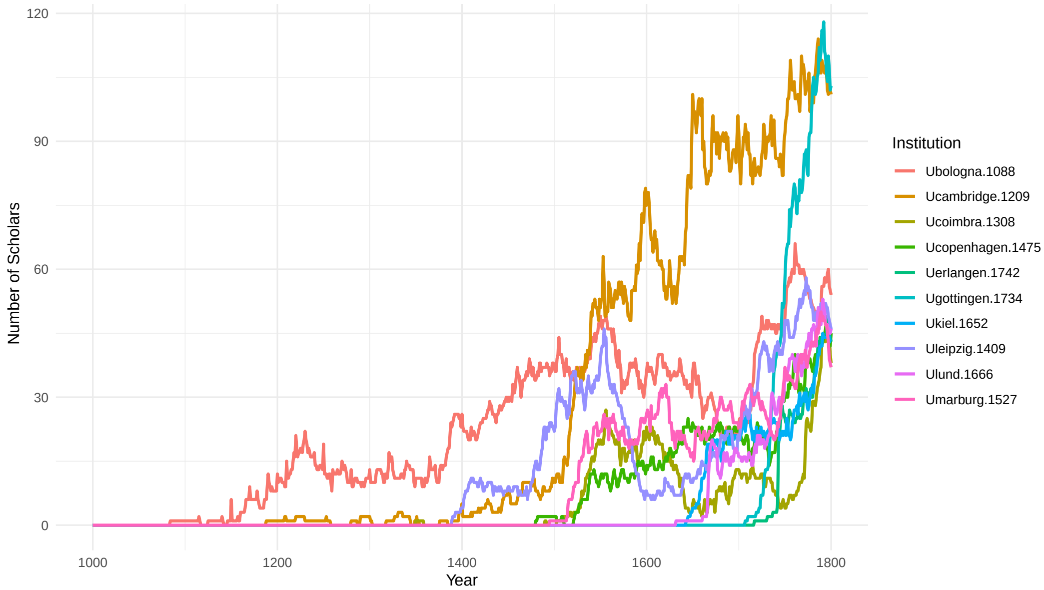


Figure 11: Number of university professors between 1000 and 1800 of the top 10 universities considering the number of scholars in 1793. In the legend, the name of the institution with the foundation date.

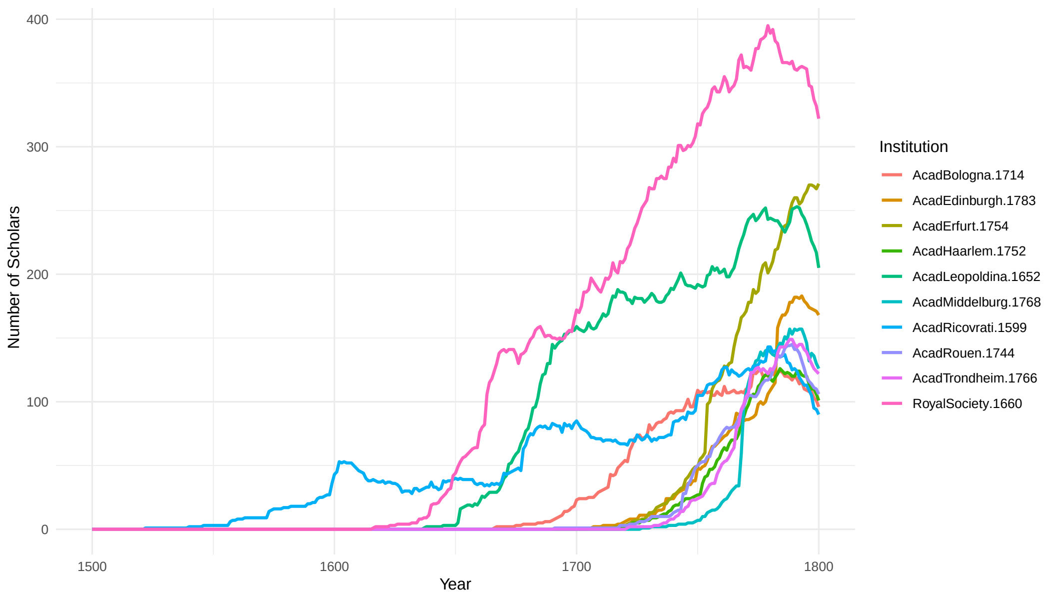


Figure 12: Number of academicians between 1500 and 1800 of the top 10 academies considering the number of scholars in 1793. In the legend, the name of the institution with the foundation date.

Institution	Mean	Median	SD	Min	Q1	Q3	Max
Ubologna.1088	34.00	36	14.64	12	25	43	54
Ucambridge.1209	57.57	92	48.78	1	8	96.5	101
Ucoimbra.1308	8.57	4	13.78	0	0	9	38
Uerlangen.1742	9.71	0	17.38	0	0	12.5	43
Ugottingen.1734	23.00	0	41.37	0	0	29	103
Ukiel.1652	12.71	4	16.42	0	0	21	43
Ucopenhagen.1475	17.71	22	17.58	0	1	27.5	45
Uleipzig.1409	21.43	20	19.17	0	7	34	48
Ulund.1666	14.00	1	19.26	0	0	25.5	46
Umarburg.1527	16.43	17	16.67	0	0.5	30	37

Table 8: Descriptive statistics for the top 10 universities, considering the number of scholars in 1793. In the first column, the name of the institution with the foundation date.

Institution	Mean	Median	SD	Min	Q1	Q3	Max
AcadBologna.1714	32.57	0	48.65	0	0	59.5	109
AcadEdinburgh.1783	30.86	0	63.06	0	0	24	168
AcadErfurt.1754	45.71	0	101.01	0	0	24.5	271
AcadHaarlem.1752	18.29	0	37.84	0	0	13.5	101
AcadLeopoldina.1652	79.86	3	99.61	0	0	175.5	205
RoyalSociety.1660	122.29	44	148.13	0	0	245	322
AcadRicovrati.1599	45.71	40	47.12	0	0	87.5	105
AcadRouen.1744	22.43	0	41.26	0	0	25.5	106
AcadTrondheim.1766	20.86	0	45.49	0	0	12	122
AcadMiddelburg.1768	19.00	0	47.25	0	0	3.5	126

Table 9: Descriptive statistics for the top 10 academies, considering the number of scholars in 1793. In the first column, the name of the institution with the foundation date.

B Empirical Assessments

B.1 Descriptive Statistics

Table presents some descriptive statistics, which supports the results in the main text, Table 2 and Table 3.

Variable	NAs	Obs	Mean	Median	SD	Min	Max
(ihs) Exposure to Botanical Realism	0	54390	0.270	0	0.842	0	6.009
(ihs) Exposure to Mathematical Astronomy	0	54390	0.398	0	1.253	0	7.789
(ihs) City population in 1500	4410	49980	2.803	2.777	1.059	0	5.522
(ihs) Distance to Tübingen	0	54390	7.042	7.146	0.872	0	8.341
(ihs) Distance to Vienna	0	54390	7.376	7.441	0.805	0	8.435

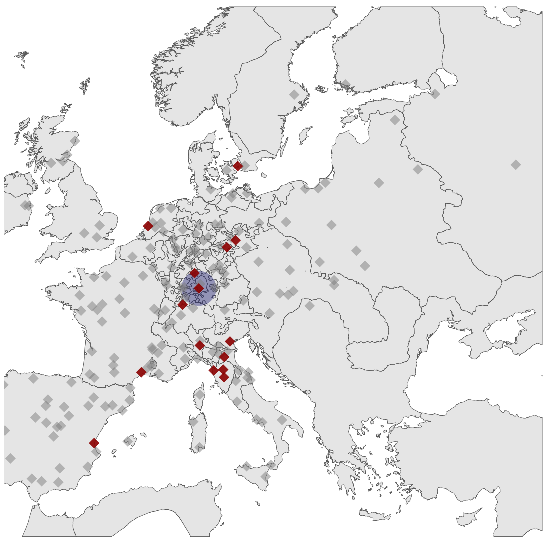
Table 10: Summary statistics. (ihs) refers to the transformation in inverse hyperbolic sine of the relative variable. The 4410 missing values for city population indicates that for 15 cities (and 294 years) we do not have population data, we assume it at zero in the analyses.

B.2 Botanical Realism

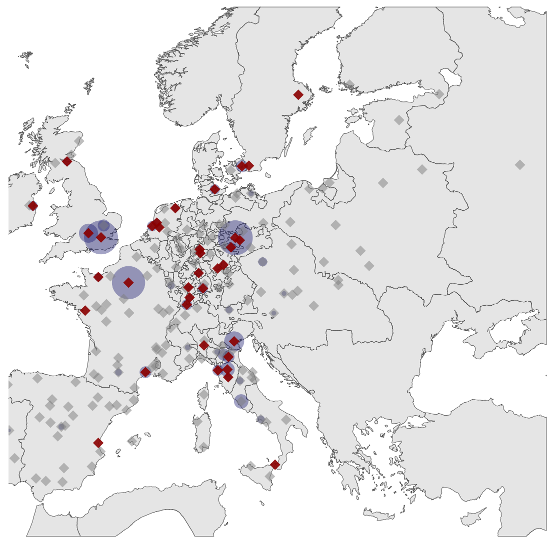
Figure 13 shows the yearly exposure to Botanical Realism in three different points in time. This figure visualizes how exposure evolves over time, allowing us to trace how these innovative ideas were initially concentrated around Tübingen in 1600, spread across Europe by 1700, and further expanded, reaching smaller and more distant urban centers by 1793. Blue bubbles represent exposure to Botanical Realism, while red diamonds indicate cities that had at least one botanic garden by the respective year.

B.3 Mathematical Astronomy

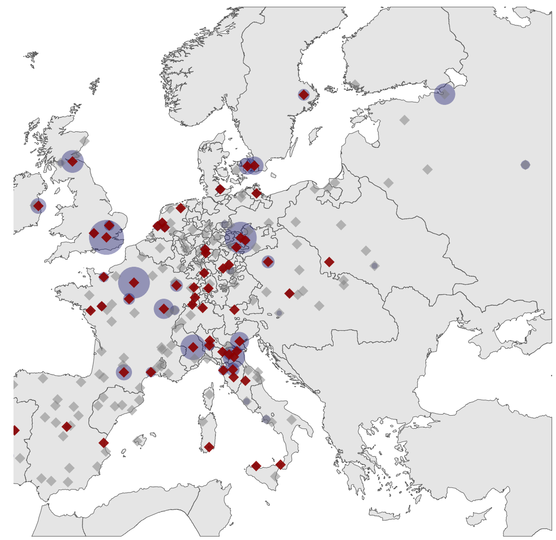
Figure 14 visualizes the sample of universities cities with their yearly exposure to Mathematical Astronomy in 1600, 1700, and 1793. This figure allows to see how the exposure evolves over time and its interaction with the creation of observatories. As in the first experiment, blue bubbles represent exposure to Mathematical Astronomy, while red diamonds indicate cities that had at least one observatory in the relative year.



(a) Year 1600

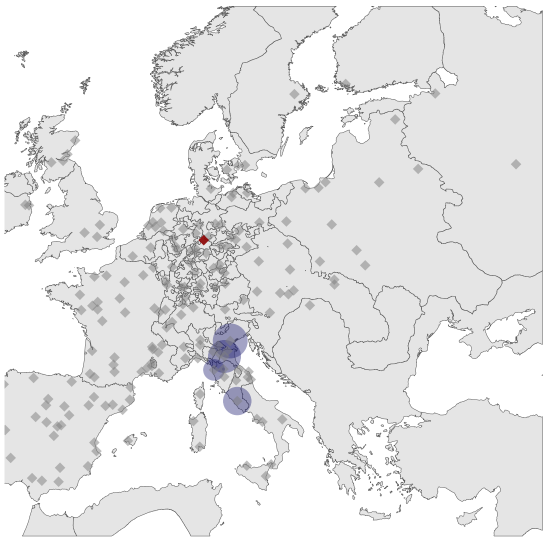


(b) Year 1700

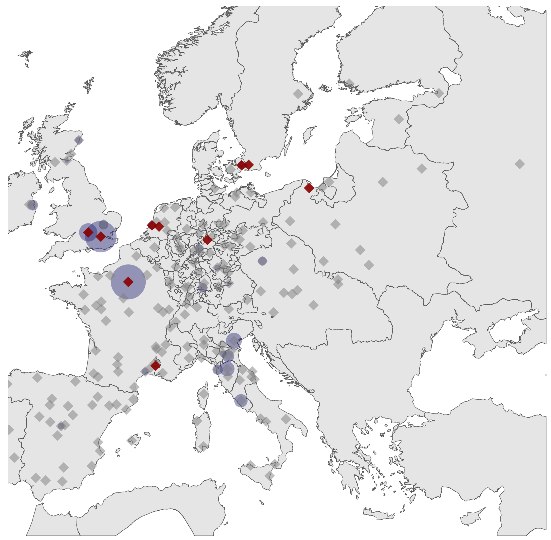


(c) Year 1800

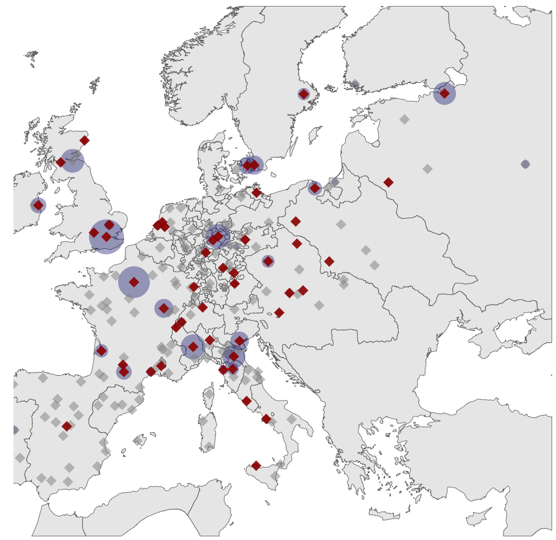
Figure 13: Blue bubbles represent the yearly exposure to Botanical Realism in years 1600, 1700, and 1793, respectively. $\alpha = 0.3$ and $D = 100$. Cities with a botanic garden are the red diamonds, and without botanic gardens are the grey diamonds.



(a) Year 1600



(b) Year 1700

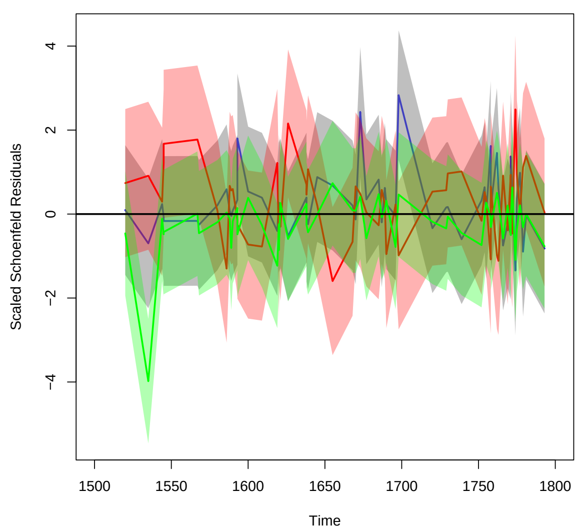


(c) Year 1800

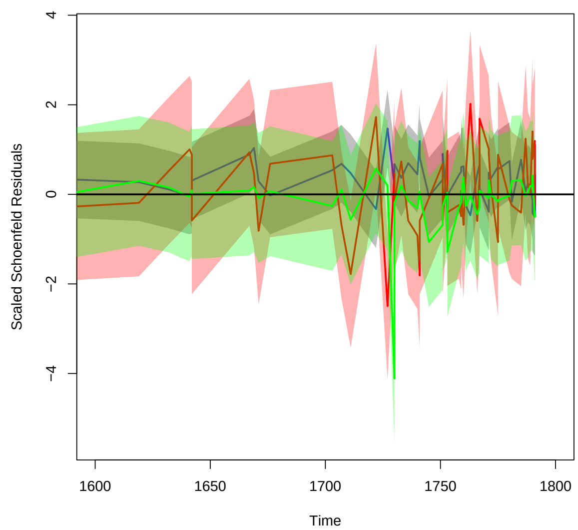
Figure 14: Blue bubbles represent the yearly exposure to Mathematical Astronomy in years 1600, 1700, and 1793, respectively. $\alpha = 0.3$ and $D = 100$. Universities cities with a botanic garden are the red diamonds, and without botanic gardens are the grey diamonds.

C Tests for the proportionality of Hazard Functions

In this section we test the proportionality of the hazard functions (e.g.,scaled Schoenfeld residuals) of all the covariates in column (3) of Table 2 and Table 3, respectively, and time. The global correlation is not statistically significant in neither of the cases, as it is indicated by the confidence intervals always overlapping with the zero line. The blue line and grey confidence interval relates to the hazard ratios of '(ihs) Exposure to Botanical Realism' (Fig 15a) and '(ihs) Exposure to Mathematical Astronomy' (Fig 15b), respectively. The red line and confidence interval correspond to the scaled Schoenfeld residuals of '(ihs) City population in 1500', while the green line and interval of confidence represent the hazard ratios of '(ihs) Distance to Tübingen' (Fig 15a) and '(ihs) Distance to Vienna' (Fig 15b), respectively.



(a) Botanical Realism



(b) Botanical Realism

Figure 15: Joint correlations between the scaled Schoenfeld residuals (e.g. hazard ratios) of all the covariates in column (3) of (a) Table 2 and time, and (b) Table 3 and time.

D Empirical assessment 3: Additional Results

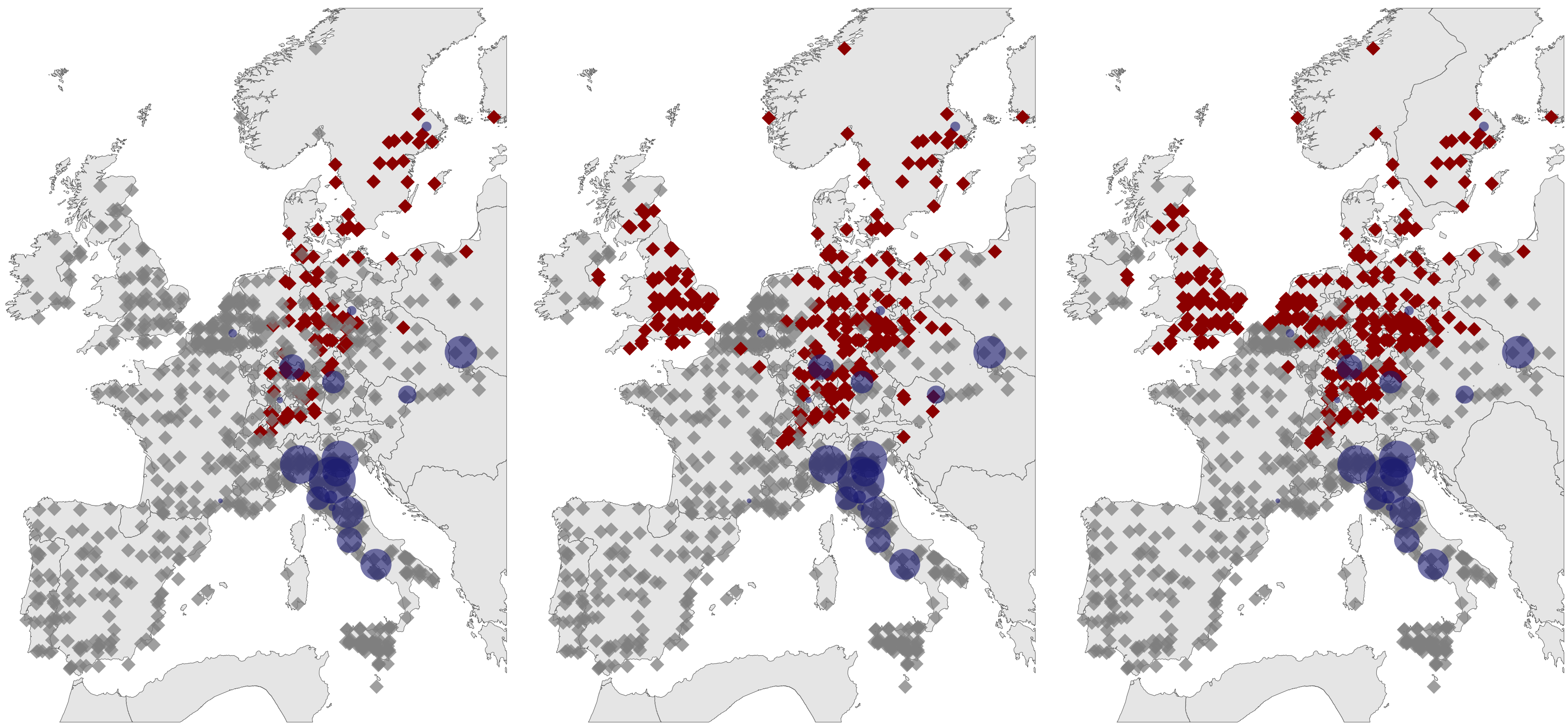
In Table 11 we show the same main explanatory variables as in Table 4 in the main text but we include more controls and fixed effects. The results are robust. In addition to controlling for the presence of all universities active in 1500 as indicated in our database (De la Croix 2021), we also include the city populations in 1500 taken from Buringh (2021), transformed in inverse hyperbolic sine (ihs) to account for cities with no recorded population estimates.[22] The remaining control variables are selected from Rubin (2014) and include factors related to the economic status of cities: the presence of a printing press by 1500, whether the city was a free city by 1517, the market potential of the city in 1500, its membership in the Hanseatic League by 1517, whether it hosted a bishop or archbishop by 1517, and whether the city had direct access to water. We also include Fixed Effects capturing time-invariant characteristics common to each imperial circle and historical country as in 1500.

22. The inverse hyperbolic sine is similar to the logarithmic transformation but can accommodate zero (Bellemare and Wichman 2020), which makes it particularly useful when dealing with the large number of cities from Rubin (2014) with no available population estimates in Buringh (2021).

Table 11: Linear Probability Model - Exposure to Scholasticism in 1508 and cities' probability to become protestant in 1530, 1560, and 1600

	Protestant in			Protestant in		
	1530	1560	1600	1530	1560	1600
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	0.001*	0.003***	0.003***	0.002**	0.005***	0.006***
Scholasticism S^c_{1508}	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Exposure to Practical				-0.001**	-0.003***	-0.003***
Surgery PS^c_{1508}				(0.0005)	(0.001)	(0.001)
Presence of university	0.004	-0.006	-0.012	0.002	-0.009	-0.016
in 1500	(0.021)	(0.030)	(0.028)	(0.021)	(0.031)	(0.030)
Printing press by 1500	-0.043*	-0.050**	-0.052**	-0.039*	-0.038*	-0.040**
	(0.023)	(0.023)	(0.022)	(0.022)	(0.021)	(0.019)
(ihs) City population	0.013**	0.007	0.009	0.011**	0.004	0.005
in 1500	(0.005)	(0.007)	(0.006)	(0.005)	(0.007)	(0.006)
Free Imperial	0.122	0.183*	0.276***	0.103	0.132	0.221**
City by 1517	(0.082)	(0.098)	(0.104)	(0.082)	(0.098)	(0.105)
Market potential	-0.006**	-0.014**	-0.013**	-0.006**	-0.013**	-0.011**
in 1500	(0.003)	(0.006)	(0.005)	(0.003)	(0.006)	(0.005)
Hanseatic by 1517	0.024	0.080	0.085*	0.020	0.069	0.074
	(0.038)	(0.052)	(0.049)	(0.039)	(0.051)	(0.047)
Lay magnate	-0.014	0.151**	0.171**	-0.024	0.123	0.142*
	(0.038)	(0.067)	(0.071)	(0.037)	(0.077)	(0.083)
(Arch)Bishop by 1517	-0.036*	-0.058**	-0.066***	-0.027	-0.031	-0.038*
	(0.019)	(0.025)	(0.022)	(0.019)	(0.025)	(0.022)
Access to water	0.008	-0.003	-0.005	0.008	-0.001	-0.003
	(0.016)	(0.019)	(0.017)	(0.016)	(0.018)	(0.016)
Imperial Circle FE	YES	YES	YES	YES	YES	YES
1500 Country FE	YES	YES	YES	YES	YES	YES
Observations	867	867	867	867	867	867
Adjusted R^2	0.501	0.719	0.766	0.504	0.731	0.779
Log Likelihood	110.32	34.57	77.05	113.45	55.44	103.44

Notes: Robust SE clustered by territory in parentheses.
A constant term is included in all regressions.



(a) Protestant cities in 1530 (b) Protestant cities in 1560 (c) Protestant cities in 1600

Figure 16: Blue bubbles represent the exposure to Practical Surgery 30 years prior 1508, $\alpha = 0.3$ and $D = 10,000$. Protestant cities are the red diamonds, and Catholic cities are the grey diamonds.

E Deterministic Case: Botanical Realism, Mathematical Astronomy, Scholasticism

In this section, we present results for each of the three 'ideas' as in the main text but we assume a transmission probability $\alpha = 1$. All our findings are confirmed also in the deterministic case, underlining the robustness of both our epidemiological model of transmission (Section 2.3) and of our empirical approach (Section 3). There are no major changes in significance, only some magnitudes slightly update. Specifically, in the case of Botanical Realism the probability to get a botanic garden increases to 31% (from 28% with $\alpha = 0.3$, Column (3)), also in the case of Mathematical Astronomy the probability to get an observatory increases to 43% (from 37% with $\alpha = 0.3$, Column (3)). Looking at the results about the exposure to scholasticism, the coefficients do not really change much: only in 1560 and 1600 the magnitude slightly increase when controlling also for the exposure to Practical Surgery as an orthogonal path of transmission.

Table 12: Cox Proportional Hazards Model with transmission probability $\alpha = 1$ – Botanical Realism and Botanic Gardens

	Risk of creating a Botanic Garden		
	(1)	(2)	(3)
(ihs) Exposure	0.345***	0.296***	0.268***
Botanical Realism S_t^k	(0.061)	(0.070)	(0.075)
(ihs) City population		0.225***	0.270***
in 1500		(0.079)	(0.085)
(ihs) Distance to Tübingen			-0.200***
(gravity model)			(0.061)
Observations	54,390	54,390	54,390
Log Likelihood	-293.274	-291.158	-289.573
Score (Logrank) Test	25.639***	29.928***	33.693***

Note: *p<0.1; **p< 0.05; ***p<0.01
Robust standard errors in parenthesis.
For 16 university cities without population data in Buringh (2021) we assume it at zero. All the variables are transformed in inverse hyperbolic sine.

Table 13: Cox Proportional Hazards Model Results with transmission probability $\alpha = 1$ – Mathematical Astronomy and astronomical observatories

	Risk of creating an Observatory		
	(1)	(2)	(3)
(ihs) Exposure to Mathematical Astronomy S_t^k	0.395***	0.356***	0.358***
	(0.050)	(0.062)	(0.063)
(ihs) City Population in 1500		0.151*	0.149*
		(0.085)	(0.088)
(ihs) Distance to Vienna (gravity model)			-0.160***
			(0.049)
Observations	54,390	54,390	54,390
Log Likelihood	-256.599	-255.709	-254.760
Score (Logrank) Test	41.942***	44.254***	46.744***

Note: *p<0.1; **p< 0.05; ***p<0.01
Robust standard errors in parenthesis.
For 16 university cities without population data in Buringh (2021) we assume it at zero. All the variables are transformed in inverse hyperbolic sine.

Table 14: Linear Probability Model - Exposure to Scholasticism in 1508 and cities' probability to become protestant in 1530, 1560, and 1600 with transmission probability $\alpha = 1$

	Protestant in			Protestant in		
	1530	1560	1600	1530	1560	1600
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure to Scholasticism S^c_{1508}	0.001*	0.003***	0.004***	0.002***	0.006***	0.008***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Presence of university in 1500	-0.036	-0.077	-0.142***	-0.027	-0.045	-0.094**
	(0.027)	(0.052)	(0.054)	(0.026)	(0.044)	(0.044)
Exposure to Practical Surgery PS^c_{1508}				-0.001*	-0.006**	-0.008***
				(0.001)	(0.002)	(0.002)
Observations	867	867	867	867	867	867
Adjusted R^2	0.021	0.058	0.100	0.031	0.131	0.254
Log Likelihood	-198.74	-506.10	-522.87	-194.10	-470.81	440.79

Notes: Robust SE clustered by territory in parentheses.
A constant term is included in all regressions.

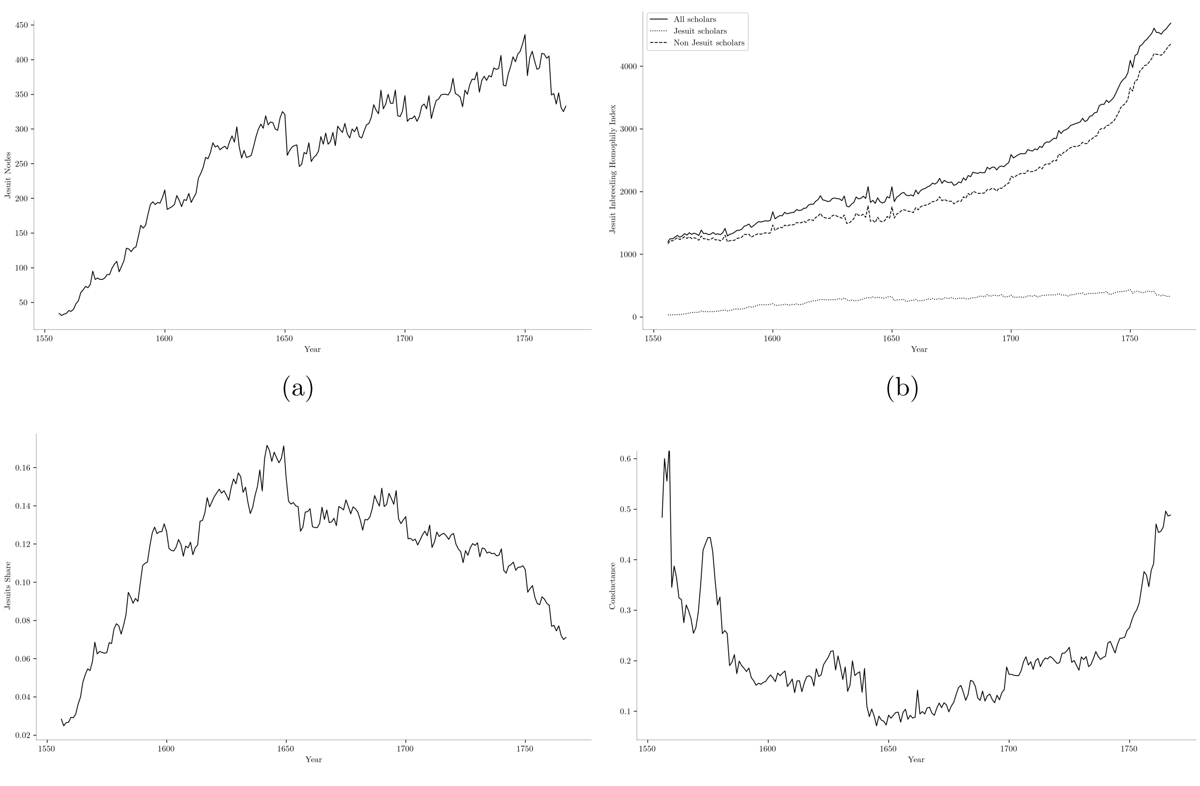
Table 15: Linear Probability Model - Exposure to Scholasticism in 1508 and cities' probability to become protestant in 1530, 1560, and 1600 with transmission probability $\alpha = 1$

	Protestant in			Protestant in		
	1530	1560	1600	1530	1560	1600
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure	0.001*	0.003***	0.003***	0.002**	0.006***	0.007***
Scholasticism S^c_{1508}	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Exposure to Practical				-0.002**	-0.005***	-0.005***
Surgery PS^c_{1508}				(0.001)	(0.001)	(0.001)
Presence of university	0.004	-0.006	-0.012	0.002	-0.010	-0.016
in 1500	(0.021)	(0.030)	(0.028)	(0.021)	(0.031)	(0.030)
Printing press by 1500	-0.043*	-0.050**	-0.052**	-0.040*	-0.039*	-0.041**
	(0.023)	(0.023)	(0.022)	(0.022)	(0.021)	(0.020)
(ihs) City population	0.013**	0.007	0.009	0.011**	0.004	0.006
in 1500	(0.005)	(0.007)	(0.006)	(0.005)	(0.007)	(0.006)
Free Imperial	0.122	0.183*	0.275***	0.104	0.136	0.224**
City by 1517	(0.082)	(0.098)	(0.104)	(0.082)	(0.098)	(0.105)
Market potential	-0.006**	-0.014**	-0.013**	-0.006**	-0.013**	-0.012**
in 1500	(0.003)	(0.006)	(0.005)	(0.003)	(0.006)	(0.005)
Hanseatic by 1517	0.024	0.080	0.085*	0.021	0.071	0.075
	(0.038)	(0.052)	(0.049)	(0.039)	(0.051)	(0.048)
Lay magnate	-0.014	0.150**	0.171**	-0.023	0.126*	0.144*
	(0.038)	(0.067)	(0.071)	(0.037)	(0.076)	(0.082)
(Arch)Bishop by 1517	-0.036*	-0.057**	-0.066***	-0.027	-0.0313	-0.039*
	(0.019)	(0.025)	(0.022)	(0.019)	(0.026)	(0.022)
Access to water	0.008	-0.002	-0.005	0.008	-0.0005	-0.002
	(0.016)	(0.019)	(0.017)	(0.016)	(0.018)	(0.016)
Imperial Circle FE	YES	YES	YES	YES	YES	YES
1500 Country FE	YES	YES	YES	YES	YES	YES
Observations	867	867	867	867	867	867
Adjusted R^2	0.501	0.718	0.765	0.504	0.729	0.777
Log Likelihood	110.31	34.16	76.93	113.07	51.64	100.18

Notes: Robust SE clustered by territory in parentheses.
A constant term is included in all regressions.

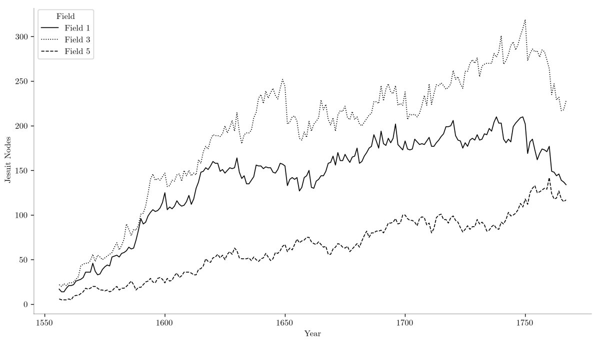
F Placebo networks and the role of the Jesuits

In the paper, we explore a counterfactual scenario examining the spread of ideas after removing Jesuit scholars from the network. Here, we present key statistics on the position and connectivity of Jesuits within the affiliation network. The network metric in Figure 17d quantifies how well-connected Jesuit-affiliated nodes are to the rest of the network. In our network structure, conductance reflects the extent to which Jesuits were integrated into mixed institutions rather than remaining isolated. The initially high conductance suggests that early Jesuits were present in diverse academic environments. Over time, the decline in conductance aligns with their increasing concentration within Jesuit institutions. Figure 18b shows the Homophily Index of Jesuits, by field between 1556 and 1767. Notably, the decreasing trend in inbreeding homophily among Jesuit scientists is likely a consequence of the rise of academies, which were largely centered on scientific disciplines and saw a relatively active participation from Jesuits.

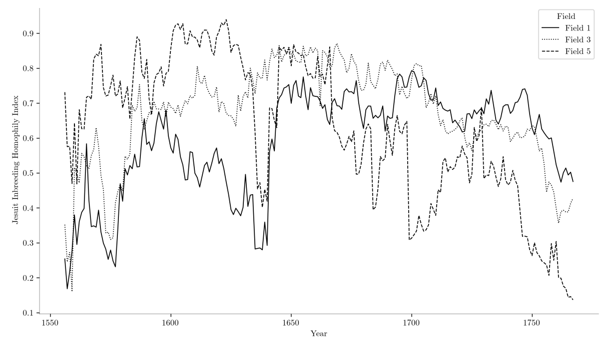


(a) (b) (c) (d)

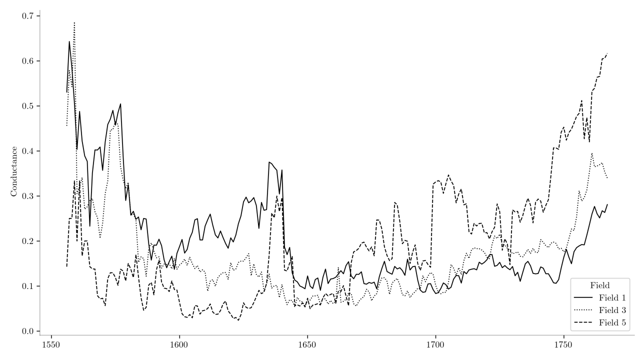
Figure 17: (a) Number of Jesuit scholars active in the network, 1556-1767. (b) Comparison of number of scholars by type: all (solid line), Jesuits (dotted line), and non Jesuit scholars (dashed line),1556-1767. (c) Fraction of Jesuit scholars active in the network, 1556-1767. (d) Conductance of Jesuits in the affiliation network, 1556–1767.



(a)



(b)



(c)

Figure 18: (a) Number of Jesuit scholars active in the network by field, 1556-1767. Field 1 stands for theology, field 3 for humanities, and field 5 for sciences. (b) Homophily Index of Jesuits, by field, 1556-1767. Field 1 stands for theology, field 3 for humanities, and field 5 for sciences. (c) Conductance of Jesuits in the affiliation network by field, 1556–1767. Field 1 stands for theology, field 3 for humanities, and field 5 for sciences.