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

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Abstract

While good ideas can emerge anywhere, it takes a community to develop and disseminate them. In premodern Europe (1084-1793), there were approximately 200 universities and 150 academies of sciences, which were home to thousands of scholars and created an extensive network of intellectual exchange. By reconstructing interpersonal connections that were made via 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 at connecting distant parts of the network. Moreover, we show that the diffusion of ideas through the network is remarkably resilient, even if we remove key regions such as France or the British Isles. In Europe, ideas gain prominence when they are channeled effectively by powerful institutions.

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1 Introduction

In Europe during the Middle Ages and Early Modern period, more than one hundred thousand scholars were engaged in the production, dissemination, and development of various forms of knowledge. These scholars did not operate in isolation: two key institutions, universities and academies, facilitated their interaction. These institutions organized teaching and research within self-governed communities of scholars, as stressed in Rashdall (1895) and McClellan (1985). From the halls of medieval universities such as the University of Paris and Bologna's *Alma mater* to, much later, lively debates in academies such as the Royal Society, formal institutions brought together scholars of diverse backgrounds to develop and disseminate scientific discovery. These institutions provided scholars not just with employment, but with a physical proximity that facilitated interaction.

In this paper, we measure how ideas spread through the academic affiliation network.[1] Our quantitative analysis 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). Similar to the approach taken by Becker et al. (2024) in their analysis of the pre-WWII period, we base connections between scholars 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 that 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 1084 to 1793. Our timeframe starts with the establishment of Irnerius's school of jurisprudence in Bologna (c. 1050 - after 1125) and concludes with the French Revolutionary Convention (1793). 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 at the same institution and work within a broadly similar field. We assume that ideas spread through networks like infections, with scholars transmitting their inventions to peers with a certain probability. In our model, idea diffusion is governed by a single parameter, the *link activation probability*. A value close to zero suggests that face-to-face interactions rarely lead to knowledge transfer (e.g., due to non-academic discussions), while a high value indicates they are an effective channel for diffusion.

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

Ideally we would estimate this parameter by comparing the model's predictions to empirical moments that reflect the historical spread of ideas. However, a key challenge is that we do not directly observe ideas as they propagate. Unlike studies that trace the trajectory of a single idea—such as the study by Xue (2025) on Wang Yangming's influence in Chinese texts, or Giorcelli, Lacetera, and Marinoni (2022) on the spread of Darwinian theory via Google Books—or those that focus on specific linguistic or regional contexts, like Chiopris (2024) on 19th-century ideas in the German library consortium, our setting lacks detailed records of idea diffusion. Contemporary work, such as that of Ahmadpoor and Jones (2017), leverages citation and patent data to track knowledge flows over time: no comparable measures exist for Early Modern Europe. Still, we can observe outcomes plausibly linked to idea adoption, even though identifying consistent, city-level measures across Europe is especially challenging for the premodern period.

Our approach is to estimate the link activation probability by simulating the diffusion of ideas through the affiliation network and constructing *measures of exposure* at the scholar, institution, and city levels. We then correlate these simulated exposures with historical outcomes in what we term *auxiliary models*, drawing on the framework of indirect inference (see Smith (2008)). We chose two intellectual breakthroughs from the Scientific Revolution that have both historical significance and observable proxies, to benchmark our diffusion model.

The first auxiliary model is the rise of botany as an independent discipline, driven by Leonhart Fuchs (1501–1566), a professor at the Universities of Tübingen and Ingolstadt. Fuchs' work emphasized direct observation of nature, culminating in the publication of a comprehensive herbal featuring accurate plant illustrations and medicinal descriptions. We label this shift "Botanical Realism". The heightened interest in botany across Europe that followed is evidenced by the spread of botanic gardens. We calculate each city's simulated exposure to Botanical Realism and use a proportional hazard model to estimate the probability of a botanic garden being established. We find that this probability increases with exposure, which is consistent with the model being accurate.

The second auxiliary model focuses on the astronomical revolution, particularly the foundational role of Johannes Regiomontanus (1436–1476) in the advancement of trigonometry and astronomy. We group his innovations, which were later instrumental to the work of Copernicus, Kepler, and Galileo, under the label "Mathematical Astronomy". Regiomontanus held positions in Vienna, Bratislava, Padua, and Rome, which facilitated the transmission of his ideas. We measure exposure to his innovations and analyze the correlation with the *creation of astronomical observatories* across Europe. Again using a proportional hazard model, we find a positive relationship between exposure and the likelihood of an observatory being established.

In both cases, we control for Euclidean distance from the place of origin of the idea, accounting for diffusion via geographic proximity (consistent with gravity models), which would be the case, for example, for books (Dittmar 2011). Our exposure measures remain predictive even after this control, which highlights the critical role of social and institutional connections in the transmission of ideas. This finding echoes apprenticeship models, in which the master-apprentice face-to-face communication is key (De la Croix, Doepke, and Mokyr 2018), but also contemporary insights, such as those of Atkin, Chen, and Popov (2022), on the persistent importance of face-to-face interactions in environments like Silicon Valley.

We then estimate the link activation probability by maximizing the joint likelihood of these two auxiliary models. Next, we use the model to carry over additional empirical analysis, going beyond the Scientific Revolution and the direct relation between ideas and outcomes, to cover an example of a backlash against an idea. Scholasticism was pioneered by Petrus Lombardus (c. 1100 – 1160), a professor in Paris, and it was the dominant approach to philosophy and theology in the Middle Ages. Followers of scholasticism used logical reasoning to explore theological questions, and this method was adopted in many universities. Over time, however, it became increasingly detached from the practical concerns of believers and devolved into abstract debates, a decline often cited in historical literature (Chaunu 2014; Barrett 2023). It is possible that Protestantism 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 measures of exposure. We use 1508, just before Martin Luther's academic career began, as the start of the simulation to minimize potential confounders. We capture the exposure to Scholasticism across universities in 1508 and 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 from Rubin (2014). The results show a strong correlation between exposure to Scholasticism and the likelihood of becoming Protestant.

In a similar vein, we extend the classical finding that pogroms against Jews are more likely to occur following major shocks—such as the Black Death (Becker and Pascali 2019; Jedwab, Johnson, and Koyama 2019; Voigtländer and Voth 2012)—by showing that the anti-Judaic ideas embedded in scholastic thought acted as a complementary force in this process. In addition, we examine a distinct case involving a demonstrably false belief: the claim that Swedes are descendants of the lost civilization of Atlantis.

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 Jesuit community. Our aim in examining these counterfactuals is to assess the network features that are most critical for idea diffusion.

In the first experiment, we reassign the intellectual origin of an idea to different individuals and ask whether it would still propagate across Europe. While some peripheral institutions are not well enough connected to guarantee the survival of an idea, we find that in most cases, ideas still reach the entire network within a couple of centuries. However, the speed and route of diffusion vary, emphasizing the non-ergodic nature of the process and the importance of initial conditions. In the second experiment we compare the role of academies to that of universities. When we remove academies from the network, there is a notable drop in the geographical reach of ideas, especially those that originated in remote or disrupted areas. Academies, with their international memberships, often served as critical diffusion channels, bridging regions and sustaining intellectual exchange during crises such as university closures during the Thirty Years' War. In the third experiment, we simulate the removal of entire countries or regions—such as the British Isles, France, or the Italian and Iberian Peninsulas—to assess their systemic importance. Surprisingly, even when major regions are excluded, most ideas continue to spread widely across Europe. This suggests that most regions were not essential to the flow of knowledge, underscoring the network's remarkable resilience to local shocks.

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.

It is important to emphasize that our focus on counterfactual scenarios is primarily methodological. We use counterfactual scenarios 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's (1964) seminal study on the impact of railroads on American economic development, which emphasized the importance of counterfactual reasoning for historical analysis.

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.[2] We primarily focus 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]

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 (2025) on teacher-student interactions in Oxford and Cambridge). However, 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' participation in university communities was more transitory than that of professors.

Other avenues, such as reading habits, undoubtedly contributed to knowledge dissemination, but quantifying their impact remains challenging. Citations could offer insight into what was being read and discussed in the academic community (Zhao and Strotmann 2015), but they would not provide a complete picture of reading patterns.[4] While citations can reflect "positive" engagement with prior work, including critical remarks, they do not capture instances where scholars deliberately avoided acknowledging influential ideas. Not all works that were read were cited, and this underscores the limitations of citation analysis for 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' as an analogy for idea diffusion does not imply endorsement

2. 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.

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. Their long-lasting intellectual bond—with Bylica amending the Regiomontanus manuscripts—mirrored that of their mentors, respectively, Georg Peuerbach and Martinus Król (Domonkos 1968), and underscores how institutional settings also fostered scholarly connections across generations.

4. Moreover, in premodern texts, citations did not follow standardized formats, making it difficult to systematically trace citations across different works.

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—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, the estimate of treatment effect is generally conservative (Gupta 2011). We apply this same principle to trace the diffusion of ideas.

Another advantage of our approach is that gaps in the affiliation network are identifiable. Gaps occur when universities are underrepresented in our sources, causing some professors to be missing. By contrast, gaps in correspondence networks—such as letters lost to history—are inherently unknown and thus impossible to assess.

In addition to the literature on network structures discussed above, our paper connects to several other strands of research. First, it engages with the history of science, from broad studies on the emergence of science and the scientific method (Needham 1964; Wootton 2015), to analyses of scientists' roles in society (Ben-David 1971; Hanlon 2025), and to work on shocks to the market for ideas and technology. Mokyr (2005; 2016; 2011), Ó Gráda (2016), and Almelhem et al. (2023) explore the roots of the industrial revolutions through the accumulation and application of useful knowledge during the Scientific Revolution and Enlightenment. Second, we contribute to the literature on the economics of innovation. Historical scholarship highlights the impact of highly skilled individuals (Meisenzahl and Mokyr 2012), specialized engineers (Hanlon 2025; Maloney and Valencia Caicedo 2022), and key inventors (Hallmann, Hanlon, and Rosenberger 2022) in driving Britain's technological edge. Other works show how the institutional context matters: classical composers thrived in more liberal environments (Borowiecki 2013), patent systems shaped the direction of innovation (Moser 2005), and external shocks—such as the U.S. Civil War—spurred targeted technological responses in Britain's textile industry (Hanlon 2015). Our approach aligns with Akcigit et al. (2018) in its focus on tracking "individuals, their productivity, and their interactions over time" (Akcigit et al. 2018, p.2). Our analysis also relates to work on academic superstars, which shows that the removal of central figures can disrupt or reconfigure knowledge networks (Azoulay, Graff Zivin, and Wang 2010; Azoulay, Fons-Rosen, and Zivin 2019). While the focus of those papers is on publication output, the underlying question—how resistant to disruption academic networks are—is also relevant to our framework.

Having described the strength of European academia in terms of connectivity and resilience, we believe it could have been instrumental to Europe's success during the Early Modern period. This remains speculative, however, as we lack comparable data on academic networks in other parts of the world, and rely only on anecdotal evidence. In 1798, Thomas Malthus (1766–1834), a fellow at the University of Cambridge from 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 modeled and debated (André and Platteau 1998; Ashraf and Galor 2011). At about the same time, 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 largely disappeared from the record 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 develop in this paper can be applied to explain Malthus' success. Malthus was integrated into the broad European academic network, where his ideas could spread. Hung Liang-Chi belonged to an administration in which ideas were developed by individuals but not subject to broad dissemination and discussion.

The paper is organized as follows. In Section 2 we present the methodology, including the construction of the database and how it is mapped into an affiliation network. We also present the epidemiological model to simulate the diffusion of ideas. In Section 3 we detail the structural estimation of the model parameter, based on *flora* and *cosmos*. In Section 4 we present further empirical assessments, based on *salvatio* (Scholasticism). The counterfactual experiments are detailed in Section 5. Section 6 concludes.

2 Data and Methodology

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

2.1 83,000 scholars

Our comprehensive database of scholars comprises information on 83,000 individuals spanning the period 1000-1800. The data were collected manually from 669 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 trained 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, mainly books on the history of these institutions and their members, which were themselves 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 who were clearly not scholars or intellectuals (e.g., Napoleon, who was elected to the Académie des Sciences in 1797).[5]

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 with each person in the database, when available, to provide a unique measure for individual quality (Curtis and De la Croix 2023).[6] This variable is intended to reflect a scholar's influence and recognition, and is obtained 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.

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

We now look at the data on scholars and their affiliation to institutions with reference to network theory, a powerful tool for studying 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 contemporaneous presence at the same institution. 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. Premodern universities were small, and it is reasonable to assume that all the professors knew each other. Appendix A presents some descriptive statistics

5. Members were admitted through an election process, which varied slightly between academies in terms of the required quorum. Typically, the process began with a nomination by existing members, which was recorded in the academy's minutes along with the scheduled election date. On that day, the academy's president ensured the quorum was met, after which the members voted (Applebaum 2003; Gunther 1925).

6. VIAF (Virtual International Authority File) is a database that connects names of people, organizations, and titles from library catalogs around the world into one shared system.

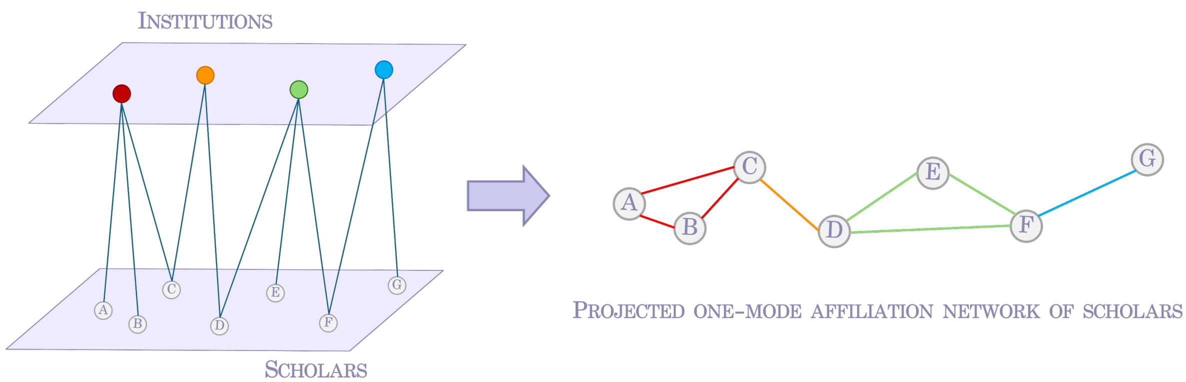


Figure 1: Intuitive representation of network projection: from a bipartite or two-mode graph to the one-mode affiliation network of scholars. Diagram inspired by (Geraerts and Vasques Filho 2024).

for the 10 institutions with the highest number of scholars in 1793, differentiating by type (university vs academy). The average university has fewer than 60 professors. Academies hosted a higher number of scholars on average, reaching 80 in Halle and 122 in London, but the average number of scholars at academies is much more variable, reflecting a more flexible structure and a higher number of corresponding members.

Our analysis spans 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 Republic. During this timeframe, the network's nodes (scholars) and edges (connections) existed 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 period of affiliation at the same 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 while scholars are active at the same institution. 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, showing overall exponential growth, in particular after 1650, with the emergence of academies.

The active period of each scholar commences at the start of their academic career and concludes at their 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

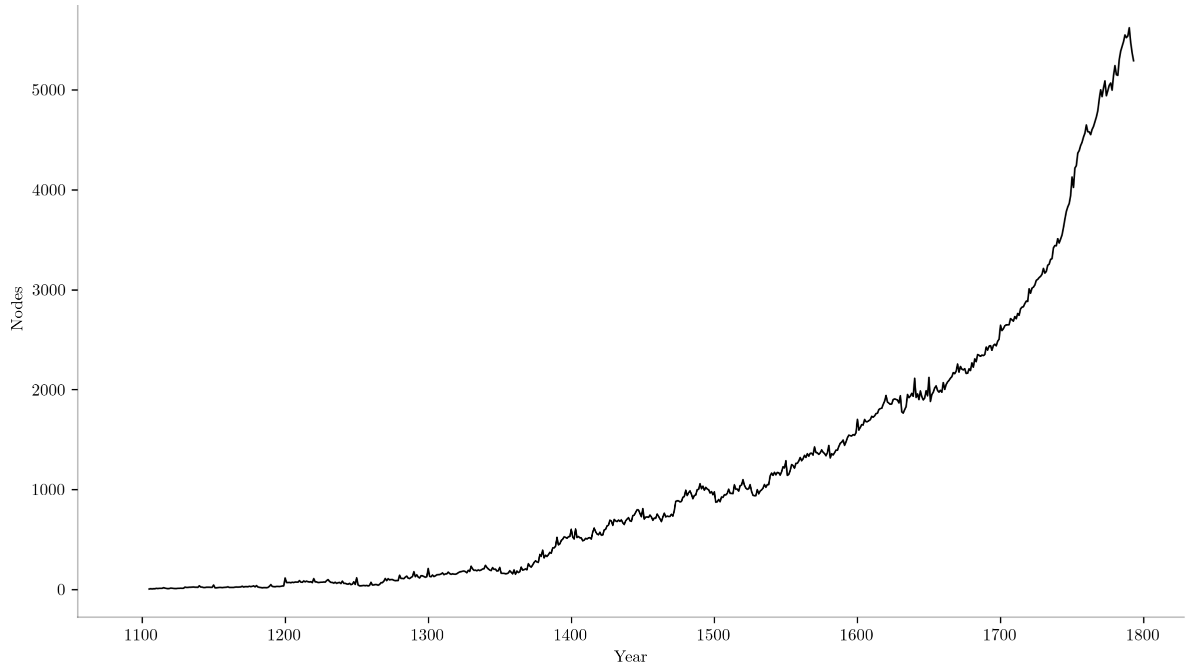


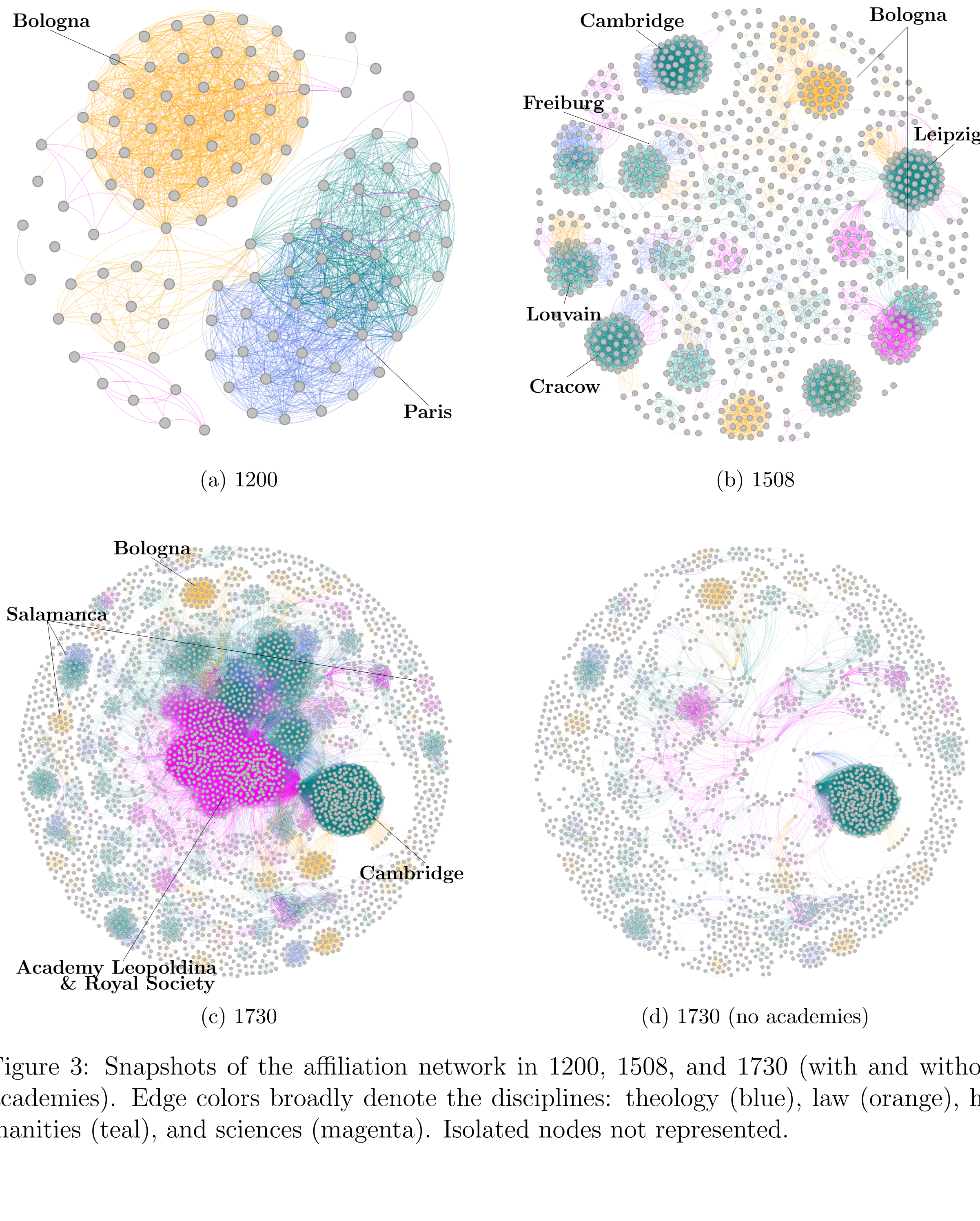
Figure 2: Number of active scholars in the network, 1084-1793.

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 of each scholar's active period.

Scholars cease to be active when 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 one of two 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

7. Eight years being the median of the affiliation years in the sample of university professors for whom we know the precise beginning and end affiliation dates. This data is consistent with the literature: Koschnick (2025) finds that the median length of academic careers at Oxford and Cambridge is 9 years.

8. Academies usually grant a lifelong affiliation.



(a) 1200 (b) 1508

(c) 1730 (d) 1730 (no academies)

Figure 3: Snapshots of the affiliation network in 1200, 1508, and 1730 (with and without academies). Edge colors broadly denote the disciplines: theology (blue), law (orange), humanities (teal), and sciences (magenta). Isolated nodes not represented.

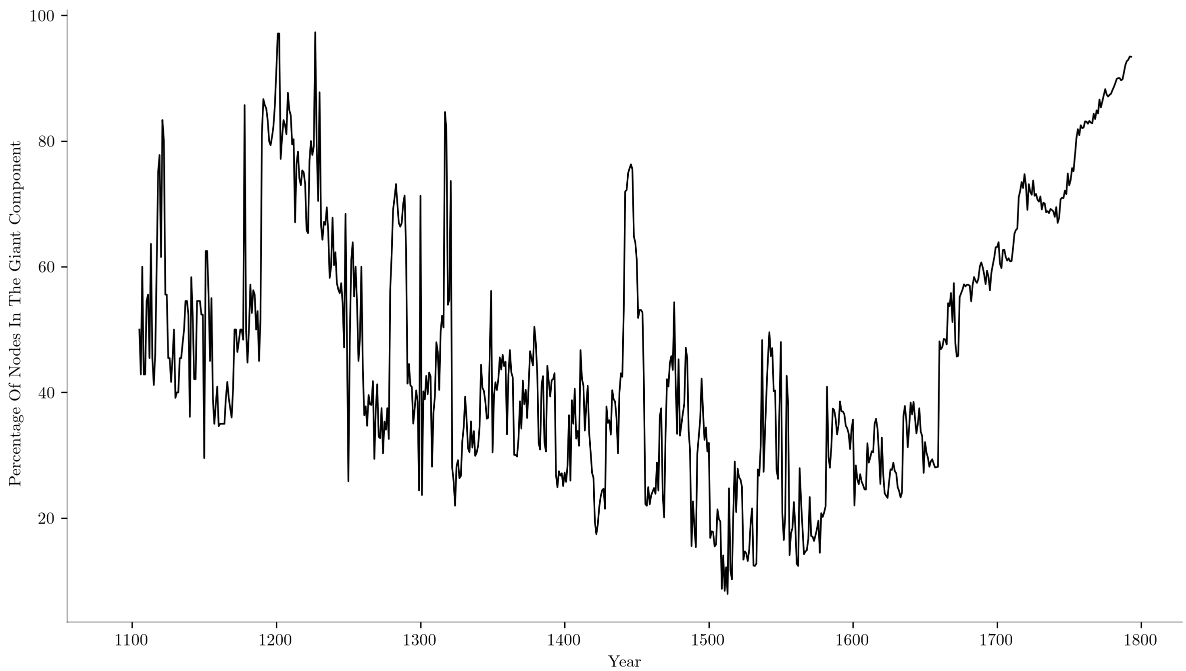


Figure 4: Percentage of active scholars in the giant or connected component over time, 1084-1793.

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.

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 comprised *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: Figure 3d depicts the 1730 network in a scenario where academies are removed. From the 1650s to the end of the timeframe, the cluster- and clique-based appearance of the early network transformed into a densely interconnected web, and this is attributable to the academies.

This effect is also visible in the share of nodes connected to the main network, known as the giant component—the largest connected subgraph in which any two nodes are mutually

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

Year	1200	1300	1400	1500	1600	1700
Total scholars	114	209	602	976	1702	2644
Avg. degree	30.54	15.86	35.27	25.10	35.45	48.30
Std. dev degree	14.57	9.43	30.82	17.50	62.93	71.03
Giant size	104	149	164	312	607	1669
Giant %	91.2	71.3	27.2	32	35.7	63.1
Second-largest comp	6	22	113	138	212	51
Clustering coef	0.9	0.91	0.92	0.91	0.88	0.89
Avg. distance (giant)	2.16	3.68	1.95	4.02	5.86	4.25
Std. dev distance	0.99	1.81	0.95	1.86	3.18	1.84

reachable—as shown in Figure 4. In the early period, around 1200, the affiliation network was nearly fully connected, reflecting a small number of institutions and high scholar mobility. From the 14th century onward, network connectedness followed a general downward trend, punctuated by occasional spikes. These spikes typically occurred when a mobile scholar bridged otherwise disconnected parts of the network. The size of the giant component reached a low point during the Reformation, which curtailed mobility across religious lines, as discussed in De la Croix and Morault (2025). Although the Thirty Years' War (1618–1648) did not drive a further decline, it prolonged the fragmentation, with the giant component remaining relatively small. Connectivity recovered with the rise of academies, as the share 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 2.16 and 5.86–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 27.2% 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 via the occasional mobility of scholars. Over time, particularly by 1700, these isolated islands began to form bridges– thanks to multiple simultaneous affiliations, which was due to the emergence 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.

This affiliation network is the structure on which we will simulate the spread of ideas. Each idea is assumed to originate in a specific year and from a particular inventor, who can transmit it to their neighbors at each time step, but under certain conditions. Each idea belongs to a broad field that reflects the main disciplines of premodern times, and can spread only among scholars active within the that field. Our assumption is that if a scholar is working in 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-round scholars who were equally fluent, for example, in both science and philosophy. Still, we decide to assign specific fields to each idea, while acknowledging that this may cause us to underestimate the speed of diffusion of ideas.

2.3 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 between the invention of the printing press (circa 1450s) and the French Revolution. From these sources, we identify some significant ideas that changed the course of history, prioritizing those for which 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 4.1.

9. Science includes mathematics, logic, physics, chemistry, biology, astronomy, earth sciences, geography, and botany.

10. Applied science includes engineering, architecture, and agronomy.

We simulate the spread of three main ideas—*flora*, *cosmos*, and *salvatio*—two from the Scientific Revolution and one from the Middle Ages, and compare simulated exposure to observed outcomes. For the Scientific Revolution, we draw on Applebaum (2003), focusing on the earliest ideas for which European-level outcome data is available. In astronomy, the first idea is attributed to Regiomontanus, whose *Mathematical Astronomy* (developed from 1450, published in 1496) formalized Ptolemaic models for future research. Its corresponding outcome is the founding of astronomical observatories. In botany, Applebaum (2003) identifies *Botanical Realism*, foundational to Fuchs's 1542 herbarium; we link exposure to this idea with the creation of botanic gardens.

For the Middle Ages, we identified key academic ideas using the index in English (2005). These include alchemy, anatomy (including practical surgery), astrology, computus, civil law, economic thought, cartography, humanism, music, optics, political theory, punctuation, and the Scholastic method. To balance the two scientific ideas above, we select one from a different domain: theology. *Scholasticism*, rooted in the work of Lombardus, emphasized rigorous logic and dialectical reasoning to reconcile faith with reason. It fostered a systematic approach to inquiry that shaped both scientific and philosophical thought. At the same time, it spurred theological backlash, especially from movements like Protestantism that emphasized scriptural authority over rational deduction. The associated outcome in our empirical analysis is the probability of a city becoming Protestant.

A key challenge, common to all three ideas, is determining when the scholar first developed the concept. To define this moment, we try to identify two dates for each idea: (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.

In our model ideas spread via 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, giving 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.

To briefly clarify some terminology: we use inventor as shorthand for the main proponent or originator of an idea—not necessarily an inventor in the traditional sense, but often someone who developed, articulated, or popularized a concept. Similarly, idea is used broadly to encompass various intellectual contributions, including theses, paradigms, and methodological approaches, which differ in scope, complexity, and impact.

2.4 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 $t \in \{\underline{t}, \ldots, \overline{t}\}$, $\underline{t}$ and $\overline{t}$ being the start and end dates of our analysis. At each date, a node can be susceptible or infectious.[11] A contact between two nodes appears 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 $N \times N$, with 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 working in the same field at the same time in the same institution (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 $[i_{s^\star}]_{t_0} = 1$, where $s^\star$ 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,

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

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 link activation 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 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:

$$I^d_{t+1} = \Omega^d(A_t)I^d_t + I^d_t \tag{2}$$

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.

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 D simulations:

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

Expected institution k exposure $S^k_t \geq 0$ is obtained as an average over individuals s

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).

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), as reflected in lifetime achievements.

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 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), which will be used in Section 4.1 and Appendix H. 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). Past this window an idea could survive the passing of its author, for example by persisting in the teaching material and/or as an influence on 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 kilometers, the influence power decreases linearly, up to 1000 kilometers. 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 kilometers.

3 Structural estimation

3.1 Methodology

How fast ideas spread in the affiliation network depends crucially on the link activation probability α. Estimating this probability is difficult because we do not observe the spread of ideas directly; we only observe some outcomes of the ideas, after some time. These outcomes are related to exposure to ideas through statistical models, described below. We will use two of these outcomes to construct a confidence interval for α based on the profile of their likelihood. This setup resembles indirect inference or simulated maximum likelihood (Smith 2008), where one chooses α to maximize the likelihood of the observed data, given the structural model's output. In practical terms, we take the following steps.

1. We fix α at gridded values over $[0, 1]$ at intervals of 0.05.
2. For each value of α, we simulate the spread of two key ideas through the affiliation network and the epidemiological model.
3. We compute exposure of university cities S_t^k, given by equation 3, to these ideas.
4. We estimate two auxiliary statistical models correlating the simulated exposure with observed outcomes (detailed below).
5. We record the log-likelihoods as the sum of the individual likelihoods at each point:

$$\ell_{\text{total}}(\alpha) = \ell_1(\alpha) + \ell_2(\alpha)$$

   This approach treats the two outcomes as conditionally independent given α.

6. We maximize the combined log-likelihood

$$\hat{\alpha} = \arg\max_{\alpha} \ell_{\text{total}}(\alpha).$$

7. We construct a likelihood-based confidence interval for α as the set of values for which

the log-likelihood is not "too much worse" than the maximum.

$$2\left[\ell_{\text{total}}(\hat{\alpha}) - \ell_{\text{total}}(\alpha)\right] \leq \chi^2_{1,0.95} \approx 3.84$$

This gives a 95% confidence interval for the link activation probability α based on both outcomes. We let this interval be: $[\alpha_{\text{low}}, \alpha_{\text{high}}]$

8. We take the lower bound for the subsequent analysis: $\alpha = \alpha_{\text{low}}$. It gives the most "conservative" link activation probability that is still consistent with the combined data under the likelihood ratio criterion. In taking the lower bound, we are conservative, in the sense that we minimize the risk of overemphasizing the role of face-to-face interactions within institutions in the spread of ideas.

We now describe the two auxiliary models referred to above in item 4.

3.2 Auxiliary model 1: Botanical Realism and botanic gardens

During the Scientific Revolution there were major advancements in botany, and it grew from being primarily a descriptive field into a more systematic and experimental science—a shift we call "Botanical Realism". A key figure in this transition 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, this work laid the foundation for modern botany. Fuchs not only provided visual representations of 511 plant species: he also included his own critical observations on their uses and characteristics, highlighting differences from ancient texts (Applebaum 2003).[14] Fuchs was based in Tübingen for the majority of his life, were he taught medicine and botany at the local university between 1535 and 1566 (Conrad 1960). Prior to that he was a professor at the University of Ingolstadt from 1522 to 1533 (Schwinges and Hesse 2019). Despite his fame, he was not a mobile scholar and he 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, and then extends further through mobile scholars—those who were 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

14. More contextual information is available in Appendix B.1.

each simulation will differ, because the probability of transmission is less than one).

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.[15] For this first experiment, we also gathered information on the existence and founding dates of European botanic gardens from Montreal Botanic Garden (1886). Figure 15 (in Appendix C.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 that each university city would host the creation of a botanic garden. Specifically, we are interested in analyzing whether this probability is affected by the institutions of the city being exposed to Botanical Realism. We estimate a Cox proportional hazard model with different levels of α. Following the Cox model, the probability $h(t)$ of building a botanic garden in a city with fixed characteristics x and time varying characteristics $y(t)$ and $z(t)$ changes with the survival time t according to

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

where $h_0(t)$ is the baseline hazard. For the 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 pathways other than our affiliation network. The regressor of interest is the time-varying exposure $y(t)$. This exposure counts the number of botanists, physicians, and scientists[16] 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. Institutional exposure also takes into account the publication output of an institution's scholars. For the time-varying control $z(t)$, we introduce "non exposure" to Botanical Realism to capture scientists who were susceptible to exposure but were not actually exposed. This coefficient, ζ, allows us to control for alternative pathways—such as different scientific ideas or the general orientation of the faculty—through which botanic gardens might have been established. This control, formally called $\check{S}_t^k$, is computed as follows:

15. 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 these universities did not survive beyond that period.

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

$$\check{S}_t^k = \sum_s \underbrace{q_s}_{\text{quality}} \left(\underbrace{I(s \in V(k,t))}_{\text{membership}} \; \underbrace{I([\bar{i}_s]_{t'} = 0)}_{\text{exposure}} \right) \tag{7}$$

where the individual exposure $[\bar{i}_s]_{t'}$ is set to zero to capture only those scholars who were not exposed, but who could have been, given their field of study and the timing of their presence at the institution. By proceeding in this way, we obtain a dynamic measure of "exposure" for non-exposed scientists that mirrors S_t^k.

We consider the time period 1500-1793. The first botanic garden is observed in 1520 in Pavia, Italy; Fuchs' invention takes place in 1542 and the affiliation data run through 1793. In some cities, no botanic garden was built during this period, and we assume that the garden was created after the censoring data cutoff of 1793, according to the construction of the Cox model.[17] 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 of experiencing the creation of a garden is just the inverse of the computed survival. We use the Nelson-Aalen estimator to compute the baseline hazard: this estimator 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 of events as follows:

$$E(g_i) = \sum_{j:t_j > t_i} \hat{h}_0(t_i) \exp(x\hat{\beta} + y(t)\hat{\gamma} + z(t)\hat{\zeta}) \tag{8}$$

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 gardens were simultaneously created in more than one city. 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". We use the Efron method to manage this in the likelihood calculation and to better clarify the order of events. This method assumes the tied events occurred in small groups and evenly distributes the risk across cities within the same group. While this

17. The fact that botanic gardens were established in only 59 out of 185 cities 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.

is an approximation, it efficiently computes the partial likelihood. To ensure robustness, we also apply the exact method, which computes partial likelihoods by systematically evaluating all combinations of tied events. The exact method is the most accurate but it 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.

Table 2: Cox Proportional Hazards Model – Botanical Realism and botanic gardens

	Dependent variable: Hazard rate of botanic garden founding					
Alphas	0	0.1	0.3	0.5	0.7	1
(ihs) Exposure to		0.079	0.225**	0.223***	0.222***	0.224***
Bot. Real. S_t^k		(0.287)	(0.090)	(0.073)	(0.069)	(0.068)
(ihs) Non exposure to	0.397***	0.505***	0.529***	0.545***	0.551***	0.554***
Bot. Real. $\check{S}_t^k$	(0.070)	(0.074)	(0.077)	(0.078)	(0.079)	(0.079)
(ihs) Distance to	-0.138**	-0.237***	-0.205***	-0.192***	-0.187***	-0.184***
Tübingen	(0.054)	(0.060)	(0.058)	(0.057)	(0.057)	(0.057)
Log Likelihood	-295.234	-295.529	-293.516	-292.034	-291.396	-291.037
(ihs) Pop in 1500	YES	YES	YES	YES	YES	YES
Observations	54390	54390	54390	54390	54390	54390

Note: *p<0.1; **p< 0.05; ***p<0.01. Robust standard errors are reported in parentheses. Similar models run for every α between 0 and 1 at an interval of 0.05. Here, we only report results for 0, 0.1, 0.3, 0.5, 0.7, and 1.
"Bot. Real." refers to "Botanical Realism". All the variables are transformed in inverse hyperbolic sine (ihs). Distance to Tübingen is computed as Euclidean distance. All models include (ihs) population in 1500.

Table 2 shows the results for the Cox proportional hazard models at different level of α. We run similar specifications for every α between 0 and 1 at an interval of 0.05 to obtain the log likelihoods which are the first necessary component for our structural estimation.

3.3 Auxiliary model 2: Mathematical Astronomy and astronomical observatories

In the 15th and 16th centuries, growing interest in experimental science led astronomers to challenge Ptolemaic models and refine them through observation and mathematics. This shift marked the start of the astronomical revolution, with advances in trigonometry, geometry, and the use of decimals, and a new focus on underlying physical causes rather than mere description.

A key figure in this astronomical revolution was Regiomontanus (which was a 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 – 1461) began collaborating on 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 (Applebaum 2003).[18] Regiomontanus published *Theoricæ novæ planetarum*, his collaboration with Peurbach, in 1472 after Peurbach's death.

In this second empirical assessment, we examine the correlation between exposure to Mathematical Astronomy and the creation of astronomical observatories. We posit that advances in trigonometric methods create demand for better places, buildings, and instruments that can manage more precise astronomical observations. With these observations, scientists can determine with more accuracy the dates of equinoxes, solstices, and other celestial events. Regiomontanus himself opened an instrument shop that specialized in building and printing works related to Mathematical Astronomy (Applebaum 2003). We collected the names and foundation dates of observatories from Howse (1986).

The computation of exposure to Mathematical Astronomy follows the same methodology that we used for Botanical Realism. The idea starts with Regiomontanus, who shared it with his colleagues in Vienna, Bratislava, Padua, and Rome, and reaches 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. Figure 17 (in Appendix C.3) depicts this sample of cities along with their exposure to Mathematical Astronomy in 1600, 1700, and 1800. Only scientists are considered to have been 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. Finally, we obtain the institutional exposure to Mathematical Astronomy.

We estimate the probability of each university city obtaining an observatory using a Cox Model similar to that used for Botanical Realism. The technical details, including equations 6 and 8, remain the same. The only difference lies in the covariates included: we replace distance from Tübingen with distance from Vienna. We focus on the same period, 1500-1793, since the first observatory was established in Kassel in 1560, and we date the spread of Regiomontanus' ideas as starting in 1454 and persisting up to 1793, the last date in our timeframe. 52 cities in the sample saw the creation of an observatory before the censoring date of 1793, while the remaining cities never saw one. However, the Cox Model assumes

18. More details are available in Appendix B.2.

by construction that these cities will eventually have an observatory after 1793.[19] 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) in which three observatories were constructed. 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.

Table 3: Cox Proportional Hazards Model – Mathematical Astronomy with Non Exposure

	Dependent variable: Hazard rate of observatory founding					
Alphas	0	0.1	0.3	0.5	0.7	1
(ihs) Exposure to		0.314***	0.293***	0.281***	0.281***	0.288***
Math. Astr. S_t^k		(0.068)	(0.057)	(0.056)	(0.054)	(0.053)
(ihs) Non exposure	0.374***	0.546***	0.562***	0.540***	0.543***	0.546***
to Math. Astr. $\check{S}_t^k$	(0.063)	(0.094)	(0.093)	(0.097)	(0.096)	(0.096)
(ihs) Distance	-0.151***	-0.169***	-0.158***	-0.153***	-0.152***	-0.151***
to Vienna	(0.044)	(0.044)	(0.043)	(0.043)	(0.043)	(0.043)
Log Likelihood	-250.707	-250.243	-248.470	-249.257	-248.944	-248.379
(ihs) Pop in 1500	YES	YES	YES	YES	YES	YES
Observations	54390	54390	54390	54390	54390	54390

Note: *p<0.1; **p< 0.05; ***p<0.01. Robust standard errors are reported in parentheses. Similar models run for every α between 0 and 1 at an interval of 0.05. Here, we only report results for 0, 0.1, 0.3, 0.5, 0.7, and 1.
"Math. Astr." refers to "Mathematical Astronomy". All the variables are transformed in inverse hyperbolic sine (ihs). Distance to Vienna is computed as Euclidean distance. All models include (ihs) population in 1500.

Table 3 shows the results for the Cox proportional hazard models at different level of α. We run similar specifications for every α between 0 and 1 at an interval of 0.05 to obtain the log likelihoods which are the other necessary part for our structural estimation, together with the log likelihood from Table 2.

3.4 Results

The joint likelihood $\ell_1(\alpha) + \ell_2(\alpha)$ attains a maximum at -539.42 with $\hat{\alpha} = 1$. The lowest admissible likelihood (i.e. not significantly different from its maximum) is

$$\ell_{\text{total}}(\alpha_{\text{low}}) = \ell_{\text{total}}(\hat{\alpha}) - 3.84 = -543.26.$$

19. 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.

This value is approached for $\alpha \approx 0.25$ with $\ell_{\text{total}}(\alpha_{\text{low}}) = -542.81$. Therefore, $\alpha = 0.25$ is a conservative estimate of the link activation probability.

Before interpreting the results with $\alpha = 0.25$, we first verify that the proportional hazards assumption holds for this level of alpha. 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 not statistically significant (Schoenfeld 1982). In our preferred specification with alpha = 0.25 (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 0.048, indicating that the joint correlation between the hazard ratios and time is significantly different from zero at the 5% level. However, we are confident in validating the proportionality assumption after analyzing the plot of this correlation in Figure 19a in the Appendix.

Having tested for the suitability of the Cox Proportional Hazard Model, we can interpret the results. For a sound interpretation, we focus on the hazard ratios, which are computed by exponentiating the coefficients (similar to interpreting odds ratios in logistic regression). The hazard ratio of "Exposure to Botanical Realism" is 1.25 ($exp^{0.221}$), implying that a city with an exposure of 1 to Botanical Realism has a 25% higher probability of having a botanic garden, compared to a city with zero exposure. Remarkably, the coefficient of exposure is significant even when we control for all the other possible pathways of idea diffusion, captured by the distance to Tübingen, and also when we introduce an additional control, "(ihs) Non exposure Botanical Realism $\check{S}_t^k$," which captures the presence of scientists at the institution who were not exposed to the idea of Botanical Realism.

It is challenging to picture the size of these coefficients due to the variation in exposure over time. To address this, in Figure 16 (in Appendix B.1) we plot 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 $\mu = 7.04$), with an average "(ihs) Non exposure" = 0.57. Figure 16 shows that if a city maintains full exposure (i.e., a maximum exposure of 5.75), over the entire 294-year 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 0.31 (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 reaches around 73% only towards the end of the period, around 1793. Conversely, cities with an average exposure of 0.31 will have almost 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 38% probability of getting a garden by 1793. Overall, these results demonstrate that being exposed to Botanical Realism exponentially increases the probability that an average city will get a garden: from 38% probability, it jumps to 50% at the mean level of exposure and reaches 75% with a constant exposure of 1.

For Mathematical Astronomy and astronomical observatories, we validate the suitability of the Cox Proportional Hazard Model in the same way as we did for Botanical Realism, following Schoenfeld (1982). We find that the correlation between "Exposure to Mathematical Astronomy" and time is not significant when taken individually. On the other hand, the joint correlation of all the covariates with time is only slightly statistically different than zero at the 10% level (global p-value = 0.098). We are confident that the proportionality assumption is validated, especially after analyzing Plot 19b of the joint correlation in Appendix D.

For the interpretation of the results we again need to consider the hazard ratios. The hazard ratio of "Exposure to Mathematical Astronomy" is 1.35 ($exp^{0.297}$), indicating that a city with an exposure of 1 to Mathematical Astronomy has a 35% higher probability of getting an observatory compared to a city with 0 exposure. Again, as in Subsection 3.2, controlling for potential alternative pathways of diffusion of Mathematical Astronomy does not undermine the relevance of our main variables of interest. In addition, our coefficient of interest, "Exposure to Mathematical Astronomy", remains highly significant when we control for the presence of other scientists at the institution who were not actually exposed to the idea (as in equation 7). This new control, "Non exposure to Mathematical Astronomy" may also capture that other ideas—orthogonal to Mathematical Astronomy—could have led independently to the creation of astronomical observatories through different channels. Hence, we also show that controlling for it does not diminish the statistical and economic significance of our main measure of exposure.

Figure 18 (in Appendix B.2) plots the probability of getting an observatory for different levels 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 $\mu = 2.8$), at an average distance from Vienna ((ihs) Distance to Vienna $\mu = 7.38$), and with an average "(ihs) Non exposure to Mathematical Astronomy" of 0.42. We can see in the Figure that a city that is never exposed to Mathematical Astronomy will have a probability of approx. 25% of seeing the creation of an observatory by 1793. This can be considered as the baseline for how an increase in exposure to Mathematical Astronomy impact the likelihood of getting an observatory: already with a constant average exposure of 0.5 (i.e., mean exposure), a city will have an almost 32% chance of getting an observatory, and this probability jumps to more than 50% with a constant exposure of 1. Finally, in the extreme case in which a city always has the maximum level of exposure to Mathematical Astronomy, it will have a 100% probability of having an Observatory after 1560, the year that the first observatory in our sample was created.

4 Further empirical assessments

We use the model to extend our empirical analyses beyond the context of the Scientific Revolution and a direct mapping between ideas and outcomes. As with the earlier sections, our analysis is shaped by the availability of outcome data. We examine three distinct cases: a backlash against an idea (the nexus between Scholasticism and Protestantism); an extension of the plague–pogrom nexus that incorporates exposure to anti-Judaic ideas, and the diffusion of a demonstrably false belief that Swedes are descendants of Atlantis.

4.1 Scholasticism and Protestantism

Scholastic theology is an approach to theological questions that uses logical analysis and systematic reasoning, influenced by ancient Greek philosophers.[20] 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 would become the University of Paris from 1145 to his death in 1160. Mazzetti (1847) claims that he was at the University of Bologna in about 1150.

Petrus Lombardus' primary work is the *Sentences*. Completed in the mid-12th century, the *Sentences* cover key theological topics such as the nature of God, creation, the Trinity, grace, and sacraments. The *Sentences* became a foundational text for theological education in medieval universities and was the starting point for many scholastic theologians who followed, including Thomas Aquinas, who wrote extensive commentaries on it.

Martin Luther (1483–1546), the 16$^{\text{th}}$-century German monk and theologian who sparked the Protestant Reformation, was initially trained in the scholastic tradition and engaged with its methods. But as his personal spiritual crisis deepened, he became increasingly critical of many aspects of the Catholic Church's theology—including Scholasticism's emphasis on

20. See an example in Appendix E.

human reason.

Luther laid out his objections in a striking document, the *Disputatio contra scholasticam theologiam* (1517), a series of 97 theses. In it, he made provocative claims such as: "No syllogistic form is valid when applied to divine terms," and "...the whole Aristotle is to theology as darkness is to light" (theses 47 and 50, respectively).

A major grievance that fueled the rise of Protestantism was the desire to reform theological teachings and Church practices that, in the Reformers' view, were not grounded in Scripture. Scholastic theology—especially in its later form known as nominalism—was a central target. The historian Chaunu (2014) argues that this style of theology, which emphasized logic and abstraction, distanced ordinary believers from their faith and ultimately left them receptive to the message of the Reformation. From this we draw our hypothesis that the adoption of Protestantism was a backlash to (exposure to) Scholasticism. This view is rarely made explicit in the scholarly literature, but it underlies much of the Reformation's intellectual context.[21]

We highlight three key ways in which Luther offered a clear and spiritually compelling response to the crisis of salvation induced by scholastic theology—each emphasizing *direct access to God* by *faith* rather than through a rational merit-based system (Chaunu 2014).

(A) The Catholic Church taught that salvation comes through both faith and works, a position formalized in scholastic doctrines of grace and merit. Luther rejected this, arguing that Scripture teaches that salvation comes by faith alone (*sola fide*), not through human effort or achievement.

(B) Catholic theology placed Scripture and Church tradition—along with papal authority—on equal footing. This framework relied on a scholastic synthesis of Aristotelian philosophy and ecclesiastical tradition. Luther broke with this, insisting that Scripture alone (*sola scriptura*) is the final authority in matters of faith. He viewed the scholastic approach as placing human reason above divine revelation.

(C) The Catholic Church mediated grace through a complex sacramental system, including the sale of indulgences and a strict divide between clergy and laity. Luther opposed this mediation of grace and denied the special status of clergy rooted in scholastic definitions of ordination and apostolic succession. Instead, he emphasized the "priesthood of all believers" (*sola gratia*).

21. 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. This view is not universally accepted. For example, Cross (2024) sees substantial continuity between Luther and late Scholasticism.

To test for a negative correlation between the exposure to Scholasticism and the rise of Protestantism, we propose the following experiment. We feed the idea of Scholasticism to Petrus Lombardus. The idea would spread to his colleagues in Paris, and then beyond, thanks to the mobility of scholars. We simulate the spread of this idea in Europe, using the epidemiological approach described in Section 2.4, all the temporary networks built from our data, and our alpha of 0.25.

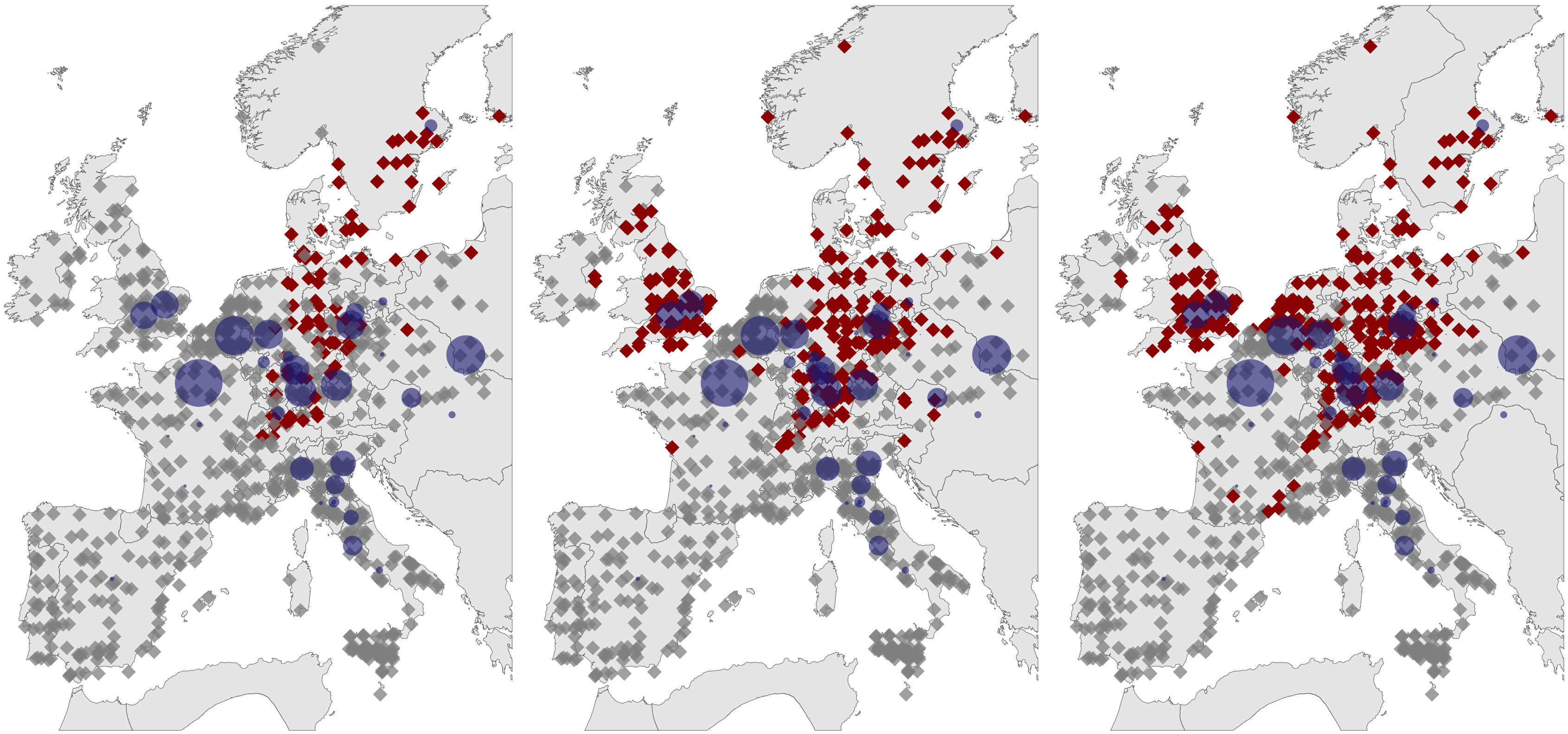
Averaging the outcomes of many simulations, we compute the $\tilde{S}_t^k$ exposure of each university to Scholasticism in 1508, the year Luther started teaching at the University of Wittenberg. We measure exposure by counting the number of theologians exposed to Scholasticism in the previous 30 years, by university. Each theologian is weighted by the importance of his publication output. We annualize this exposure by dividing by the 30 years over which we counted the active theologians. We then obtain the exposure to Scholasticism of each university in the network, using equation 4.[22] Figure 5 depicts this level of exposure. We can further 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).[23]

Figure 5 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. The blue bubbles represent universities' exposure in 1508, as described earlier. The figure already suggests a possible positive correlation between exposure to Scholasticism, and the likelihood that a city would reject Scholasticism in favor of Protestantism. However, it is important to note that in Italy, institutional exposure to Scholasticism was weaker than in Northern Europe. This is because in Italy 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 (c. 1483 - 1546).

22. It is important to note the difference between this "static" exposure and the "yearly" exposures used in the previous two empirical assessments.

23. We updated Rubin's data to better account for the fact that in France and the Low Countries (modern-day Belgium), several cities adopted Protestantism temporarily before being reconquered by Catholic forces. See Appendix F.



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

Figure 5: Blue bubbles represent the exposure to Scholasticism 30 years prior to 1508, $\alpha = 0.25$ and $D = 5,000$. Protestant cities are the red diamonds, and Catholic cities are the grey diamonds. Data on cities' religion are taken from Rubin (2014) and updated as in Appendix F.

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 such that all the cities became Protestant on the same day. This would create too many ties, violating the Cox model's assumption of time being continuous.

Columns (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 it is not sufficient that a city has a university: it must also be exposed to Scholasticism either directly via the university in that city, or indirectly, by being close to other exposed cities. In Appendix G Table 12, we include additional controls and fixed effects.

Using the estimated coefficients in Table 4, 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 place most exposed 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 12.3% in 1530, by approximately 37% in 1560 and by 49% in 1600. Looking at a city in the second quartile, such as Copenhagen in Denmark, the increase in probability would be 9.6% in 1530, 28.7% in 1560, and 38.3% in 1600. For Bologna in Italy, which falls in the middle of the third quartile, the increase would have been about 5.8% in 1530, approximately 17% in 1560, and 23% in 1600. In contrast, a city in the same quartile as Heidelberg, such as Leuven in Belgium, which has a difference in exposure of only 12.4 absolute points compared to Heidelberg, would have a much lower increase in probability: 1.2% in 1530, approximately 4% in 1560, and 5% in 1600.

In Columns (4)-(6) we show how the correlation between the *Exposure to Scholasticism* S^c_{1508} and the probability of becoming Protestant does not change much when we control for the "Non exposure to Scholasticism $\check{S}^k_{1508}$", capturing the theologians susceptible to being exposed to Scholasticism but who are not, as in the case of Botanical Realism and Mathematical Astronomy. It is remarkable that also when introducing this additional control,

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

	Protestant in			Protestant in		
	1530	1560	1600	1530	1560	1600
	(1)	(2)	(3)	(4)	(5)	(6)
Exposure to	0.001	0.003***	0.004***	0.0005	0.005***	0.006***
Scholasticism S^c_{1508}	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Presence of university	-0.034	-0.075	-0.130**	-0.044	-0.018	-0.056
in 1500	(0.027)	(0.051)	(0.054)	(0.027)	(0.045)	(0.047)
Non exposure to				0.006	-0.034	-0.043**
Scholasticism $\check{S}^k_{1508}$				(0.005)	(0.024)	(0.020)
Observations	867	867	867	867	867	867
Adjusted R^2	0.016	0.072	0.127	0.018	0.116	0.194
Log Likelihood	-201.02	-500.48	-515.10	-199.68	-478.98	-480.13

Note: *p<0.1; **p< 0.05; ***p<0.01. Robust standard errors clustered by territory are reported in parentheses. A constant term is included in all regressions.
Dependent variable "Protestant" takes value 1 if the city is Protestant in 1530, 1560, 1600, respectively. Data on cities' religion taken from Rubin (2014) and updated as in Appendix F. "Presence of university in 1500" is a dummy variable taking value 1 if our database shows the city having a university in 1500 (De la Croix 2021). "Exposure to Scholasticism S^c_{1508}" and "Non Exposure to Scholasticism $\check{S}^k_{1508}$" are computed as in equations 4 and 7, respectively.

our coefficients of interest in Columns (5)-(6) remain highly significant and with a slightly larger magnitude than Columns (2)-(3). We interpret this as an indication of robustness: controlling for both the simple presence of a university and the "Non exposure", we still see a positive and significant correlation between the latter and the probability that the city would become Protestant. This reinforces our initial hypothesis of a backlash to exposure to Scholasticism.

4.2 Anti-Judaism and the Persecution of Jews

Our model can propagate not only good ideas, but also bad or even false ones. One such idea is anti-Judaism. The availability of data on Jewish persecutions from Anderson, Johnson, and Koyama (2017) and Jedwab, Johnson, and Koyama (2019) allows us to apply the same approach as in Section 4.1 to analyze the spread of anti-Judaism.

The roots of anti-Judaism run deep and are widely discussed in the literature. Scholasticism, once again, played a role in rationalizing prejudice against Jews. Thomas Aquinas (1225–1274)—one of the most influential scholars at the University of Paris and the intellectual heir of Lombardus—endorsed many prevailing medieval Christian views about Jews. He supported the idea that Jews should live in subjugation as a reminder of their supposed rejection of Christ. In the *Summa Theologiae*, he also discusses Jews in ways that reinforce their marginalization.

The next generation of scholastic theologians, such as John Duns Scotus (c. 1266–1308) and William of Ockham (c. 1287–1347), contributed to the broader scholastic discourse that pathologized Judaism as a theological error (see Abulafia (2011), which provides a substantial discussion of how scholastic theology and legal reasoning shaped Christian–Jewish relations between 1000 and 1300). While these theological ideas do not explicitly advocate persecution, they may have interacted with the mechanisms identified by Anderson, Johnson, and Koyama (2017) and Jedwab, Johnson, and Koyama (2019). In Anderson, Johnson, and Koyama (2017), cold temperatures are shown to increase the probability of persecution of Jewish communities. Jedwab, Johnson, and Koyama (2019) extend this insight, showing that negative shocks more broadly—particularly plagues—raise the likelihood of minority persecution.

To study the correlation between yearly *Exposure to Scholasticism* S_t^c and the probability of violent acts against Jews, we use data from Anderson, Johnson, and Koyama (2017) and Jedwab, Johnson, and Koyama (2019).[24] Building on this literature, we hypothesize that the effect of negative shocks on the likelihood of Jewish persecutions is amplified in cities with greater *Exposure to Scholasticism* S_t^c. The underlying intuition is that when local priests—shaped by scholastic teachings—disseminate anti-Judaic arguments, they create conditions that make communities more likely to scapegoat Jews in times of crisis. To test this hypothesis, we augment the empirical framework of Anderson, Johnson, and Koyama (2017) by including an interaction term between our measure of scholastic exposure and the incidence of plague outbreaks.

Table 5 presents the results of this linear probability model. The dependent variable, $Persecutions$, takes the value 1 when either an expulsion or another violent act against Jews occurred in a given year, following the definition in Jedwab, Johnson, and Koyama (2019). As in both Anderson, Johnson, and Koyama (2017) and Jedwab, Johnson, and Koyama (2019), we restrict the analysis to cities with a documented Jewish presence.

Column (1) replicates specification (2) of Table 3 in Anderson, Johnson, and Koyama (2017, p. 940). The estimated coefficient on lagged temperature is nearly identical: we find that a one-degree decrease in temperature increases the probability of Jewish persecutions

24. We thank the authors for sharing the most recent (and still unpublished) version of the pogroms and persecutions data.

Table 5: Linear Probability Model - Yearly Exposure to Scholasticism and cities' probability of persecution of Jews

	Persecutions	
	Replication	S_{ct} x Plague
	(1)	(2)
$Temperature_{c,t-1}$	-0.467***	-0.496***
	(0.125)	(0.129)
Plague	5.100**	-0.719
	(2.149)	(1.274)
Exposure to Scholasticism S_{ct}		0.025
		(0.052)
Exp. to Scholasticism S_{ct} x Plague		3.621***
		(1.131)
Controls	YES	YES
City Fixed Effects	YES	YES
Observations	273,879	273,879
R^2	0.013	0.015

Note: *p<0.1; **p< 0.05; ***p<0.01. Standard errors clustered at the climate grid level in parentheses. City fixed effects are always included.
Column (1) replicates Anderson, Johnson, and Koyama (2017) specification (2) Table 3, p.940.
Coefficients are multiplied by 100 to represent percentage points.
Controls include a slope variable for the 10 years surrounding the Black Death and a measure of population density as in Anderson, Johnson, and Koyama (2017).

in the following year by 0.467 percentage points, compared to 0.464 percentage points in Anderson, Johnson, and Koyama (2017). Despite this similarity, our sample differs slightly for two main reasons: (i) our dependent variable is drawn from a more recent version of the dataset used by Anderson, Johnson, and Koyama (2017), and (ii) we eliminate duplicate city entries prior to estimation.

Column (2) introduces an interaction between our yearly *Exposure to Scholasticism* S_t^c at the city level and a dummy variable indicating the presence of a plague, following Anderson, Johnson, and Koyama (2017). Interestingly, neither *Exposure to Scholasticism* S_t^c nor the plague dummy is statistically significant on its own. However, their interaction is both statistically and substantively significant. This suggests that when a theoretical framework exists that portrays Jews as a threat, and a plague occurs simultaneously, the probability of violence against Jews rises significantly. The coefficient on the interaction term is also sizable: during a plague, a one-unit increase in exposure to Scholasticism is associated with a 3.6 percentage point increase in the likelihood of Jewish persecutions.

4.3 Finding Atlantis: A True Story of Genius and Madness

We now turn to Olaus Rudbeck's (1630 – 1702) claim that Sweden was the cradle of civilization and the site of the lost city of Atlantis. It is an interesting case to simulate using our model for two reasons. First, it illustrates that ideas–whether accurate or not–can still spread through affiliation networks, which further underscores the crucial role of institutions in shaping intellectual diffusion. Second, it highlights that individuals do not necessarily need to agree with an idea in order to help propagate it.

Rudbeck, who was professor of medicine at the University of Uppsala from 1658 to 1692 (Von Bahr 1945), claimed that Sweden was in fact the mythical island of Atlantis, and thus the cradle of all ancient civilization. He supported this sweeping theory by drawing connections between the Norse mythology, the Bible, and classical sources. Rudbeck explained his thesis in the book *Atlantica* (also known as Atland eller Manheim), first published in four volumes between 1679 and 1702 (King 2005). It was written in Latin (vol. 1) and Swedish (vols. 2–4). *Atlantica* was not fully translated into major European languages during the 18th century. The length, complexity, and eccentricity of Rudbeck's arguments likely discouraged publishers. His ideas were seen by many contemporaries as extravagant, although some Nordic nationalist thinkers admired them. Despite its eccentricity, *Atlantica* was referenced and critiqued by various 18th-century thinkers, including two academic scholars, Denis Diderot and Ludvig Holberg. They may have been exposed to Rudbeck's ideas indirectly through the affiliation network, given that they are unlikely to have read his books in Swedish themselves.

Denis Diderot (1713–1784) was a member of the Prussian Academy of Sciences from 1751 (Amburger 1950). Diderot's radical thinking, conflict with French authorities, and nonconformist personality kept him outside the fold of French academies. In the article *Étymologie* of his Encyclopédie (published over the period 1751–1765), Diderot used Rudbeck's work as a cautionary example of how speculative etymology can lead to erroneous conclusions, critiquing the methodology employed in *Atlantica*. Our simulation reveals that Diderot had a 100% chance of being exposed to Rudbeck's ideas as early as 1751–the year of his election–because he hypothetically encountered numerous members who were already exposed to the idea.

Ludvig Holberg (1684–1754) was a prominent Danish-Norwegian writer and philosopher, and professor at the University of Copenhagen from 1717 to 1754 (Slottved 1978). He satirized Rudbeck's theories, mocking the idea of Sweden as Atlantis and highlighting the speculative nature of Rudbeck's claims. According to our simulation, the chance Holberg was exposed to Rudbeck's idea is 0 until 1753, when it goes to 22.9%. It gains an additional 49.4% in the following year, before he died. This highlights two features of our approach: first, our exposure is a lower bound, and in this case Holberg might have been acquainted with Rudbeck's work through other means. In other words, even in cases where we know from historical evidence that a scholar engaged with an idea, our model still captures eventual exposure through the network alone. Second, Holberg was never affiliated with an academy, but only with a university, which in our model means it must have taken more time for ideas to reach him. As we will later show, this institutional feature plays a key role in shaping how easily ideas circulate through the network.

5 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. We assign ownership of an idea to fictitious inventors, in order to track whether the idea would spread differently in alternative realities. In the second experiment we remove some parts of the network to assess their importance in spreading ideas. We first exclude academies, which were more innovative and more connected institutions than traditional universities, from the network. 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, who were an important component with their c. 6000 scholars and c. 50 higher education institutions.

5.1 Placebo inventors of Botanical Realism

To better understand how the structure of a network influences the speed at which ideas spread, we run 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), from 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). Appendix I presents a short biography of each of these scholars. 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.

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.[25]

Figure 6 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 two cases, the idea fails to spread. Wieliczki in Cracow (professor from 1513 to 1552) and Lax in Zaragoza (professor from 1521 to his death in 1560) lacked other mobile peers for meaningful intellectual exchange, and in these two scenarios the idea does not take hold. In ten other cases, we observe that by the end of the period, nearly all relevant scholars had encountered the idea. It is important to note that these results are averaged over 5,000 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, but reached 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.

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.[26] 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

25. That said, Botanical Realism required not just empirical skills but also an interest in plants themselves, which some of these figures might not have had. 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.

26. Appendix I.1 provides a more detailed discussion of this point.

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) for a history of the idea of ergodicity).

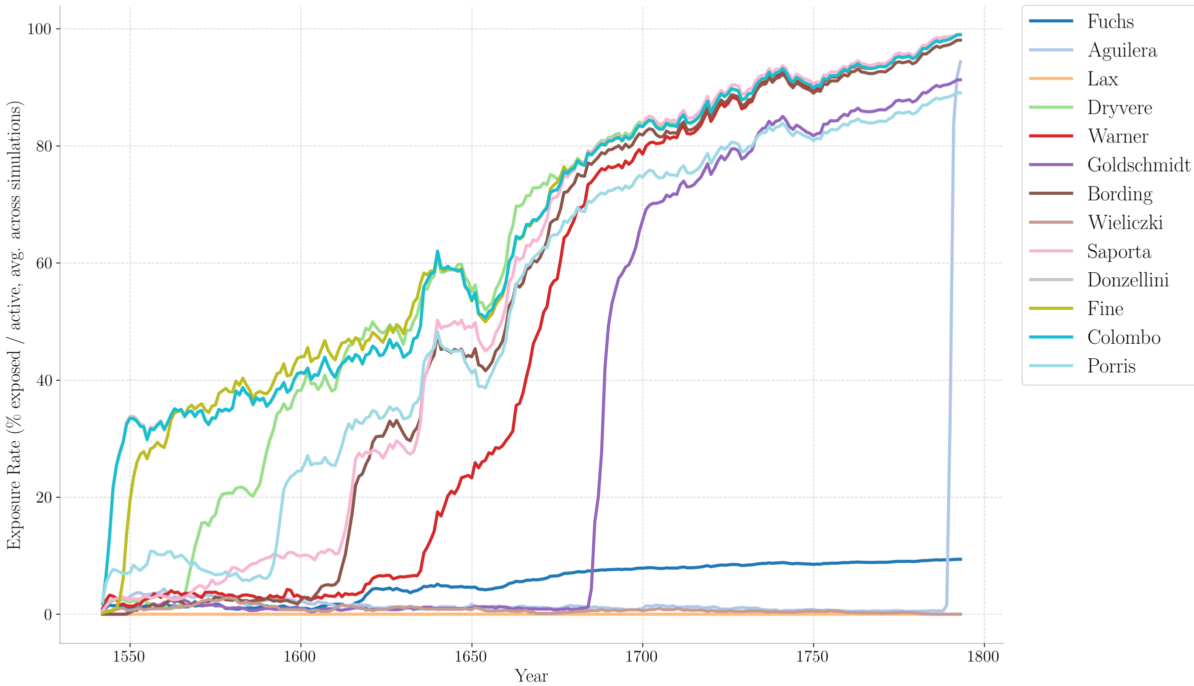


Figure 6: Exposure rates of active scholars in the network from 1084 to 1793, considering different hypothesized proponents of Botanical Realism.

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 7 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 effectively closed the university and disrupted this continuity, especially 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 via 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. Thus Adrien Van Roomen, Jakob Degen, Michael Mästlin, and Kasper Maliński are necessary for the survival of the idea. Van Roomen is only the last of a series of key players according to Zenou's (2016) 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 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 was strongly path-dependent and non-ergodic as described in (David 1985): it was shaped by more or less random historical events "rather than systematic forces" (p.332).

5.2 Removing components of the network

As explained above, we simulate the spread of ideas in a network stripped of certain components. This gives us better insight into the role of each component. Under this approach, we rewrite equation 1 as

$$I_{t+1}^B = B_t I_t^B + I_t^B \tag{9}$$

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 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

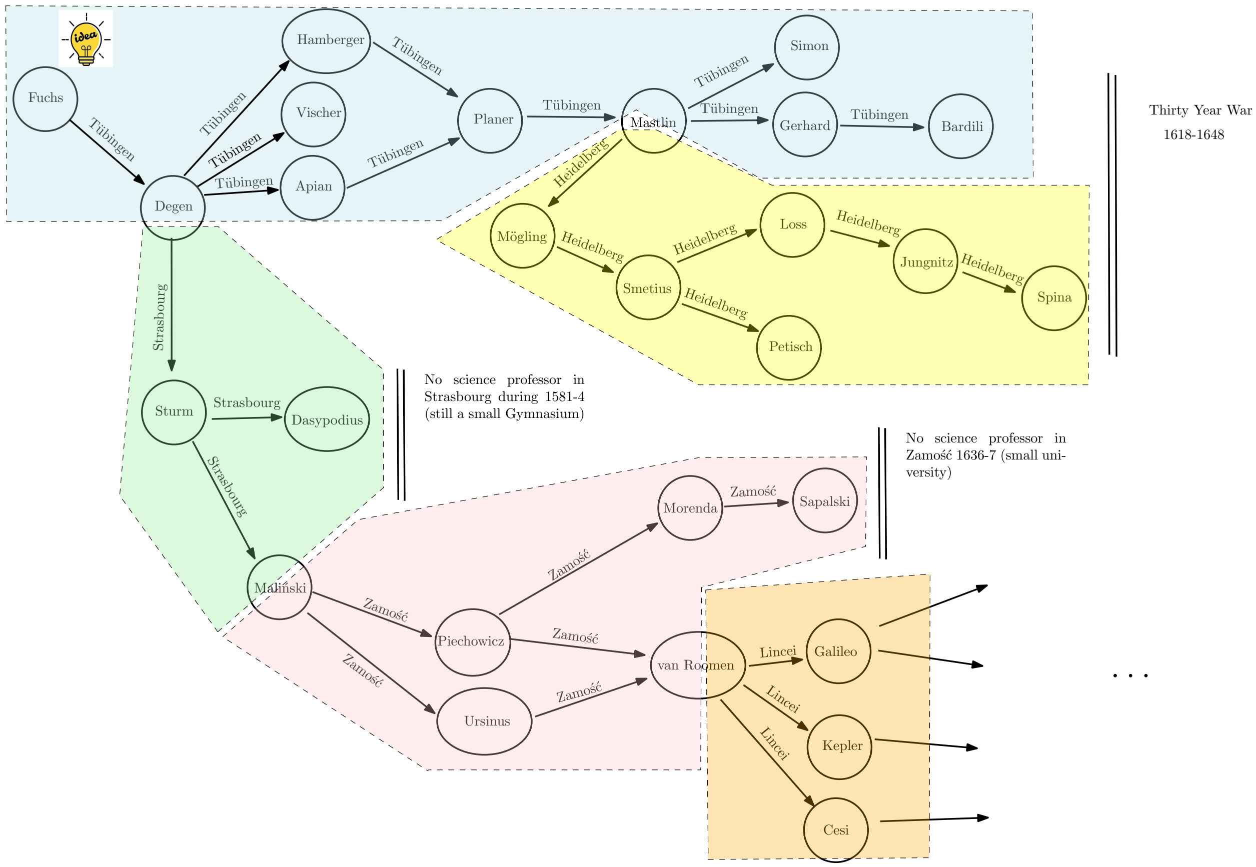


Figure 7: Botanical Realism path

fewer exposed persons at every time step, since reducing the number of connections reduces the opportunities for 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, 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 6, the line "No direct effect" gives the exposure distribution 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 Academies 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 first line for each year "With Academies" represents the baseline exposure distribution, which can be used for comparison.

The following insights can be drawn from Table 6: there are very few academies in 1600. The Ricovrati in Padua was only just created (in 1599), and it was mostly literary at that time. The same is true of the Accademia della Crusca (founded in Florence in 1583 to preserve the purity of the Italian language). The Lincei, already mentioned above in the context of its relationship with Romanus and Botanical Realism, was founded in 1603 (Gabrieli 1989). As a result, academies did not have a big influence on the exposure to Botanical Realism, and both lines remain pretty similar to the benchmark. However, academies already played a role in spreading Mathematical Astronomy, as the exposure distributions drops with respect to the benchmark: the median drops by 23%. The indirect effect is smaller, as removing it lead to a larger drop of 25%. 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. After 1700 academies are increasingly significant. For Botanical Realism, academies are essential, as indicated by the third row in each scenario dropping to zero. In contrast, while Mathematical Astronomy does not depend strictly on academies for its survival, they play a crucial role in amplifying exposure. By 1793, the absence of academies would lead to a dramatic reduction in exposure to Mathematical Astronomy: in the scenario without academies at all, the median would drop by

Table 6: Counterfactual experiment with and without academies.

	Q1	Median	Q3
Botanical Realism			
With Academies in 1600	0	5.18	12.63
No direct effect in 1600	0	5.18	12.63
No Academies at all in 1600	0	5.16	12.58
With Academies in 1650	6.02	16.06	25.42
No direct effect in 1650	3.72	10.04	16.67
No Academies at all in 1650	0	2.51	5.72
With Academies in 1700	12.84	44.42	82.76
No direct effect in 1700	5.57	17.66	28.45
No Academies at all in 1700	0	0	0
With Academies in 1750	29.11	110.34	190.68
No direct effect in 1750	9.13	29.70	53.02
No Academies at all in 1750	0	0	0
With Academies in 1793	78.39	308.81	521.35
No direct effect in 1793	13.02	41.49	75.11
No Academies at all in 1793	0	0	0
Mathematical Astronomy			
With Academies in 1600	0.15	8.67	22.73
No direct effect in 1600	0.14	6.66	16.97
No Academies at all in 1600	0.14	6.45	16.41
With Academies in 1650	20.60	56.15	90.09
No direct effect in 1650	8.38	23.98	39.55
No Academies at all in 1650	0.01	5.38	20.25
With Academies in 1700	45.79	144.73	292.56
No direct effect in 1700	18.21	49.81	77.38
No Academies at all in 1700	0.11	4.57	17.18
With Academies in 1750	124.38	444.15	759.10
No direct effect in 1750	37.99	114.45	200.55
No Academies at all in 1750	11.34	33.27	58.02
With Academies in 1793	358.77	1381.77	2291.75
No direct effect in 1793	51.06	161.96	285.24
No Academies at all in 1793	23.92	60.56	105.60

Summary Statistics of cities' exposure distributions to ideas when [0] academies are fully considered (benchmark) [1] academies have no direct effect on cities but are still present in the network [2] academies have no effect at all.

more than 95%.

We can use this same tool 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 intellectual and scientific transformations. For example, Italy laid the foundations with the Renaissance and early scientific methods (Applebaum 2003); the British Isles drove empiricism and practical applications (Mokyr 2011a); France spearheaded Enlightenment thinking and institutional science (Ferris, Stella, and Yon 2010); the Iberic Peninsula advanced economic theory and natural law, and the Holy Roman Empire advanced theoretical frameworks in mathematics and astronomy.

Table 7: Counterfactual Experiment with and without European regions.

	Q1	Median	Q3
Botanical Realism			
No Italian Peninsula	0	0	0
No British Isles	67.34	240.88	455.91
No France	64.40	280.03	480.19
No Iberic Peninsula	78.39	308.81	521.35
No Holy Roman Empire	0	0	0
Benchmark	78.39	308.81	521.35
Mathematical Astronomy			
No Italian Peninsula	0	0	0
No British Isles	290.39	1021.46	1911.36
No France	234.06	991.08	1668.37
No Iberic Peninsula	340.63	1348.13	2237.27
No Holy Roman Empire	339.30	1282.77	2118.87
Benchmark	358.77	1381.77	2291.75

Summary Statistics of cities' exposure distributions to ideas in five counterfactual networks without a specific European region, and the benchmark in 1793.

We apply our model to study separately the importance of each nation in spreading and keeping alive each idea. To measure 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,[27] one without the Iberian peninsula, and one without the Holy Roman Empire (as defined in

27. 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, and in the benchmark model.

Results are presented in Table 7. Each number is a summary statistic of the exposure S^c_{1793} of the cities' distributions, together with the relative exposure distribution in the benchmark. Without the Italian Peninsula, neither Botanical Realism nor Mathematical Astronomy would have survived. For example, for the latter, the universities of Rome and Bologna were critical hubs, allowing scholars previously exposed to the Mathematical Astronomy in Vienna or Bratislava to continue disseminating it among their colleagues. It appears that the Holy Roman Empire is necessary for Botanical Realism, but not for Mathematical Astronomy. No other regions in this simulation were necessary for either idea to spread. For example, both Botanical Realism and Mathematical Astronomy spread throughout Europe even without the British Isles, although the median drops by 22% and by 26%, respectively. Even if the British Isles had a key role in the propagation and implementation of useful knowledge (Hallmann, Hanlon, and Rosenberger (2022) show that British inventors worked on 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 ideas across Europe is not significantly hindered by the absence of France, and the contribution of the Iberian Peninsula appears particularly limited or even negligible.

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 the sample is limited to the period after the Jesuit order was founded. 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 after the order was established). 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, where Georgetown University was founded in Washington DC).

Table 8: Counterfactual experiment with and without Jesuits

	Q1	Median	Q3
Botanical Realism			
Benchmark	33.29	126.13	218.01
No direct effect	32.37	121.72	212.79
No Jesuits at all	28.49	107.00	187.43
Mathematical Astronomy			
Benchmark	122.51	437.48	747.74
No direct effect	114.02	417.16	718.26
No Jesuits at all	115.86	423.61	729.94

Summary Statistics of cities' exposure distributions to ideas in the counterfactual network without Jesuits and the benchmark in 1750.

Table 8 presents the results for 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, and 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). The median drop is between 3% (No Jesuits at all) and 4.6% (No direct effect). 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.

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:

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

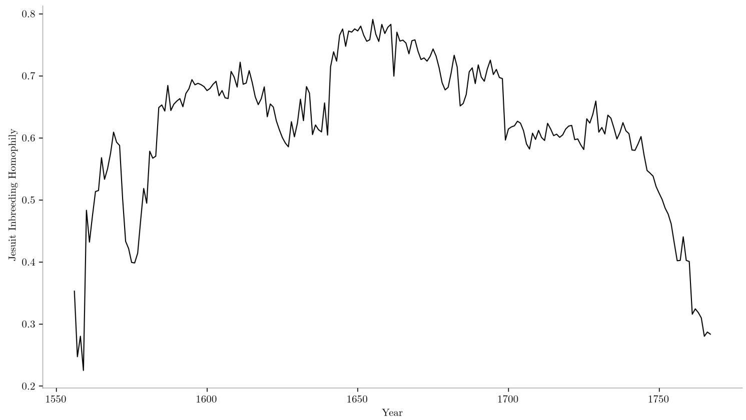


Figure 8: Jesuit inbreeding homophily over time

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 8 plots $IH_{Jesuits,t}$ from 1556 to 1767, the period over which Jesuits were most active. 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.[28]

6 Conclusions

We have studied 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 to spread more widely. By examining the diffusion of groundbreaking ideas and paradigm shifts such as Botanical Realism, Mathematical Astronomy, and Scholasticism, we have validated the role of higher-education institutions in European development.

The counterfactual experiments reveal the nuanced importance of academies: not only did they act as hubs of direct idea dissemination, but they also enhanced the connectivity of the broader network, bridging university communities. Without academies, the spread of ideas born in university settings would have been significantly slower. Our approach also provided insights into regional contributions to scientific progress, highlighting the resilience

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

of the European network of academies and universities, which was dense enough to sustain the circulation of ideas even if certain parts were removed.

While our results are robust to several modelling choices, the analysis is carried out under the assumption that the affiliation network is exogenous, and determined by the data we observe. This is of course a limitation of our approach. We know that the affiliation network results from location choices of individuals, and these choices are determined by several elements, including 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 with respect to ideas themselves, an extension of the analysis could consider exogenous changes in the network, either through shocks to nodes (a popular source of exogenous changes in network is through the unexpected death of some nodes, as in Benzell and Cooke (2021) and Azoulay, Fons-Rosen, and Zivin (2019)), or through direct shocks to edges (as in Cervellati et al. (2025)—improvement of the English postal service—or Chiopris (2024)—delays in building the German train network).

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A Descriptive Statistics

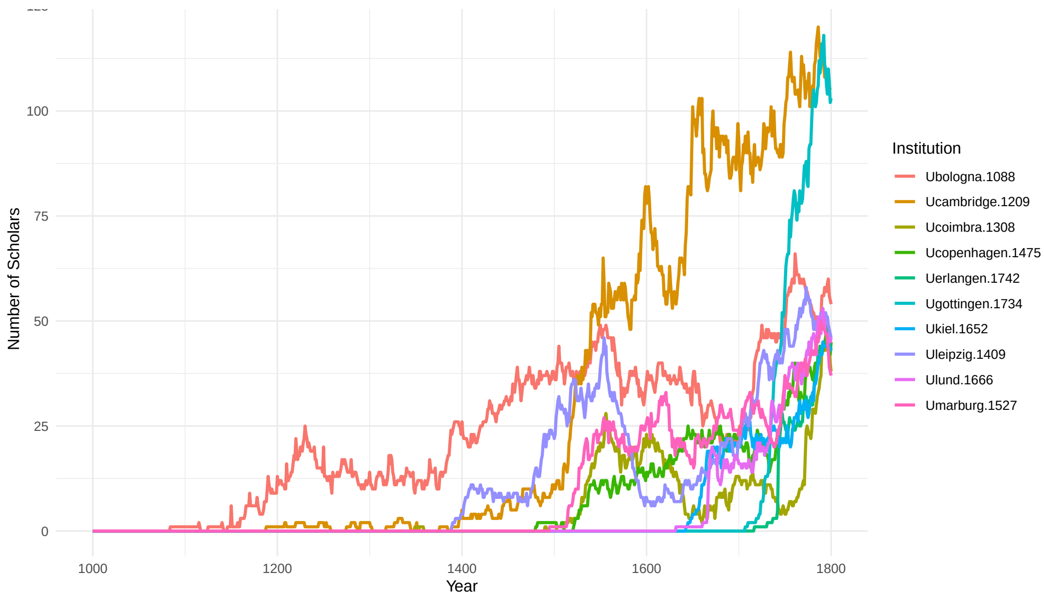


Figure 9: Number of university professors between 1000 and 1800 of the top 10 universities considering the number of scholars in 1793. In the legend, the name of the institution with the foundation date.

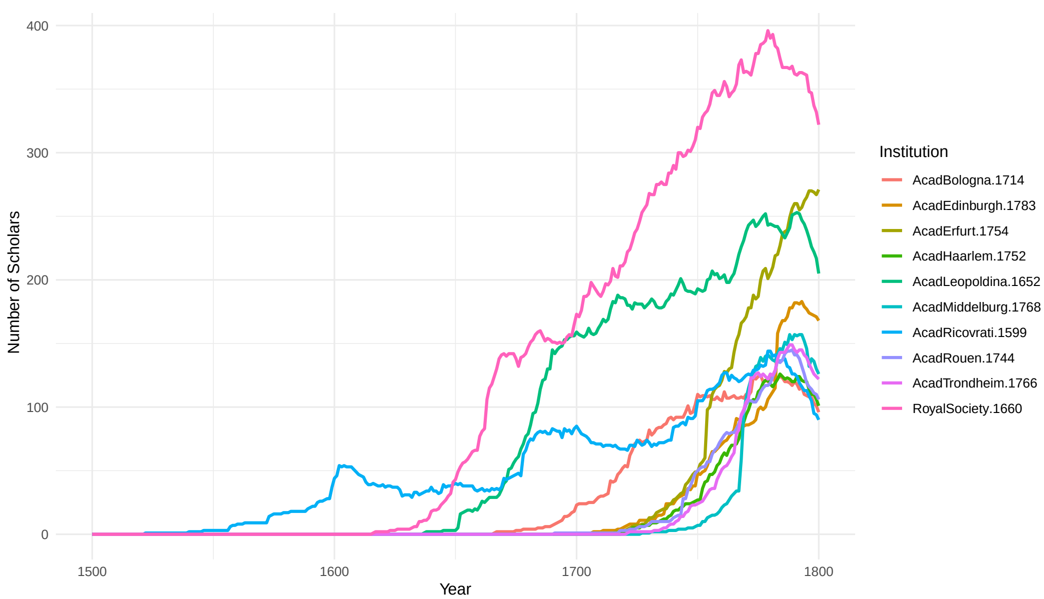


Figure 10: Number of academicians between 1500 and 1800 of the top 10 academies considering the number of scholars in 1793. In the legend, the name of the institution with the foundation date.

Institution	Mean	Median	SD	Min	Q1	Q3	Max
Ubologna.1088	34.14	36	14.39	13	25	43	54
Ucambridge.1209	59.29	93	50.36	1	8	100	105
Ucoimbra.1308	8.57	4	13.78	0	0	9	38
Uerlangen.1742	9.71	0	17.39	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 9: 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. "SD" stands for Standard Deviation, "Min" for minimum, "Q1" for first quantile, "Q3" for third quantile, and "Max" for maximum.

Institution	Mean	Median	SD	Min	Q1	Q3	Max
AcadBologna.1714	32.71	0	48.91	0	0	59.5	110
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	80.00	3	99.80	0	0	176	205
RoyalSociety.1660	122.57	44	148.71	0	0	246.5	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 10: 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. "SD" stands for Standard Deviation, "Min" for minimum, "Q1" for first quantile, "Q3" for third quantile, and "Max" for maximum.

B Contextual information

B.1 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". First 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). Figure 11 shows a page of this book, emphasizing the realistic description of a plant.

Figure 11: A page of *De historia stirpium commentarii insignes*

Furthermore, we 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). To fix ideas, Figure 12 shows the *Hortus botanicus* (botanic garden) of the University of Leiden, which was opened in 1590. This is a case of a large garden with a dedicated building, but some other gardens were much smaller.

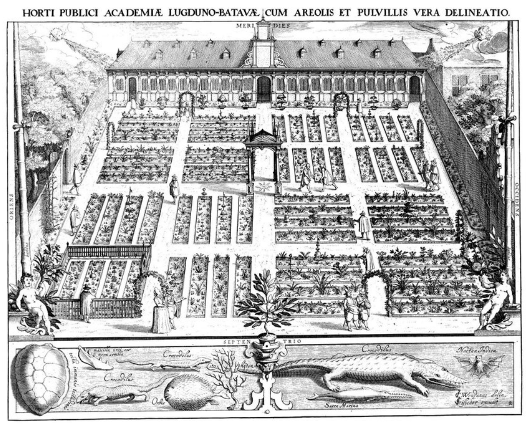


Figure 12: The Hortus botanicus of Leiden

B.2 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 refine them through observation 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 celestial motions to understanding the physical mechanisms behind them.

A key figure in this 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 (1423–1461), began collaborating on *Theoricæ novæ planetarum*. 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 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, he settled in Nuremberg, drawn by its status as a free city and central location. There, he established a workshop and printing press, dedicating himself to the dissemination of scientific knowledge. In 1463, he published *Epitoma in Almagestum Ptolemaei*, which clarified, corrected, and expanded Ptolemaic astronomy. Two pages of *Epitoma* are shown if Figure 13. 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 age 41.

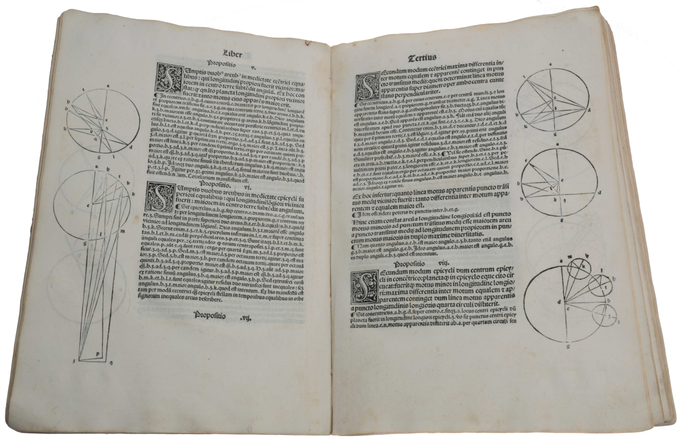


Figure 13: Two pages of *Epitoma in Almagestum Ptolemaei*

We examine the creation of observatories in the same 185 university 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 with the botanic gardens, we only considered observatories in continental Europe, assuming that a location lacked one if it was not listed in our source. To fix ideas, Figure 14 shows the main building of the University of Prague, the Clementinum. There, a tower was built in 1722. Later, in 1751, instruments were installed, and the tower became an astronomical observatory.

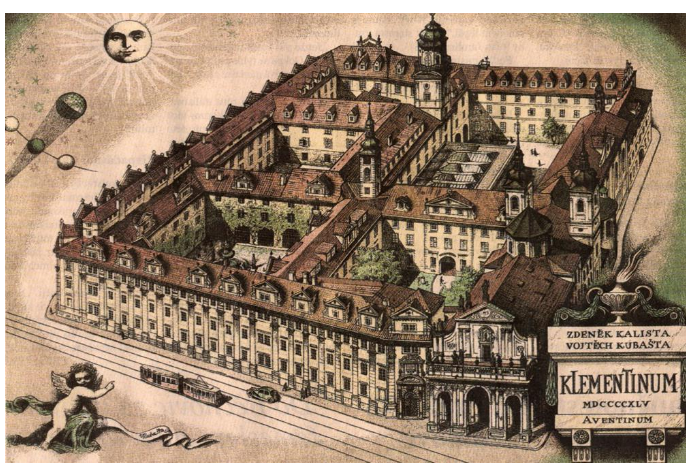


Figure 14: The *Clementinum* in Prague with its observatory

C Empirical Assessments

C.1 Descriptive Statistics

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

Table 11: Summary statistics.

Variable	NAs	Obs	Mean	Median	SD	Min	Max
(ihs) Exposure to Botanical Realism	0	54390	0.313	0	0.832	0	5.745
(ihs) Non exposure to Botanical Realism	0	54390	0.572	0	1.194	0	6.139
(ihs) Exposure to Mathematical Astronomy	0	54390	0.495	0	1.253	0	7.318
(ihs) Non exposure to Mathematical Astronomy	0	54390	0.418	0	0.987	0	5.675
(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

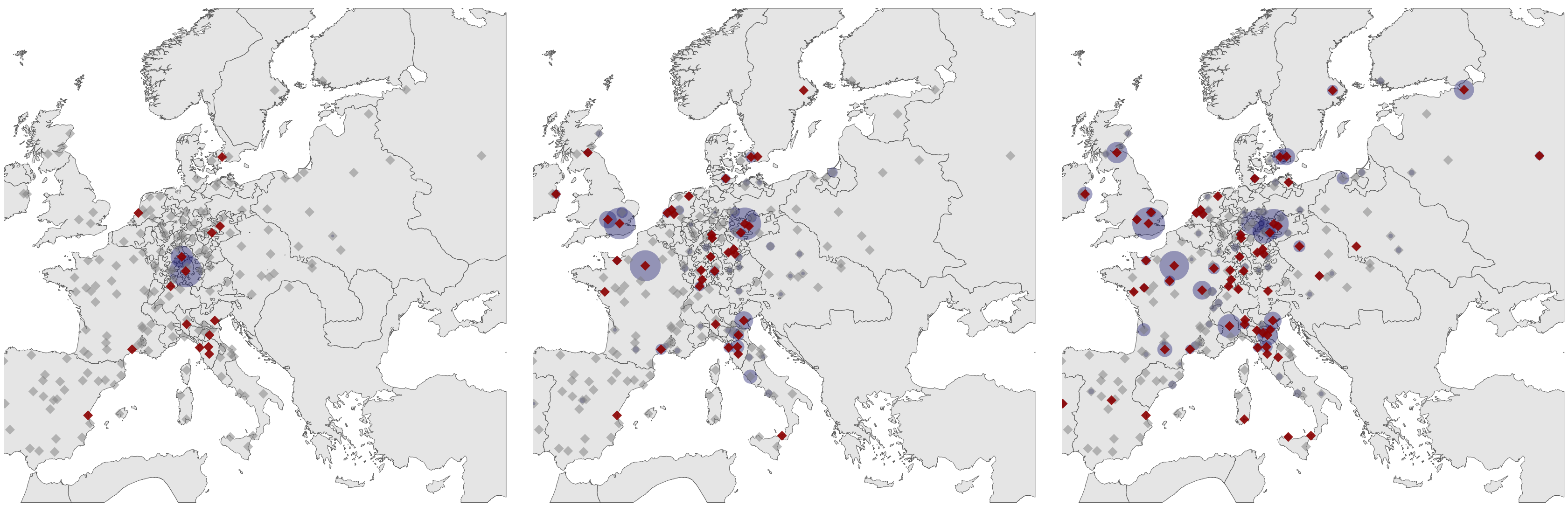
(ihs) refers to the transformation in inverse hyperbolic sine of the relative variable. The 4410 missing values for city population indicates that for 15 cities (and 294 years) we do not have population data. "NAs" stands for missing values, "Obs" for observation counts, "SD" for Standard Deviation, "Min" for minimum, and "Max" for maximum.

C.2 Botanical Realism

Figure 15 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.

C.3 Mathematical Astronomy

Figure 17 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 15: Blue bubbles represent the yearly exposure to Botanical Realism in years 1600, 1700, and 1793, respectively. $\alpha = 0.25$ and $D = 5,000$. Cities with a botanic garden are the red diamonds, and without botanic gardens are the grey diamonds.

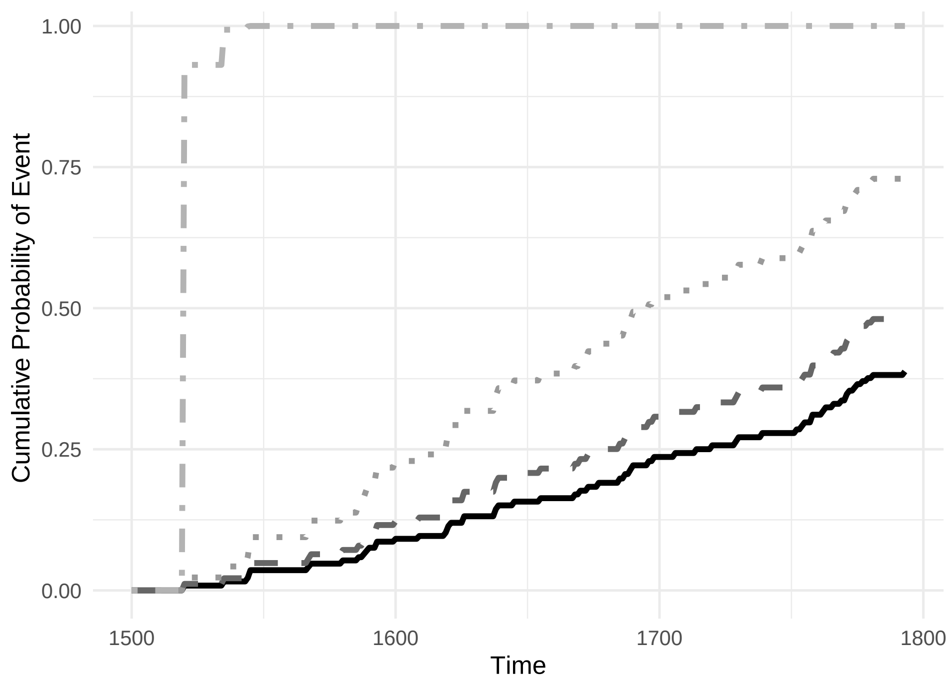
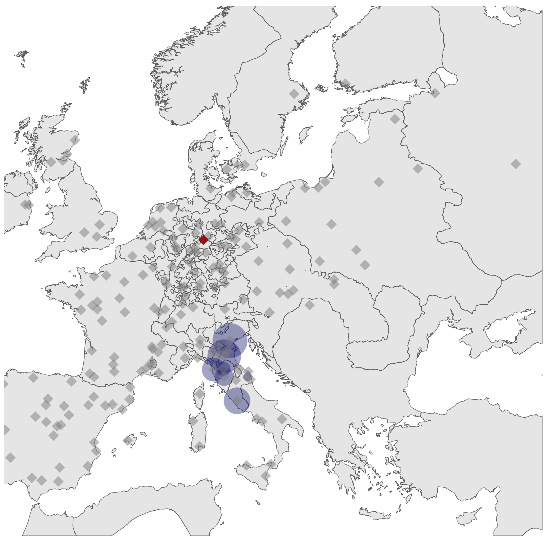
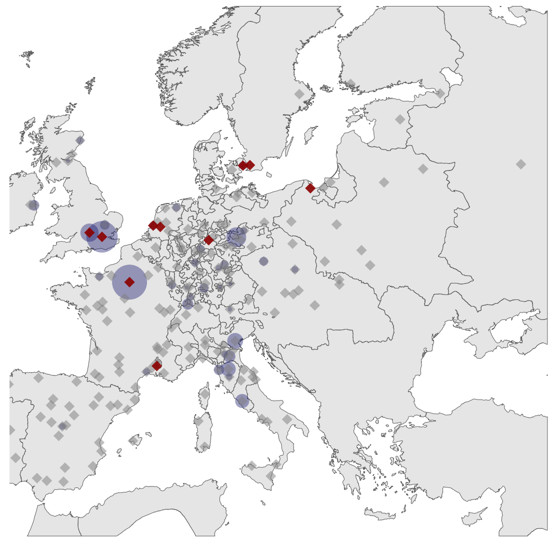


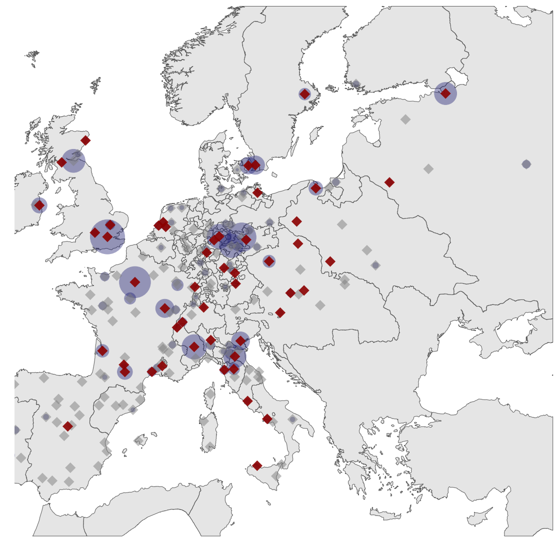
Figure 16: Probability of getting a botanic garden by time for different exposure to Botanical Realism levels: dot-dashed line considers a constant exposure of 5.75 (max exposure), the dotted line a constant exposure of 1, the dashed line a constant exposure of 0.31 (mean exposure), and the solid line a constant null exposure.



(a) Year 1600



(b) Year 1700



(c) Year 1800

Figure 17: Blue bubbles represent the yearly exposure to Mathematical Astronomy in years 1600, 1700, and 1793, respectively. $\alpha = 0.25$ and $D = 5,000$. Universities cities with an astronomical observatory are the red diamonds, and without botanic gardens are the grey diamonds.

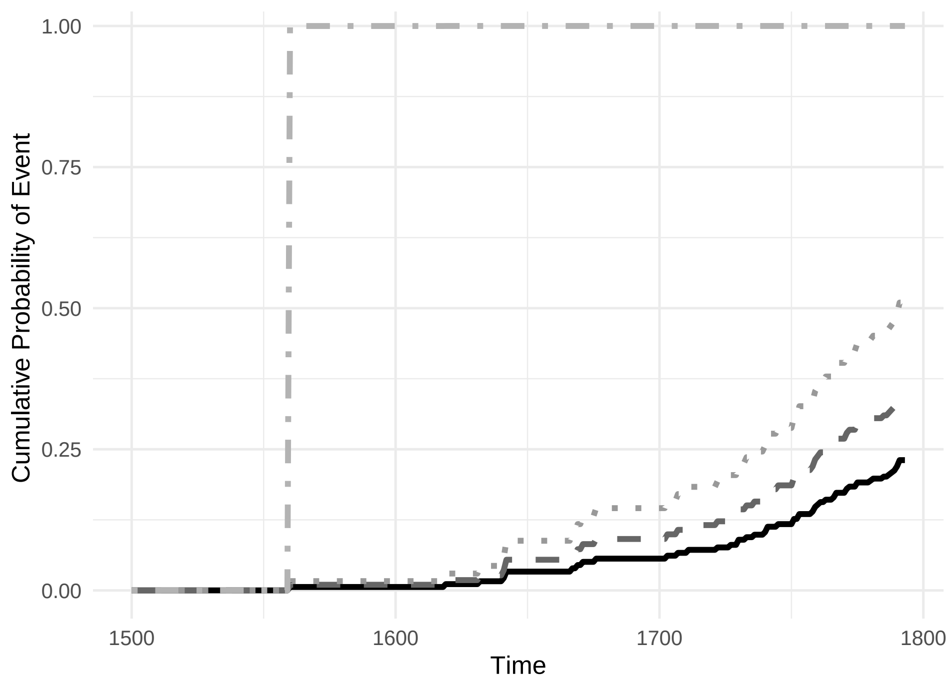
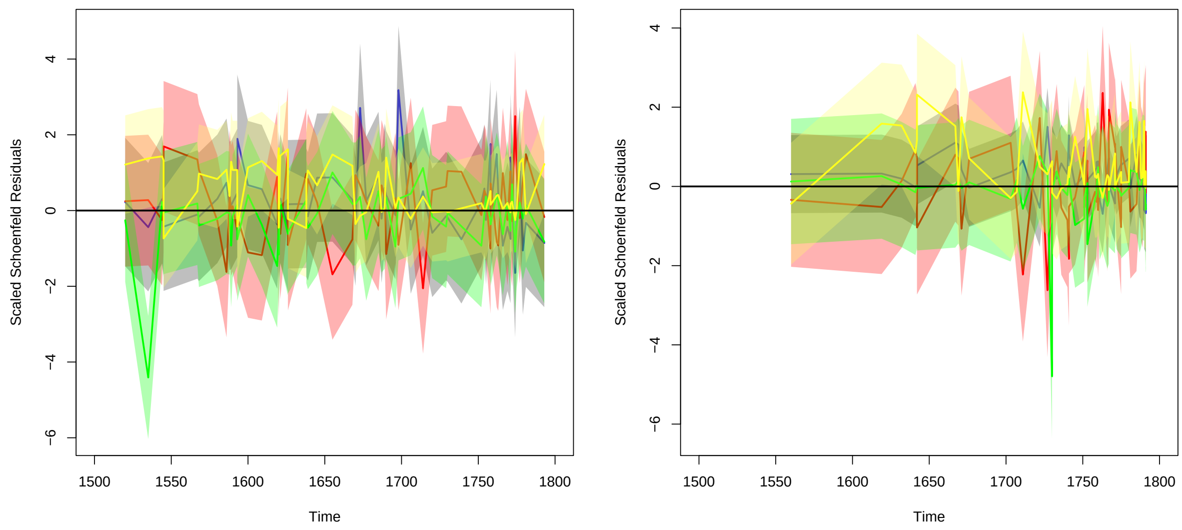


Figure 18: Probability of getting an Observatory by time for different exposure to Mathematical Astronomy levels: dot-dashed line considers a constant exposure of 7.32 (max exposure), the dotted line a constant exposure of 1, the dashed line a constant exposure of 0.5 (mean exposure), and the solid line a constant null exposure.

D 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 of Table 2 and Table 3, respectively, and time. The global correlation is only slightly significant in the case of Botanical Realism, while it is not at all significant for Mathematical Astronomy. We can see that by looking at the confidence intervals almost 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 19a) and “(ihs) Exposure to Mathematical Astronomy” (Fig 19b), respectively. The yellow line and confidence interval correspond to the hazard ratios of “(ihs) Non exposure” to Botanical Realism (Panel a) and to Mathematical Astronomy (Panel b). 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 19a) and “(ihs) Distance to Vienna” (Fig 19b), respectively.



(a) Botanical Realism

(b) Botanical Realism

Figure 19: 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.

E Example of scholastic reasoning

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.

F Augmenting Rubin's data

Rubin (2014) compiled data on whether European cities were Protestant in 1530, 1560, and 1600, focusing primarily on cities within the Holy Roman Empire. His approach assumed that cities located in officially Catholic countries remained Catholic throughout the period. However, this assumption does not hold for regions such as France and the Low Countries (modern-day Belgium), where several cities adopted Protestantism temporarily before being reconquered by Catholic forces.

To address this limitation, we have updated the religious status of the following cities to reflect periods of Protestant control, based on information from the Catholic Encyclopedia (Herbermann 1913).

- Die. Protestant control: 1562-1628/1629. Became a Protestant stronghold in Dauphiné during the Wars of Religion. Occupied by royal troops during Richelieu's repression of Huguenot fortresses.
- La Rochelle. Protestant period: 1550s-1628. Key Huguenot stronghold. Besieged and subdued by royal forces under Richelieu in 1628.
- Montauban. De facto Protestant Rule: 1561-1629. Montauban became one of the most fortified and independent Huguenot cities in France. Finally capitulated (1629) to royal troops under Richelieu after the fall of La Rochelle and a renewed campaign to suppress Huguenot political autonomy.
- Montpellier. Protestant control: 1562-1622. Served briefly as a de facto capital of Huguenot political assemblies. Lost military and political autonomy after Siege of Montpellier (1622) by royal troops under Louis XIII.
- Nîmes. Protestant control: 1561-1629. After violent iconoclasm in 1561, the city came under Huguenot control. Held by Protestants throughout the Wars of Religion; formally lost autonomy in 1629 after Richelieu's campaigns.

- Ostend. In 1572, Ostend joined the Dutch Revolt and came under the control of the rebel States-General of the Netherlands, aligning with Protestant (Reformed) forces. After the Siege of Ostend (1601-1604), the city was almost entirely destroyed, and Catholicism was restored under Spanish Habsburg rule.
- Uzès. Protestant control: ca. 1562-1629. Important center in the Languedoc region. Remained predominantly Protestant until submission to royal forces in 1629, when Richelieu dismantled Protestant strongholds.

For the sake of completeness, we list here the cities with Protestant control outside Rubin's years 1530,1560, and 1600.

- Antwerp. Protestant period: ca. 1566-1585. During the Reformation, Antwerp became a Calvinist stronghold. After the Fall of Antwerp in 1585, Protestant worship was banned, and many Protestants fled north.
- Caen. Protestant control: 1562-1572. Important Protestant stronghold in Normandy. The St. Bartholomew's Day Massacre (1572) led to widespread killings and ended Protestant rule.
- Ghent. Protestant period: ca. 1577-1584. Calvinist Republic of Ghent established during the Dutch Revolt. Ended with Spanish reconquest.
- Tournai. Protestant control: 1577-1581. Strong Calvinist presence; fell to Spanish forces in 1581.

G Scholasticism: Additional Results

In Table 12 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.[29] 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.

29. 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 12: 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***	0.001*	0.003***	0.002**
Scholasticism S^c_{1508}	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Non exposure to				-0.002	-0.007	-0.001
Scholasticism $\check{S}^c_{1508}$				(0.003)	(0.005)	(0.007)
Presence of university	0.003	-0.007	-0.006	0.004	-0.003	-0.006
in 1500	(0.021)	(0.030)	(0.031)	(0.022)	(0.031)	(0.031)
Printing press by 1500	-0.043*	-0.051**	-0.059***	-0.043*	-0.048**	-0.060***
	(0.023)	(0.023)	(0.023)	(0.023)	(0.023)	(0.022)
(ihs) City population	0.012**	0.005	0.005	0.012**	0.005	0.005
in 1500	(0.005)	(0.007)	(0.007)	(0.005)	(0.007)	(0.007)
Free Imperial	0.120	0.179*	0.274***	0.119	0.174*	0.274***
City by 1517	(0.082)	(0.098)	(0.104)	(0.082)	(0.097)	(0.104)
Market potential	-0.006**	-0.014**	-0.013**	-0.006**	-0.013**	-0.013**
in 1500	(0.003)	(0.006)	(0.006)	(0.003)	(0.006)	(0.006)
Hanseatic by 1517	0.024	0.080	0.082*	0.024	0.081	0.082*
	(0.038)	(0.052)	(0.049)	(0.039)	(0.052)	(0.049)
Lay magnate	-0.014	0.149**	0.168**	-0.015	0.146**	0.169**
	(0.038)	(0.067)	(0.071)	(0.038)	(0.069)	(0.071)
(Arch)Bishop by 1517	-0.035*	-0.057**	-0.062***	-0.033*	-0.052**	-0.063**
	(0.019)	(0.025)	(0.024)	(0.019)	(0.025)	(0.025)
Access to water	0.008	-0.0003	-0.004	0.008	-0.001	-0.005
	(0.016)	(0.019)	(0.019)	(0.016)	(0.019)	(0.020)
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	0.715	0.733	0.501	0.715	0.733
Log Likelihood	110.49	27.35	15.84	110.62	28.65	15.86

Notes: Robust SE clustered by territory in parentheses. A constant term is included in all regressions.
Dependent variable 'Protestant' takes value 1 if the city is protestant in 1530, 1560, 1600, respectively. Data on cities' religion taken from Rubin (2014) and updated as in Appendix F. "Presence of university in 1500" is a dummy variable taking value 1 if the city had a university in 1500 as in our database (De la Croix 2021). "Exposure to Scholasticism S^c_{1508}" and "Non Exposure to Scholasticism $\check{S}^k_t$" are computed as in equations 4 and 7, respectively. The remaining control variables are selected from Rubin (2014).

H Additional Results with Practical Surgery

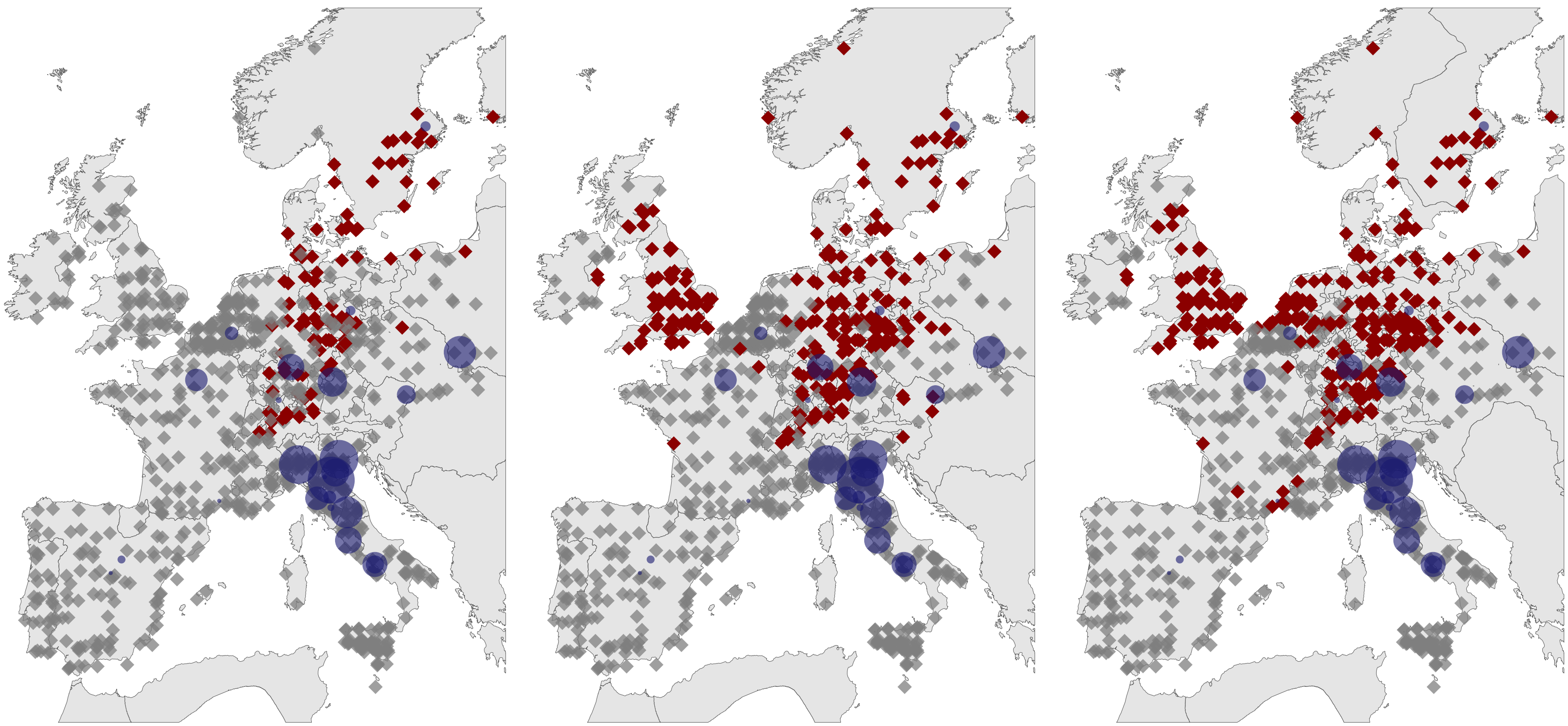
In addition to the results in Table 4 and Table 12, where we include 'Non exposure to scholasticism' to control for other orthogonal pathways that might have influenced the shift towards Protestantism, we present results controlling for a specific, orthogonal idea: *Exposure to Practical Surgery* PS^c_{1508}. This is interesting because it captures a distinct effect, separate from Scholasticism. We compute exposure to Practical Surgery similarly to Scholasticism, with the only difference being the starting point. Its "inventor", Guy de Chauliac (c. 1300–1368), was the most prominent physician and surgeon of the Middle Ages. His most famous work *Chirurgia Magna*, published in 1363, was the first to detail surgical procedures, previously handled mostly by charlatans. It remained the main reference well into the 17$^{\text{th}}$ century (The Editors of Encyclopaedia Britannica 2024).

The orthogonal relationship between Scholasticism and Practical Surgery is evident in Figure 20 (Appendix H): Practical Surgery was more prominent in Southern Europe, spreading independently of Scholasticism. In the linear probability model shown in Columns (1)–(3) of Table 13, *Exposure to Practical Surgery* PS^c_{1508} always has a negative sign and is significant in 1560 and 1600. We interpret this as further evidence of robustness: even when controlling for university presence and exposure to an orthogonal intellectual tradition, the correlation between Scholasticism and a city's likelihood of becoming Protestant remains positive and significant. This reinforces our hypothesis of a "disgust" effect triggered by Scholasticism.

Table 13: Linear Probability Model - Exposure to Scholasticism in 1508 and cities' probability to become protestant in 1530, 1560, and 1600

	Protestant in		
	1530	1560	1600
	(1)	(2)	(3)
Exposure to Scholasticism S^c_{1508}	0.001**	0.004***	0.006***
	(0.001)	(0.001)	(0.001)
Presence of university in 1500	-0.027	-0.042	-0.082*
	(0.027)	(0.044)	(0.045)
Exposure to Practical Surgery PS^c_{1508}	-0.001	-0.003**	-0.005***
	(0.001)	(0.001)	(0.001)
Observations	867	867	867
Adjusted R^2	0.022	0.139	0.259
Log Likelihood	-197.79	-467.50	-443.61

Notes: Robust SE clustered by territory in parentheses. A constant term is included in all regressions. Dependent variable "Protestant" takes value 1 if the city is protestant in 1530, 1560, 1600, respectively. Data on cities' religion taken from Rubin (2014) and updated as in Appendix F. "Presence of university in 1500" is a dummy variable taking value 1 if the city had a university in 1500 as in our database (De la Croix 2021). "Exposure to Scholasticism S^c_{1508}" and "Exposure to Practical Surgery PS^c_{1508}" are computed as in equation 4.



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

Figure 20: Blue bubbles represent the exposure to Practical Surgery 30 years prior 1508, $\alpha = 0.25$ and $D = 5,000$. Protestant cities are the red diamonds, and Catholic cities are the grey diamonds. Data on cities' religion are taken from Rubin (2014) and updated as in Appendix F.

I Placebo Inventors of Botanical Realism

Here, we list the twelve scholars we use as "placebo" inventors in the counterfactual analysis in Section 5.1. 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.

I.1 Centrality of the Placebo inventors

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. In two cases (Wieliczki (3) in Cracow, and Lax (0) in Zaragoza), the idea fails to spread. 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.

J 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 21d 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 22b 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.

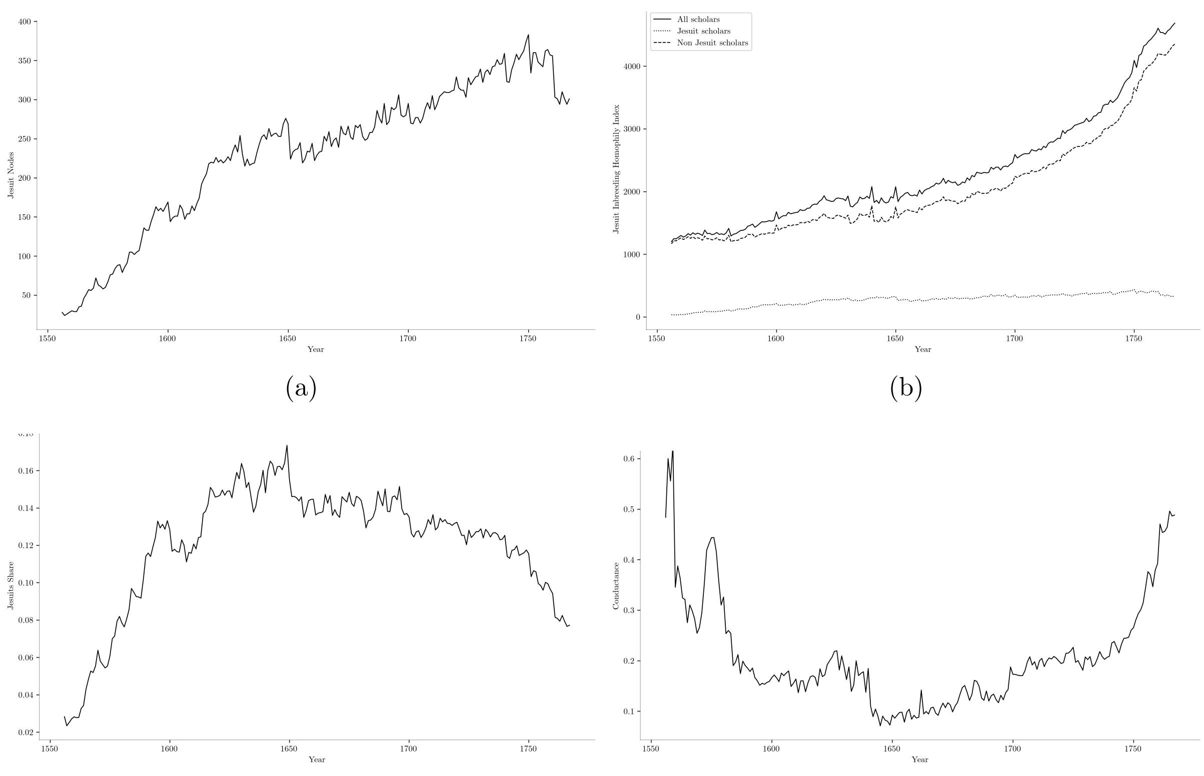
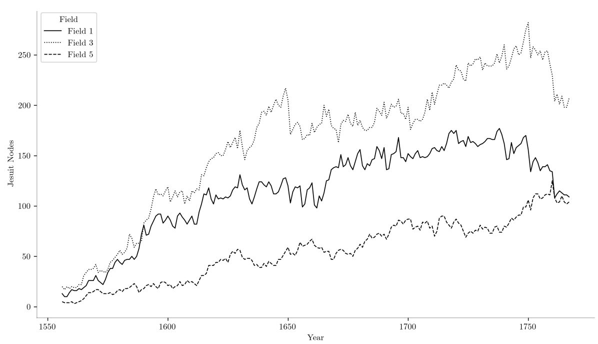
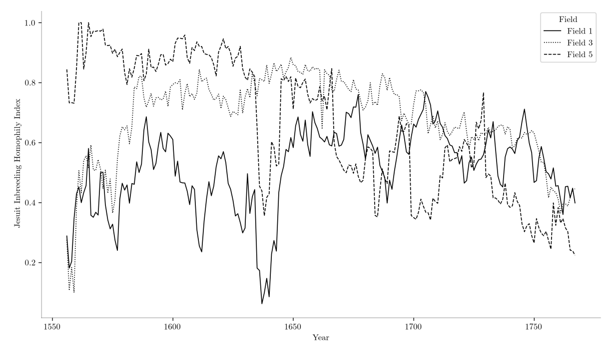


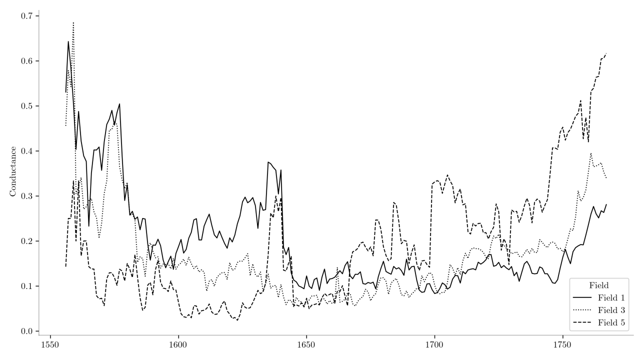
Figure 21: (a) Number of Jesuit scholars active in the network, 1556-1767. (b) Comparison of number of scholars by type: all (solid line), Jesuits (dotted line), and non Jesuit scholars (dashed line),1556-1767. (c) Fraction of Jesuit scholars active in the network, 1556-1767. (d) Conductance of Jesuits in the affiliation network, 1556–1767.



(a)



(b)



(c)

Figure 22: (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.