

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, home to thousands of scholars from the Middle Ages to the First Industrial Revolution. By inferring co-presence from institutional affiliations, we simulate how ideas would spread from a scholar to another across the European academic network. We find that the implied exposure patterns align with observed urban developments: examples include botanic gardens, astronomical observatories, and Protestantism. Scholars' mobility and multiple affiliations sustain the diffusion, and counterfactual simulations underscore the bridging role played by scientific academies. We also show that the spread of ideas through the affiliation network was locally fragile but globally robust, pointing towards academia as being a connective infrastructure underlying early European development.

JEL classifications: N33, O33, I23

Keywords: Temporal Network, Structural Estimation, Scientific Revolution, European Academia, Epidemiological model

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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 preservation of various forms of knowledge. Rarely did they accomplish these pursuits in complete isolation; rather, they were sustained by collective settings and aggregation centers. Chief among those were universities and academies, self-governed communities of scholars, as stressed in Rashdall (1895) and McClellan (1985). From medieval universities such as Paris and Bologna, to the Royal Society centuries later, these institutions physically gathered scholars in one place and gave them the means to work there, thus providing a fertile setting in which new knowledge emerged and spread.

Over this period, Europe experienced successive waves of transformation from the medieval urban revolution to the Enlightenment through humanism, the Reformation, and the Scientific Revolution. Universities and academies were closely entwined with these foundational shifts. Whether such institutions were central to Europe’s intellectual success, or instead functioned largely as privileged and resource-consuming corporations (Adam Smith 1776), remains an open issue. We address this question by studying one mechanism through which they could matter: the diffusion of ideas through face-to-face interactions within academic institutions.

Specifically, we propose a structural, microdata-driven model to measure how ideas would spread from one scholar to another based on historically recorded co-presence at the same academic institution. Similar to the approach taken by Becker et al. (2024) in their analysis of the pre-WWII period, we create an affiliation network where connections between scholars are based on their overlapping presence at a university or an academy. We then simulate the transmission of ideas combining an epidemiological approach with the network structure (Banerjee et al. 2013; Koher et al. 2016; Fogli and Veldkamp 2021). Our framework fits within the class of network diffusion models, such as that formalized in Bramoullé and Genicot (2024). This is the first analysis to reconstruct the European academic affiliation network at such a long-run and granular scale, making it possible to model both continent-wide dynamics of idea diffusion and local conditions under which ideas spread—or failed to do so.

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 them to peers with a certain probability, the *link activation probability*.

This parameter governs the overall diffusion of ideas through the network by regulating the likelihood that an interaction between two connected scholars leads to exposure. 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.

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 diffusion of specific ideas, such as Xue (2025) on Wang Yangming’s influence in Chinese writings, Lin and Ma (2026) on the intellectual proximity of Chinese philosophers to Francis Bacon, and Giorcelli, Lacetera, and Marinoni (2022) on the spread of Darwinian theory, or studies confined to particular linguistic or geographical contexts, such as Chiopris (2024) on nineteenth-century knowledge production in Germany, our setting lacks detailed evidence on the transmission of ideas. Work on contemporary data, 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. Nevertheless, we observe outcomes plausibly linked to idea adoption, which we use to conduct indirect inference.

Our approach is thus 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 Anthony Smith (2008)). We benchmark our diffusion model on two breakthroughs of the Scientific Revolution that have both clear historical importance and observable city-level proxies.

The first auxiliary model is the rise of botany as an independent discipline (*flora*), 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 speed at which a botanic garden is being established. We find that higher exposure is associated with a faster establishment of botanic gardens, especially in cities with a smaller scholarly mass susceptible to be exposed.

The second auxiliary model focuses on the mathematical reform of astronomy (*cosmos*), particularly on 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 (Universität Wien 2024), Bratislava (Gabriel 1969), Padua (Facciolati 1757), and Rome (Renazzi 1803), 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 that higher exposure is associated with a faster establishment of observatories, with the effect strongest in cities with a smaller eligible scholarly mass.

Admittedly, the historical foundation of botanical gardens or of astronomical observatories may have depended on many local factors beyond intellectual exposure, such as institutional resources and patronage, whose systematic reconstruction is not possible. The correlations we document between network exposure and the speed at which these infrastructures are established should therefore not be read as exposure alone determining the outcome, but as indicating that exposure paved the way to act earlier, *ceteris paribus*.

We estimate the link activation probability by maximizing the joint likelihood of the two auxiliary models. To be conservative, we take the lower bound of the confidence interval of this parameter. The estimated value is 0.20. This relatively low value generates exposure patterns that align with related historical outcomes and is sufficient to give an important role of social and institutional connections in the transmission of ideas. In that sense, our results echo both apprenticeship-based models in which the master-apprentice face-to-face communication is key (De la Croix, Doepke, and Mokyr 2018), but also contemporary insights on the persistent importance of face-to-face interactions in innovative environments like the Silicon Valley (Atkin, Chen, and Popov 2022).

With the estimated link activation probability, we use the model in two additional applications by linking exposure to scholasticism (*salvatio*) to the probability of cities adopting Protestantism and the spread of anti-Semitic ideas. 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). Exposure to scholasticism may have been associated with an intellectual climate receptive to Reformation ideas, possibly reflecting a backlash against intellectualized theological debate and a stronger emphasis on scripture (Chaunu 2014). To document this association, we simulate the diffusion of scholasticism through the affiliation network. We capture the exposure to scholasticism across universities in 1508 and infer the exposure of nearby cities. Using a linear probability model, we show that a higher exposure to scholasticism correlates with the adoption of Protestantism. In a similar vein, we extend the classical finding that pogroms against Jews were 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 climate embedded in scholastic thought acted as a complementary force in this process.

To assess the features of the affiliation network that are most critical for idea diffusion, we turn to exploring counterfactual scenarios. In this analysis, we compare observed outcomes with the hypothetical scenarios that would have emerged under alternative conditions. In the first counterfactual 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.

Taken together, these counterfactuals reveal an affiliation network that is globally robust yet locally fragile. While alternative paths almost always exist, early diffusion often depends on narrow institutional channels, making the survival of ideas partly contingent on chance. For example, in our simulations Fuchs’ Botanical Realism reaches the Accademia dei Lincei, and from there the rest of Europe, through a single chain of co-affiliations running from Tübingen through Strasbourg and Zamość (see Figure 2 in Section 3.2).

Our paper relates to several strands of the literature. First, we contribute to the growing body of work on the diffusion of knowledge in historical contexts. Existing studies have explored complementary channels such as printed books (Chiopris 2024), correspondence networks (Cervellati et al. 2025; Roller 2023), translations (Abramitzky and Sin 2014), and mentorship influences (Koschnick 2025b). Other contributions combine multiple channels to reconstruct broader diffusion processes (Becker et al. 2020, 2025). By contrast, we emphasize academic institutions as aggregating centers, fostering repeated opportunities for intellectual exchange among their members.¹ This could occur via physical proximity but also through

1. 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

institutionally-organized epistolary exchanges, as practiced in some academies. Focusing on institutional proximity offers two key advantages. On the one hand, observing whether scholars were affiliated with the same institution at the same time allows us to infer potential exposure to ideas, independently of whether those ideas were ultimately adopted or endorsed. *This distinction matters because exposure may precede observable adoption by many years: ideas can remain latent within the scholarly network, passing through individuals who leave no visible trace of adoption before being taken up by later scholars.* On the other, gaps in the network are, at least in part, observable. Gaps occur when universities are underrepresented in our sources, causing some professors to be missing. In contrast, gaps in correspondence networks, such as letters that have not survived, are fundamentally unobservable and thus impossible to systematically evaluate.

Second, our paper engages with the history of science and upper tail human capital, 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). 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. In addition, 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. Our analysis mostly covers propositional knowledge, complementing these studies by tracing the intellectual roots from which practical knowledge later emerged—for example, when early modern advances in atmospheric science associated with Torricelli and Boyle paved the way for practical applications in the eighteenth century. More generally, Koschnick (2025a) provides evidence, through automated text analysis, of knowledge spillovers between propositional and practical knowledge in England, 1600–1800.

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 also 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—

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

how resistant to disruption academic networks are—is also relevant to our framework.

Finally, we also engage tentatively with the literature on the rise of the West, and the Europe-China differences (Greif, Mokyr, and Tabellini 2025). Indeed, 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*. 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 88,792 scholars

Our database of scholars comprises information on 88,792 individuals spanning the period 1000-1800. We collected the data manually from approximately 700 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.²

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). In treating universities and academies together, we do not consider them as equivalent. They differed fundamentally in constitution, purpose, and membership. We treat them together because a substantial share of scholars in our database appear in both. That overlap in affiliations is itself of interest as a substantive feature of the European academic network.

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 different issues of the *Repertorium Eruditorum Totius Europae*. For academies this process was generally easier, 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 differ-

2. Universities and academies were not the only institutions that gathered scholars: monasteries, cathedral schools, and royal courts did so as well. Nor was physical proximity the only channel of contact: scholars corresponded across Europe, and printed books separated dissemination from proximity.

ent fields of study within academies. Academies often have 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).

Appendix A reports descriptive statistics. Among the 88,792 scholars, 26,549 lack any personal information (no place of birth, vital dates, or Wikipedia link), while another large group is known only by place of birth. Complete information on all three indicators exists for 17,200 scholars. Overall, 19,579 scholars, about one fifth of the dataset, have a Wikipedia page. Hence, for academia, our dataset is much more comprehensive than Wikipedia-based samples such as Laouenan et al. (2022). Around 80% of scholars are associated with a single field, most commonly the humanities, followed by the sciences (including medicine), theology, and law. For 6,939 scholars the field is unknown, and 3,744 are classified as “honorary,” reflecting administrative or ceremonial roles and will be excluded from the analyses. Among multi-field scholars, the most common combinations are theology and humanities (6,707) and humanities and sciences (3,382). Start years of affiliation are known in most cases (90,416), typically corresponding to university appointments or elections to academies. End dates are less systematically recorded, as sources often report when a professorship begins but not when it ends. Academy membership can generally be assumed to last until death, whereas no comparable assumption can be made for university posts. For 12,965 scholars only an approximate activity date can be assigned, and for 1,162 no dating information is available. More details about activity dates in Appendix B.

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 (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. Premodern universities were small, and it is reasonable to assume that professors had regular opportunities for interaction. Supplementary Material 3.1 presents some descriptive statistics for the 10 institutions with the highest number of scholars in 1793, differentiating by type (university vs academy). The average university has fewer than 70 professors. Academies hosted a higher number of scholars on average, reaching almost 80 in Halle and 123 in London.

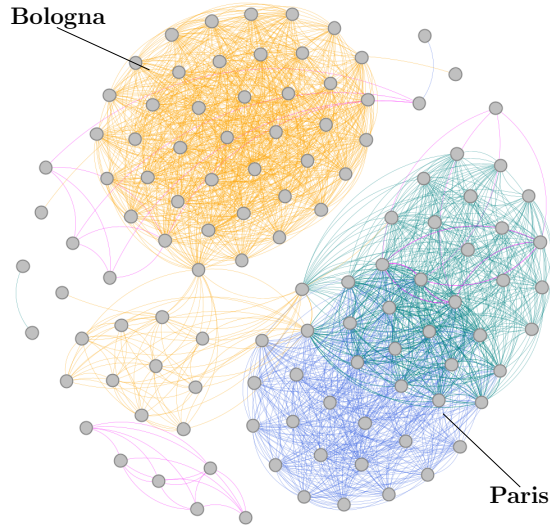
Our analysis spans the foundation of a new school of jurisprudence, which would later

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.

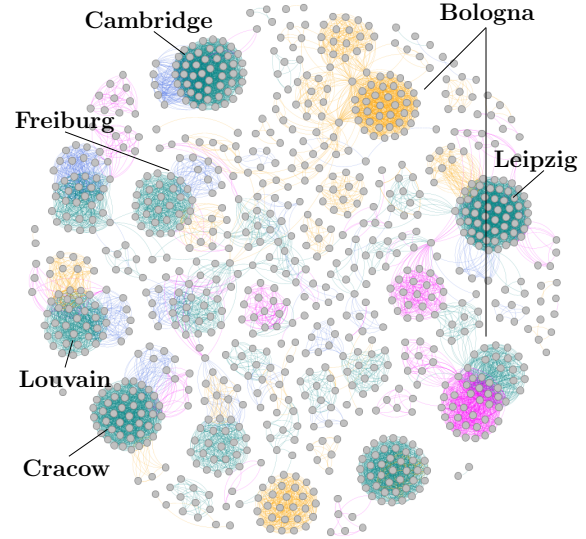
More formally, given two scholars i_s and i_v , the link between i_s and i_v lasts as long as i_s and i_v share an overlapping period of affiliation at the same institution. This implies that the collection of edges is dynamic over time: edges serve as channels for the spread of ideas, appearing and 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 4 in Appendix A.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. Appendix B gives more details on how activity periods are computed.

The affiliation network reveals several important characteristics, visualized in Figure 1. 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. As scholars move, occasional links 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 1d 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 likely due to the academies.

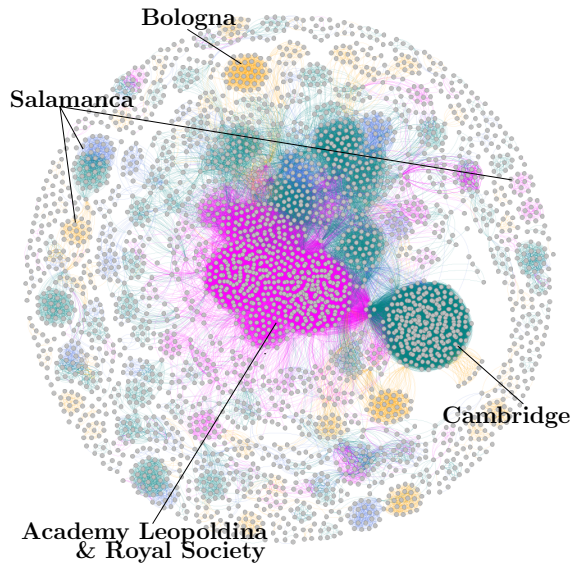
This effect is also visible in the share of nodes connected to the main network, known as the giant component—the largest connected subgraph in which any two nodes are mutually reachable—as shown in Figure 5 in Appendix A.2. In the early period, around 1200, the affiliation network was nearly fully connected, 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



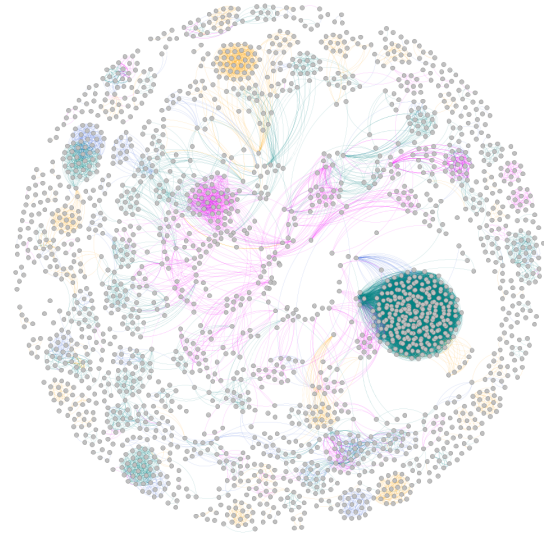
(a) 1200



(b) 1508



(c) 1730



(d) 1730 (No academies)

Figure 1: 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.

academies, as the share of nodes in the giant component increased from 40% in 1650 to 90% by 1793.

In Table 1 in Appendix A.2, 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 5.51—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 33.63% 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 scholar, 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 that field. Our assumption is that if a scholar is working in science³ they are presumed to engage productively with peers in medicine or applied science.⁴ 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 (albeit broadly defined rather than finely specialized) to each idea. We acknowledge that attributing an intellectual tradition to a single originator, on the one hand, and assuming ideas circulate within fields, on the other, are deliberate simplifications of a more nuanced and complex

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

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

reality. They are, however, necessary given the constraints of our data and model.

2.3 Ideas, inventors and exposed scholars

Ideas originate from *inventors*, i.e., scholars credited as the principal proponents of a new *idea* at a specific point in time.⁵ As noted above, this assumption compresses what was in reality a collective, cumulative and sometimes disputed process, but it provides the diffusion model with a well-defined initial condition. The intuition for the spread logic (described in depth in Section 2.4) is as follows: inventors can propagate their ideas to their peers; those peers, once exposed, can further spread them to their own colleagues, and so on. A scholar can therefore be exposed to an idea without necessarily maintaining a direct link with the original inventor, but a chain tracing back to the inventor always exists.

We draw inventors and ideas from two major historical encyclopedias: English (2005) for the period before 1500 C.E., and Applebaum (2003) for period between the invention of the printing press (circa 1450s) and the French Revolution. Our selection prioritizes inventors with an academic affiliation, and ideas that can be paired to available Europe-wide historical outcomes at the most granular level.

We simulate the spread of three main ideas: *flora*, *cosmos*, and *salvatio*. The first two date back to the Scientific Revolution. Specifically, Applebaum (2003) identifies Leonhart Fuchs’s 1542 herbarium as a foundational shift for the field of botany, and Regiomontanus’s formalization of Ptolemaic models (developed from 1450, published in 1496) fundamental for future research in astronomy. To balance the two early-modern scientific ideas above, we select the third one from a distinct period and domain. The index in English (2005) lists key medieval academic ideas spanning vastly different fields, including alchemy, anatomy (e.g., practical surgery), astrology, computus, civil law, economic thought, cartography, humanism, music, optics, political theory, punctuation, and the Scholastic method. We end up choosing the latter, also referred to as Scholasticism. Rooted in the work of Petrus Lombardus, Scholasticism emphasized rigorous logic and dialectical reasoning to reconcile faith with reason, and fostered a systematic approach to inquiry that shaped both scientific and philosophical thought.

After simulating the spread of each idea on the affiliation network, we can reconstruct, for every scholar, whether and when they were exposed in each simulation, from which we build exposure metrics (Section 2.4). Ideally we would compare these metrics to the actual diffusion of the ideas themselves. Since that is not cleanly traceable, we rely instead on

5. We use the term inventor as shorthand for the main originator of an idea according to the historical literature, not necessarily an inventor in the traditional sense, but often someone who developed, articulated, or popularized a concept. Similarly, the term idea is used broadly to encompass various intellectual contributions, including theses, paradigms, and methodological approaches, which differ in scope, complexity, and impact.

historical outcomes that proxy the presence of an idea in a given city at a given time. For botany we use the founding of botanic gardens; for the mathematical reform of astronomy, the founding of astronomical observatories.

For Scholasticism the outcome is less clear-cut, both because an abstract paradigm resists measurable expression and because Scholasticism became ubiquitous in European higher learning. We draw on the argument advanced in Chaunu (2014), explored further in Section 4, that the spread of Scholasticism provoked a theological backlash from religious movements—Protestantism above all—that placed scriptural authority above rational deduction. Our outcome is therefore the city-level adoption of Protestantism, which we expect to be positively associated with exposure.

A key challenge, common to all three ideas, is determining when the scholar first developed the concept. To define this moment, we try to establish 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.

2.4 Epidemiological model

In our framework, the random nature of the spread of ideas within institutions is essential. The process mirrors infectious disease contagion: contact between colleagues creates the probability of transmission, but not its certainty. We hence adopt an epidemiological approach to model the spread of ideas from a scholar to another (Fogli and Veldkamp 2021; Banerjee et al. 2013). There is a fixed number of nodes, N , each representing a scholar. Time is discrete, with $t \in \{\underline{t}, \dots, \bar{t}\}$, $\underline{t}$ and $\bar{t}$ being the start and end dates of our analysis. At each

date, a node can be susceptible or infectious.⁶ A contact between two nodes appears as an 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 $[i_{s^*}]_{t_0} = 1$, where s^* 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:

$$I_{t+1} = A_t I_t + I_t \quad (1)$$

To understand this formula, consider the s scholar. If they are alive at period t , their infection status at $t + 1$ is given by $\sum_v a_{sv} i_v$. With Boolean arithmetics, this term is equal to 1 if there is at least one v such that $a_{sv} = 1$ (s has met v) and $i_v = 1$ (v is infected). If, instead, s is either unborn or dead at time t , $a_{sv} = 0 \forall v$, and their infection status does not change.⁷

We also assume that once exposed to 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 $\alpha \in [0, 1]$,⁸ 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.

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

7. 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.

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

Dynamics of the state vector I are now represented by:

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

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 levels of exposure. These levels are expected levels, given the stochastic nature of the simulations. The expected scholar s exposure $[\bar{i}_s]_t \in [0, 1]$ to a given idea is obtained by averaging individual exposure over D simulations:

$$[\bar{i}_s]_t = \frac{1}{D} \sum_{d=1}^D [i_s^d]_t \quad (3)$$

Next let us define the set of members of institution k at time t in field φ as $V(k, t, \varphi)$. Institution k Eligible Mass in field φ is:

$$M_t^{k,\varphi} = \#V(k, t, \varphi). \quad (4)$$

It is the number of scholars at each point in time susceptible of receiving an idea in field φ at institution k .

Institution k Prevalence⁹ is then obtained as an average individual exposure over the set of individuals s belonging to $V(k, t, \varphi)$, at time t :

$$P_t^{k,\varphi} = \left(\sum_{s \in V(k, t, \varphi)} [\bar{i}_s]_t \right) / M_t^{k,\varphi} \quad (5)$$

Eligible Mass and Prevalence will be used in the proportional hazard models of Sections 3.2 and 3.3 to assess how these measures at a certain date are correlated with the emergence of botanic gardens or observatories.

Furthermore, by multiplying Eligible Mass by Prevalence we obtain institution k exposure

9. We borrow this term directly from epidemiology, where the prevalence of a disease denotes the share of a population affected at time t , as opposed to incidence, which measure instead the number of new ‘infections’.

as

$$S_t^{k,\varphi} = M_t^{k,\varphi} \times P_t^{k,\varphi} \quad (6)$$

So far, the above measures only concern cities which are the headquarter of an institution. To define a measure of exposure for all cities in Europe, we assume that headquarters' exposure affects nearby cities. We accordingly define expected city c exposure $S_t^{c,\varphi} \geq 0$ by averaging over nearby institutions, weighting by inverse distance:

$$S_t^{c,\varphi} = \sum_k w_{ck} S_t^{k,\varphi} \quad (7)$$

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.¹⁰

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 estimate α . This setup resembles indirect inference (Anthony 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 Eligible Mass and Prevalence of cities with a university or academy, given by Equations (4) and (5), for these two ideas.
4. We estimate two auxiliary statistical models correlating the simulated exposure with

10. The results are robust to alternative functional forms, such as exponential decay or varying distance thresholds.

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

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

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

3.2 Auxiliary model 1: Botanical Realism

During the Scientific Revolution, there were major advancements in botany, which 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* (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). More contextual information is available in Supplementary Material 4.1. Fuchs was based in Tübingen for the majority of his life, where 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 Prevalence $P_t^{k,\phi}$ of Botanical Realism and the establishment of botanic gardens. The founding of a botanic garden is admittedly an imperfect proxy for the spread and adoption of Botanical Realism, as local resources and a willingness to invest also mattered. Yet the material threshold for establishing a garden at a basic level was comparatively low. A university medical garden could consist essentially of a modest plot of land, a gardener, a knowledgeable professor, and a collection of seeds and plants. Its durability and scientific value depended on complementary investments in water, enclosure, skilled labour, and the maintenance and expansion of living collections, and some gardens eventually became substantial undertakings through expansion, relocation, glasshouses, and international collecting (Egmond 2010). Thus, for the extensive margin studied here—the initial establishment of a garden—the relevant constraint need not have been large fixed investment. We argue that access to botanical

knowledge and expertise could itself be an important determinant of when a city was able or willing to create one.

Using our epidemiological approach with link activation probability α , the diffusion of the idea begins with Leonhart Fuchs and spreads to his colleagues at the University of Tübingen from 1542 onwards. Exposed scholars can in turn contaminate their own peers with probability α , and so the idea propagates through the network until 1793 (the end of our timeframe). Figure 2 illustrates one chain along which the idea survives. At the University of Tübingen it circulates for several generations of scholars in medicine and science, until the Thirty Years’ War disrupts the university, in particular during its occupation by Imperial forces between 1628 and 1634. Before that, the idea leaves Tübingen with scholars who take up positions elsewhere: Michael Mästlin carries it to Heidelberg (Drüll 2002), which faces the same wartime disruption, and Jakob Degen to Strasbourg (Berger-Levrault 1890). Strasbourg is too small to sustain permanent positions in the sciences, but there, through Johannes Aeschines Sturm, the physician Kasper Maliński may have encountered the idea before moving to the University of Zamość (Kedzoria 2021). At Zamość it could have reached Adriaan van Roomen (Adrianus Romanus), professor of medicine at Louvain and Würzburg and a noted mathematician, who near the end of his life became a member of the Accademia dei Lincei, from where it could spread internationally.

An affiliation link records an opportunity for exchange, not proof that an idea was transmitted. We therefore ask what the scholars on this path had in common with Fuchs. The first link is the strongest. Degen, also known as Schegk, took his medical doctorate in Tübingen in 1539 after studying with Fuchs, and taught medicine beside him from 1543 until Fuchs’ death (Conrad 1960). He shared Fuchs’ humanist return to the Greek sources, although his own work lay in logic and natural philosophy, not botany. Van Roomen stands closer to Fuchs in subject. Already in 1598 he presided in Würzburg over the *Phytologia*, a disputation on plants as the source of remedies, which by his own account describes one hundred species growing wild in Germany, “where we have observed them”, and gives their names in several vernacular languages (Ruland 1867). One of his Würzburg students, Johann Faber, later became a botanist in Rome and a member of the Lincei (Ruland 1867; Gabrieli 1989). For Maliński we find no such engagement. The path thus mixes scholars who shared Fuchs’ method, his subject, or neither: in our framework exposure does not require adoption. *This distinction also allows for a latent phase in the diffusion of an idea: scholars may be exposed to, and potentially transmit, knowledge without adopting it in a way that leaves an observable trace, before it is taken up more visibly by later scholars.*¹¹ *An approach based only on observable adoption would, by construction, miss such intermediate carriers and compress*

11. This is related to the literature on “Sleeping Beauties” and delayed recognition in science (Van Raan 2004; Ke et al. 2015), although here the latent period concerns the transmission of an idea rather than the delayed recognition of a published work.

exposure and adoption into a single event.

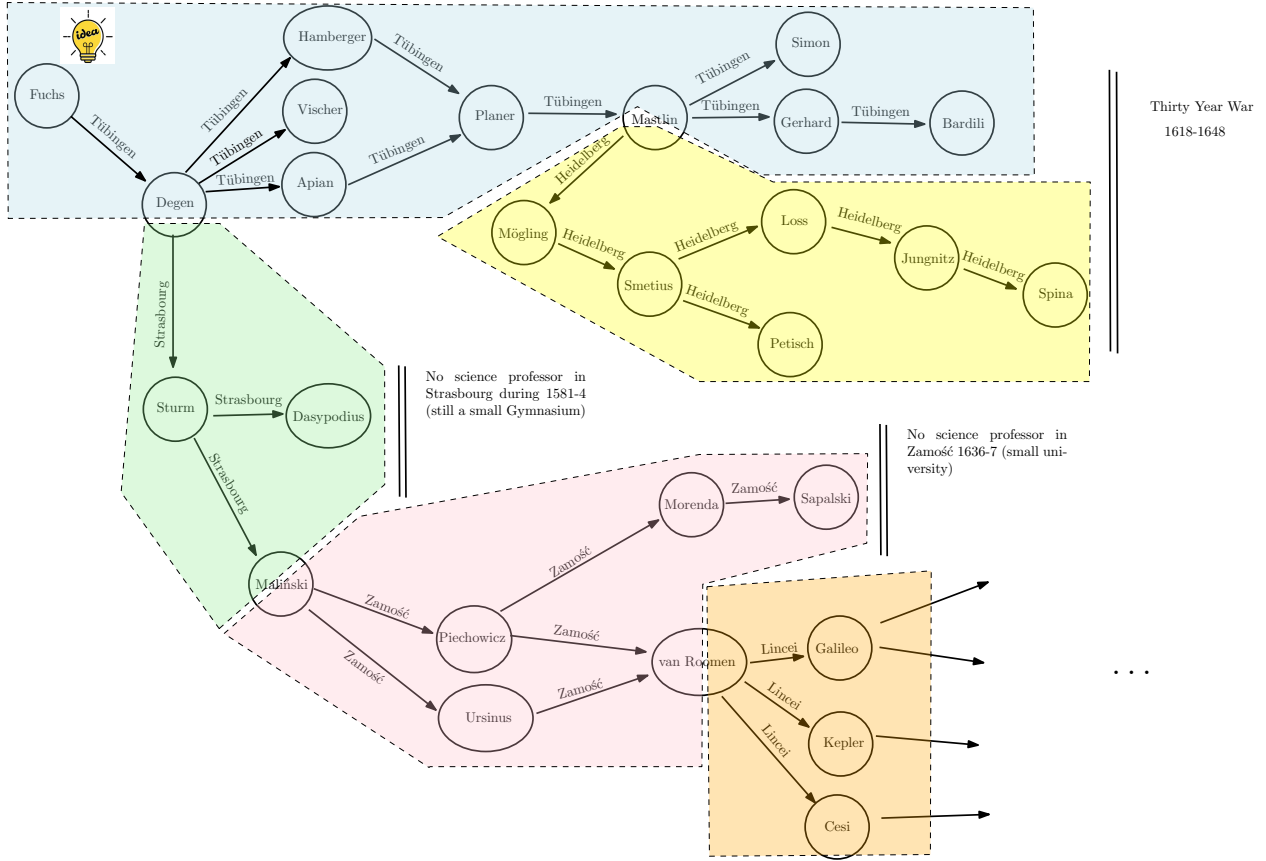


Figure 2: Hypothetical Botanical Realism path from Fuchs to van Roomen

For each value of α on the grid, we average over $D = 5,000$ simulations, and we compute for each headquarter k the Prevalence $P_t^{k,\varphi}$ of Botanical Realism as defined in Equation (5). We use the sample of cities that hosted at least one institution, either a university or an academy before 1800, as recorded in our database, resulting in a total of 241 cities, 230 of which have non-null Eligible Mass $M_t^{k,\varphi}$ of scholars susceptible to Botanical Realism. We also gather information on the existence and founding dates of European botanic gardens from Montreal Botanic Garden (1886). Figure 6 in Appendix C.2 illustrates this sample of cities along with their Prevalence $P_t^{k,\varphi}$ of Botanical Realism in 1600, 1700, and 1800.

In what follows, we analyze whether exposure to Botanical Realism raises the rate at which cities founded botanic gardens, taking the timing of first establishment as our outcome. The object of interest is not whether a city eventually establishes a botanic garden, but when. This makes the Cox proportional hazards model the natural specification. Its partial likelihood compares, at each observed founding date, only the cities still at risk, evaluating their covariates as of that date. It therefore accommodates time-varying regressors such as our measures of Prevalence $P_t^{k,\varphi}$ and Eligible Mass $M_t^{k,\varphi}$ without imposing any functional

form on the baseline hazard.

The use of the Cox model presents two additional advantages particularly convenient to the structure of our data. First, the very foundation of a garden may attract scholars active in botany, raising a city’s measured Prevalence *after* the event. Under Cox however a city exits the risk set at the garden’s founding date and contributes nothing thereafter, so only pre-founding variation in $P_t^{k,\varphi}$ enters the likelihood. By comparison, in a panel regression with city and year fixed effects, cities would remain in the sample throughout, and the coefficient would absorb prevalence that the garden itself generated. Second, some cities founded gardens early, before the idea had spread much (30 cities out of 68), and a few (2 out of 68) before it existed at all. In the Cox partial likelihood, each founding is compared against the time-varying covariate Prevalence of all cities still at risk that year. These early establishments happened at low or zero $P_t^{k,\varphi}$, while other cities in the risk set had higher values, so if anything, they push the coefficient toward zero, making our estimate conservative. This is also why an event-study design is ill-suited here (supposing we collapsed Prevalence from a continuous variable into a binary indicator), many cities would found their garden before their assigned treatment date, so they would have no pre-period and could not serve as controls for later-treated cities.

Following the Cox model, the instantaneous hazard $h_k(t)$ that a city k founds its first botanic garden at time t , conditional on covariates, is

$$h_k(t) = h_0(t) \exp(\beta_p P_t^{k,\varphi} + \beta_m M_t^{k,\varphi} + \beta_{pm} P_t^{k,\varphi} M_t^{k,\varphi} + \beta_{pop} Pop^k + \beta_d Dist^k) \quad (8)$$

where $h_0(t)$ is the baseline hazard. We include population in 1500, Pop_k , to account for broad differences in city size and the local resource base. Comparable city-level income measures are not available systematically over this period. This limitation is less restrictive for our outcomes than it would be for capital-intensive investments, since, as discussed above, the material threshold for the initial establishment of a botanic garden was relatively modest.

A related concern is that exposure may simply proxy for urban wealth, so that our estimates would capture rich cities acquiring infrastructure rather than academic diffusion. Premodern universities, however, were frequently located away from political capitals and leading commercial centers: Oxford and Cambridge rather than London, Louvain rather than Brussels or Antwerp, Padua rather than Venice, Pavia rather than Milan, Salamanca rather than Burgos, Sevilla or Madrid, Leiden rather than Amsterdam. Scholarly exposure is therefore far from collinear with economic or political primacy.

We also include the distance from Tübingen, $Dist^k$. In a simple gravity model of diffusion, distance from Tübingen captures the spread of the idea through pathways other than our affiliation network.

Our regressors of interest are time-varying and include the Eligible Mass of scholars, $M_t^{k,\varphi}$, that counts the number of botanists, physicians, and scientists susceptible to be exposed to Botanical Realism at time t in city k ,¹² the Prevalence of Botanical Realism, $P_t^{k,\varphi}$ (see Equation (5)), and their interaction term. The interaction allows for heterogeneous effects by institutional size: a negative sign implies that the smaller the Eligible Mass, the stronger the association between Prevalence and the ‘hazard’ of founding a botanic garden; a positive sign implies the opposite.

We consider the period 1500–1793. The first botanic garden in our data is observed in 1520 (Pavia). Fuchs’ invention dates to 1542, and our affiliation data runs through 1793. Cities that do not build a botanic garden during this period are treated as right-censored.¹³ We estimate the baseline hazard using the Nelson–Aalen estimator. The Cox model’s partial likelihood assumes no two events occur simultaneously. In our data, nine years record the founding of two botanic gardens, introducing ties that we handle using the Efron method, confirming robustness with the exact method.

Table 1: Cox Proportional Hazards Model – Botanical Realism and botanic gardens

α	Dependent variable: Hazard of botanic garden founding					
	0	0.1	0.3	0.5	0.7	1
Prevalence $P_t^{k,\varphi}$		27.91 (156.66)	7.45*** (2.16)	2.96*** (1.00)	1.93*** (0.63)	1.67*** (0.52)
(ihs) Eligible Mass $M_t^{k,\varphi}$	0.54*** (0.07)	0.57*** (0.19)	0.88*** (0.10)	0.90*** (0.10)	0.89*** (0.10)	0.89*** (0.10)
Prevalence $P_t^{k,\varphi}$ × (ihs) Eligible Mass $M_t^{k,\varphi}$		-26.69 (177.85)	-4.02*** (0.77)	-1.38*** (0.28)	-0.89*** (0.18)	-0.75*** (0.15)
(ihs) Distance to Tübingen	-0.15*** (0.06)	-0.19*** (0.07)	-0.12 (0.10)	-0.11 (0.07)	-0.11* (0.07)	-0.11* (0.06)
Log Likelihood $\ell_1(\alpha)$	-343.18	-342.51	-335.76	-335.28	-335.32	-335.28
(ihs) Pop in 1500	✓	✓	✓	✓	✓	✓
Observations	67620	67620	67620	67620	67620	67620

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.

Distance to Tübingen is computed using the Haversine formula. All models include (ihs) population in 1500. All the variables with (ihs) are transformed in inverse hyperbolic sine.

Table 1 shows the results for the Cox proportional hazard models at different levels 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 enter the joint maximization described in Section 3.

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

13. Because botanic gardens are established in only 68 out of 230 cities before 1793, we do not stratify the baseline hazard by city. Instead, we cluster standard errors at the city level.

3.3 Auxiliary model 2: Mathematical Astronomy

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 important shift, characterized by advances in trigonometry, geometry, and the use of decimals, laid the groundwork for the later Copernican revolution. A central figure in this groundbreaking transformation was Regiomontanus, a pseudonym of Johannes Müller. He studied the original works of Ptolemy through his mastery of Greek and mathematics, and around 1454 began collaborating with his mentor Georg Peurbach (1423–1461) at the University of Vienna 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, and published *Theoricæ novæ planetarum*, his collaboration with Peurbach, in 1472, after Peurbach’s death. He can thus be considered a pioneer of Mathematical Astronomy (Applebaum 2003). More details are available in Supplementary Material 4.2.

In this second empirical assessment, we examine whether cities more exposed to what we label Mathematical Astronomy—the transition towards higher mathematical precision in astronomical practice—were faster to establish astronomical observatories. Advances in trigonometry and decimal calculation created demand for more precise instruments and dedicated observation sites, providing a direct link between the diffusion of Mathematical Astronomy and the founding of observatories. Regiomontanus himself opened an instrument shop that specialized in building and printing works related to Mathematical Astronomy (Applebaum 2003). We collect the names and foundation dates of observatories from Howse (1986).

Here too, the material threshold for initial establishment was often modest. Systematic astronomical observation did not necessarily require a purpose-built monumental observatory: observing platforms for rooms could be installed in existing university buildings, towers, palaces, or private houses. What mattered for effective observation was access to appropriate instruments and clocks, together with astronomers possessing the knowledge required to use, calibrate, and maintain them. Large purpose-built observatories such as Paris or Greenwich represented the upper end of the investment distribution rather than a prerequisite for astronomical observation (R. W. Smith 2016).

For each value of α on the grid, the diffusion of Mathematical Astronomy begins with Regiomontanus, who shared it with his colleagues in Vienna, Bratislava, Padua, and Rome. Exposed scholars can in turn contaminate their own peers with probability α , and so the idea propagates through the network until 1793. Averaging over D simulations, we compute for each institution k the yearly Prevalence $P_t^{k,\varphi}$ of Mathematical Astronomy as defined in Equation (5), restricting to scholars working in fields such as mathematics, logic, physics,

chemistry, biology, astronomy, geography, and botany. Figure 7 in Appendix C.3 depicts the resulting exposure patterns in 1600, 1700, and 1793.

We estimate the hazard of establishing an observatory for each city using a Cox model identical to that used for Botanical Realism, replacing distance from Tübingen with distance from Vienna. We focus on the same period, 1500–1793, dating the spread of Regiomontanus’ ideas from 1454. The first observatory in our data was established in Kassel in 1560. Cities that do not establish an observatory by 1793 are treated as right-censored.¹⁴

Table 2: Cox Proportional Hazards Model – Mathematical Astronomy and observatories

	Dep. var.: Hazard of astronomical observatory creation					
α	0	0.1	0.3	0.5	0.7	1
Prevalence $P_t^{k,\varphi}$		6.39*** (1.94)	2.49*** (0.73)	1.83*** (0.53)	1.66*** (0.48)	1.62*** (0.45)
(ihs) Eligible Mass $M_t^{k,\varphi}$	0.46*** (0.07)	1.11*** (0.18)	1.11*** (0.19)	1.12*** (0.19)	1.11*** (0.20)	1.06*** (0.20)
Prevalence $P_t^{k,\varphi}$ × (ihs) Eligible Mass $M_t^{k,\varphi}$		-3.69*** (0.77)	-1.44*** (0.32)	-1.08*** (0.24)	-0.97*** (0.22)	-0.89*** (0.21)
(ihs) Distance to Vienna	-0.16*** (0.05)	-0.08* (0.05)	-0.09** (0.04)	-0.10** (0.04)	-0.10** (0.04)	-0.10** (0.04)
Log Likelihood $\ell_2(\alpha)$	-324.83	-316.08	-317.22	-317.31	-317.49	-318.04
(ihs) Pop in 1500	✓	✓	✓	✓	✓	✓
Observations	67620	67620	67620	67620	67620	67620

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.

Distance to Vienna is computed using the Haversine formula. All models include (ihs) population in 1500. All the variables with (ihs) are transformed in inverse hyperbolic sine.

Table 2 shows the results for the Cox proportional hazard models at different levels 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 enter the joint maximization described in Section 3.

3.4 Results

The joint likelihood $\ell_1(\alpha) + \ell_2(\alpha)$ achieves a maximum of -652.568 at $\hat{\alpha} = 0.45$, which we interpret as the estimated link activation probability. Appendix D reports the full likelihood table, and the Cox model results at $\hat{\alpha} = 0.45$. Figure 3 shows the likelihood visually.

At this stage, however, the flatness of the likelihood function around its maximum calls for some caution in interpreting the estimated value of α . We estimated several alternative specifications of the Cox model: with and without latitude, with and without urban

14. As with Botanical Realism, tied events are handled using the Efron method, with the exact method as a robustness check. There are 64 astronomical observatories in our sample.

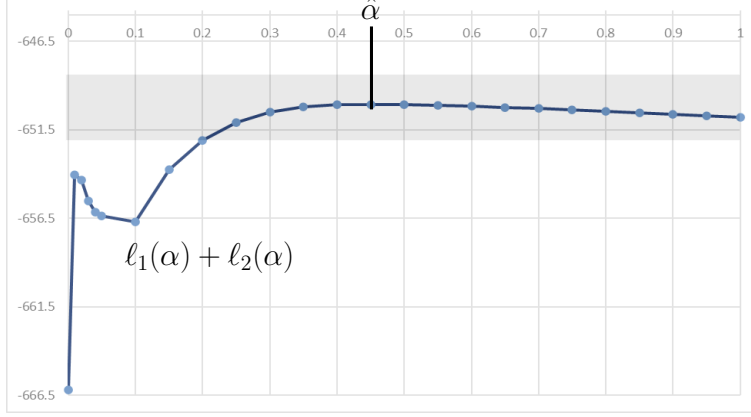


Figure 3: Plot of log-likelihood values for different values of α . 95% likelihood-ratio confidence set is light grey.

population, using population in 1400 rather than population at the date of invention, and controlling for pre-invention intellectual capacity, measured by the total stock of human capital across all fields. Reassuringly, all these specifications yield a maximum of the profile likelihood at $\hat{\alpha} = 0.45$. The location of the maximum is therefore remarkably robust to changes in the conditioning variables.

This robustness should not, however, be confused with precise identification. Figure 3 plots the profile likelihood for α together with the 5% likelihood-ratio cutoff. The resulting 95% likelihood-ratio confidence set is wide: values of α between approximately 0.2 and 1 cannot be rejected. Thus, although $\alpha = 0.45$ consistently provides the best fit, the data contain relatively little information for discriminating among a broad range of link-activation probabilities above roughly 0.2.

The reason is related to the way α affects diffusion through the network. Increasing α raises the probability that an idea is transmitted through an existing face-to-face link in any given year. Consequently, for a given date, a larger α produces more infected scholars and generally raises the measured exposure of institutions to the idea. Yet much of this change concerns the *level* of exposure rather than its *cross-sectional pattern*. Because diffusion takes place over the same underlying affiliation network, institutions that are highly exposed when α is low tend also to be highly exposed when α is high, while relatively peripheral institutions tend to remain less exposed. Changing α therefore modifies the speed and intensity of diffusion much more than it modifies which institutions are relatively more exposed.

This feature makes α intrinsically difficult to identify precisely from the Cox model. Identification comes from differences in exposure across institutions within the relevant risk sets. If changing α mostly rescales exposure while leaving its relative pattern largely unchanged, the estimated coefficient on exposure can partly compensate for this change. Different combinations of the link-activation probability and the Cox coefficient can then generate very

similar relative hazards and, consequently, very similar values of the partial likelihood. The data are therefore substantially more informative about *which* institutions are relatively more exposed to an idea than about the precise annual probability with which knowledge is transmitted at the micro level along each face-to-face link.

This weak identification leads us to adopt a deliberately conservative value of α in the remainder of the analysis. Rather than using the likelihood-maximizing value $\hat{\alpha} = 0.45$, we set $\alpha = 0.2$, corresponding approximately to the lower bound of the 95% likelihood-ratio confidence set. This choice should not be interpreted as an alternative estimate of the most likely value of α : the likelihood is maximized at 0.45. Instead, it is a conservative calibration designed to avoid overstating the contribution of face-to-face transmission to the diffusion of ideas. With $\alpha = 0.2$, each active link has a substantially lower annual probability of transmitting an idea than under the maximum-likelihood calibration, so that any role subsequently attributed to the affiliation network is obtained under relatively slow interpersonal diffusion.¹⁵

There is an additional reason for regarding this choice as a useful benchmark. Although the profile likelihood is flat over a broad range above 0.2, it falls much more rapidly for values below this threshold. Moreover, the location of this lower boundary is stable across the alternative Cox specifications considered above. The data therefore appear considerably more informative about how small α can plausibly be than about its exact value once it exceeds this lower range. We consequently fix $\alpha = 0.2$ throughout the remainder of the paper.

An important open question is whether α varies systematically across fields, periods, religions, institutional types, or other dimensions. Unfortunately, the available data do not permit a reliable estimation of such variation. A related concern is that, because the auxiliary outcomes reflect not only intellectual exposure but also the capacity and willingness of institutions to act on it, α may compound two distinct probabilities: that an interaction successfully transmits an idea, and that cumulatively, exposure translates into an observable institutional outcome. Disentangling the two would require an outcome that captures exposure independently of local material conditions at any given point in time: a measure that, to our knowledge, is not systematically recoverable for early modern European academia. Alternative proxies that might offer a more direct link to, say, *individual* (rather than in-

15. α is a probability per link and per year, so that $\alpha = 0.2$ does not imply slow diffusion within an institution. Two colleagues who overlap for two years transmit the idea with probability $1 - (1 - \alpha)^2 = 0.2 + 0.8 \times 0.2 = 0.36$, and with probability $1 - 0.8^{10} \approx 0.89$ after ten years of co-presence. Exposure also compounds across colleagues: a scholar with n exposed colleagues is exposed within the year with probability $1 - (1 - \alpha)^n$, that is, 0.67 for $n = 5$ and 0.87 for $n = 9$. In an institution with ten scholars active in the field of the idea, exposure thus becomes almost certain within a few years of the idea's arrival. The value of α matters mostly where links are few and short-lived, namely on the bridges between institutions created by mobile scholars and multiple affiliations.

stitutional) exposure with comparable coverage are equally unavailable. In a contemporary setting, for instance, citations to Fuchs or Regiomontanus could serve this purpose; in early modern Europe, however, not only were citation practices not standardized, but such a measure would in any case capture only the fraction of scholars who left a footprint in today’s libraries (estimated, for scholars in our database, at roughly one third), not the broader academic population through which ideas circulated.

Before interpreting the results, we verify the proportional hazards assumption—which requires that the effect of each covariate on the hazard remains constant over time—using scaled Schoenfeld residuals (Schoenfeld 1982). For Botanical Realism, the coefficients on Prevalence $P_t^{k,\varphi}$, and their interaction show no evidence of drift over time when tested individually, while Eligible Mass $M_t^{k,\varphi}$ is borderline at 5% significance level. The global test rejects proportionality ($p = 0.016$), driven by the distance to Tübingen control. We therefore verify robustness to allowing the effect of distance to Tübingen to vary linearly over time. The coefficients of interest remain substantively unchanged under this alternative specification, and our conservative choice of $\alpha = 0.20$ is unchanged. The corresponding estimates are reported in Appendix Table 5.¹⁶ For Mathematical Astronomy, the global test does not reject proportionality ($p = 0.215$), and the residual plots in Appendix E show no systematic drift. We proceed on this basis for both models.

We interpret results through hazard ratios, computed by exponentiating the estimated coefficients. Since Eligible Mass enters the Cox model in inverse hyperbolic sine, let $\widetilde{M}_t^{k,\varphi} = \text{asinh}(M_t^{k,\varphi})$. For Botanical Realism, the association between Prevalence $P_t^{k,\varphi}$ and the hazard of founding a botanic garden varies with Eligible Mass—and vice versa. At our preferred value $\alpha = 0.20$, the estimated coefficients are $\beta_p = 14.04$, $\beta_m = 0.82$, and $\beta_{pm} = -10.32$. The hazard ratio associated with a change $\Delta P_t^{k,\varphi}$ in Prevalence at a given level of Eligible Mass is therefore:

$$HR(\Delta P_t^{k,\varphi} \mid \widetilde{M}_t^{k,\varphi}) = \exp \left[\left(\beta_p + \beta_{pm} \widetilde{M}_t^{k,\varphi} \right) \Delta P_t^{k,\varphi} \right]. \quad (9)$$

Evaluated at average (ihs) Eligible Mass ($\mu = 0.93$), a one-standard-deviation increase in Prevalence ($SD = 0.038$) is associated with approximately a 19% higher hazard of founding a botanic garden.¹⁷ The negative interaction implies that the positive association between Prevalence and garden founding attenuates as the susceptible scholarly mass increases. Conversely, the positive association between Eligible Mass and garden founding becomes weaker

16. Allowing the coefficient on distance to Tübingen to vary over time leaves $\alpha = 0.20$ as the first simulated value within the 95% likelihood-ratio confidence set. The interpolated lower bound moves from approximately 0.20 to 0.16. In particular, $\alpha = 0.15$, although closest to the interpolated threshold, remains outside the 95% confidence set. On the other hand, the likelihood-maximizing value moves more substantially, from 0.45 to 0.35. This additional sensitivity of the exact maximum provides further motivation for relying on the conservative lower-bound value rather than on the maximizing value.

17. See summary statistics of the covariates in Table 2 in the Appendix.

as Prevalence rises. This pattern is consistent with a substitutability between the size of the susceptible scholarly pool and the share of that pool already exposed to the idea.

The pattern for Mathematical Astronomy is similar. At $\alpha = 0.20$, the estimated coefficients are $\beta_p = 3.39$, $\beta_m = 1.11$, and $\beta_{pm} = -1.97$. Evaluated at average (ihs) Eligible Mass ($\mu = 0.62$), a one-standard-deviation increase in Prevalence ($SD = 0.157$) is associated with approximately a 41% higher hazard of establishing an astronomical observatory. Again, the negative interaction implies that the association between Prevalence and institutional adoption becomes weaker as the susceptible scholarly mass increases.

Appendix F reports a series of alternative specifications at our preferred value $\alpha = 0.20$. The coefficients on Prevalence, Eligible Mass, and their interaction remain stable in sign, magnitude, and statistical significance across these specifications.

4 Scholasticism and Protestantism

In the analysis of Botanical Realism and Mathematical Astronomy, we examined both the correlation between the Prevalence (Equation (5)) of these ideas and the Eligible Mass (Equation (4)) of scholars, and the time required to establish a botanic garden or an observatory at the headquarters of institution k . We now extend our empirical analysis beyond the early modern period and the context of the Scientific Revolution by studying the relationship between exposure to scholasticism and the adoption of Protestantism. Unlike the auxiliary models in Section 3, this exercise covers a broad sample of European cities, including cities without academic scholars. For such cities, Prevalence and Eligible Mass are not meaningful concepts. We therefore use city-level exposure, as defined in Equation (7), which captures intellectual influences originating from nearby institutions.

Scholastic theology is an approach to theological questions that uses logical analysis and systematic reasoning, influenced by ancient Greek philosophers (see an example in Appendix G). 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 16th-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 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.¹⁸ To be clear, our hypothesis does not imply that scholastic reasoning was abandoned after the Reformation; on the contrary, Protestant theologians themselves later developed systematic theological frameworks that drew on scholastic method (Muller 1986). The backlash we posit concerns rather the popular reception of late medieval scholastic theology as institutionally practiced.

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

18. Theologian Matthew 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.

of ordination and apostolic succession. Instead, he emphasized the “priesthood of all believers” (*sola gratia*).

To test for a positive 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 yearly network snapshots built from our data, and our $\alpha = 0.2$.

Averaging the outcomes of many simulations, we compute the $S_t^{k,\varphi}$ exposure of each institution 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 1508, by institution. We then obtain the exposure to scholasticism of each institution in the network, using Equation (6). Figure 9 in Appendix I depicts this level of exposure. We can further compute the exposure to this paradigm for European cities even if they do not host any institution, as in Equation (7). We do this by computing the distance between each city in our sample and each institution in our network, and summing up institutions’ 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 1600.¹⁹ Figure 9 illustrates the sample of cities and the spread of Protestantism as in 1600. Cities that remained Catholic are shown in grey, while those that became Protestant are marked in red. The blue bubbles represent institutions’ exposure to scholasticism as in 1508. The figure already suggests a possible positive correlation between exposure to scholasticism, and the likelihood that a city would become Protestant.

We employ a linear probability model to 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, meaning hundreds of cities share the same event year. With ties of this magnitude, the partial likelihood approximation underlying the Cox model breaks down, and a linear probability model is more appropriate.

The top panel of Table 3 shows the results. The key variable of interest is exposure to scholasticism S_{1508}^c , whose estimated coefficient is consistently positive and statistically

19. 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 H.

significant in 1560 and 1600. Columns (1)-(3) show the variable of interest alone. Columns (4)-(6) show that the results are robust at the addition of controls and fixed effects. We control for the presence of all universities active in 1500 as indicated in our database to show that exposure to scholasticism S_{1508}^c is not merely proxying for the presence of a university. 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.²⁰ The remaining control variables are taken 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.

Using the estimated coefficients in the benchmark panel of Table 3, Columns (1)–(3), we quantify the association between scholastic exposure and the estimated probability of adopting Protestantism. Taking Louvain—the most exposed city in the sample—as a reference point, we evaluate how estimated Protestant adoption probabilities differ for other cities when exposure is set to Louvain’s observed level. For Barcelona, in the lowest quartile of the exposure distribution, the estimated probability is 9.4 percentage points higher in 1530, 37.8 percentage points higher in 1560, and 46.7 percentage points higher in 1600. The corresponding differences are 6.8, 27.1, and 40.7 percentage points for Copenhagen; 5.3, 21.3, and 32 percentage points for Padova; and only 0.1, 0.3, and 0.4 percentage points for Koln, whose observed exposure is already close to Louvain’s.

To rule out the possibility that the result reflects intellectual centrality rather than scholasticism specifically, we repeat the analysis replacing scholastic exposure with exposure to two contemporaneous but non-theological ideas: Practical Surgery and Civil Law (see Appendix J for further details and context). The placebo panels of Table 3 report the results alongside the benchmark regression. Neither idea predicts the adoption of Protestantism in any specification, reinforcing the interpretation that the association documented above is specific to scholasticism rather than to university culture or intellectual activity in general.

Two additional applications are reported in Section 5 of the Supplementary Material. First, exposure to scholasticism significantly amplifies the association between plague outbreaks and anti-Jewish persecutions. Second, the case of Olaus Rudbeck’s Atlantis hypothesis illustrates that affiliation networks can also transmit demonstrably false ideas and that exposure need not imply adoption or agreement.

20. 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 3: 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)
BENCHMARK REGRESSION WITH EXPOSURE TO SCHOLASTICISM						
Exposure to scholasticism S_{1508}^c	0.001 (0.001)	0.004*** (0.001)	0.006*** (0.001)	0.002** (0.001)	0.004*** (0.001)	0.004*** (0.001)
Adjusted R ²	0.016	0.107	0.193	0.503	0.719	0.737
PLACEBO REGRESSION WITH EXPOSURE TO PRACTICAL SURGERY						
Exposure to Practical Surgery PS_{1508}^c	-0.0001 (0.001)	-0.001 (0.002)	-0.002 (0.002)	-0.0004 (0.001)	-0.001 (0.001)	-0.001 (0.001)
Adjusted R ²	-0.001	0.003	0.008	0.499	0.708	0.727
PLACEBO REGRESSION WITH EXPOSURE TO CIVIL LAW						
Exposure to Civil Law CL_{1508}^c	0.001 (0.002)	0.001 (0.004)	0.001 (0.004)	-0.0001 (0.001)	-0.001 (0.002)	0.0001 (0.002)
Adjusted R ²	0.001	-0.001	-0.0005	0.499	0.707	0.726
Rubin's controls	✗	✗	✗	✓	✓	✓
Imperial Circle FE	✗	✗	✗	✓	✓	✓
1500 Country FE	✗	✗	✗	✓	✓	✓
Observations	867	867	867	867	867	867

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 H. “Exposure to scholasticism S_{1508}^c ”, “Exposure to Practical Surgery PS_{1508}^c ”, and “Exposure to Civil Law CL_{1508}^c ” are computed as in Equation (7). Rubin’s controls, selected from Rubin (2014), include: printing press by 1500, (ihs) city population in 1500, free imperial city by 1517, market potential in 1500, Hanseatic League membership by 1517, lay magnate, (arch)bishop by 1517, and access to water. We also include in all specifications the dummy variable “Presence of university in 1500”, taking value 1 if the city had a university in 1500 as in our database (De la Croix 2021).

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.

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 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 K 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.²¹

Figure 4 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 one case, the idea fails to spread: Wieliczki in Cracow (professor from 1513 to 1552) lacked other mobile peers for meaningful intellectual exchange, and 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

21. 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.

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. Appendix K.1 provides a more detailed discussion about this point. This implies that the distribution of successful ideas does not converge to a single stationary form, i.e. even as time progresses, the expected success of an idea remains contingent on the initial conditions. It also implies that outcomes across different realizations of the process do not average out over time (in an ergodic process, averaging over time should yield the same result as averaging over different realizations of the process: see Peters (2019) for a history of the idea of ergodicity).

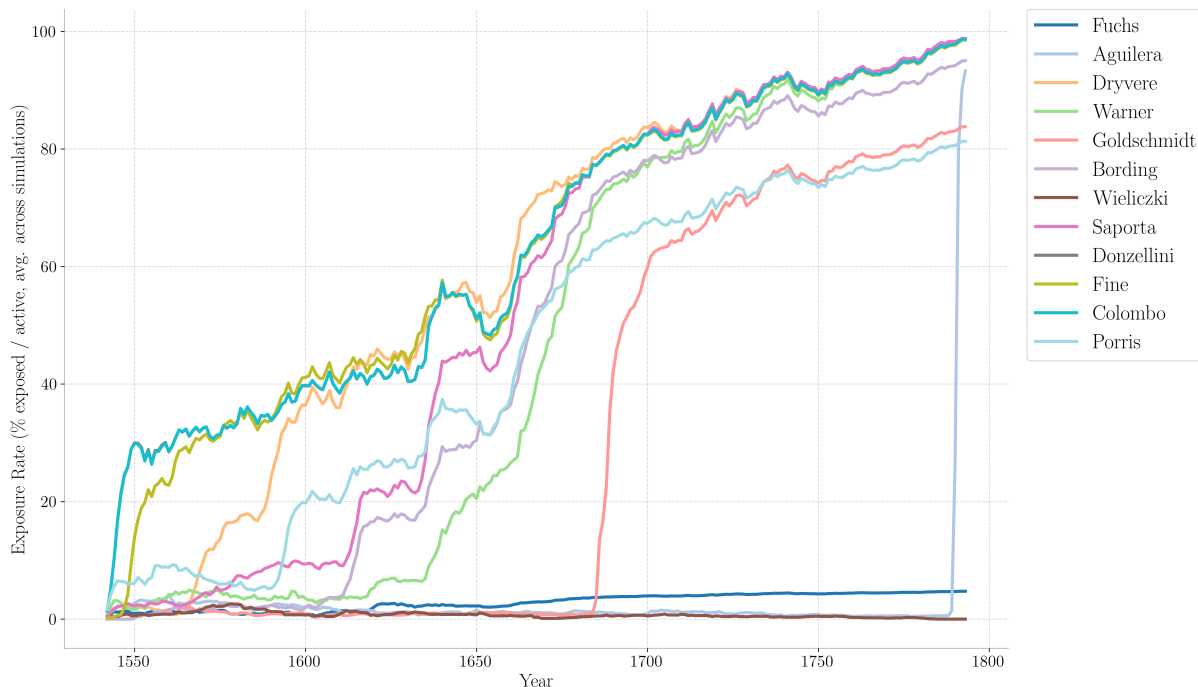


Figure 4: Exposure rates of active scholars in the network from 1542 to 1793, considering different hypothesized proponents of Botanical Realism.

The case of Fuchs is particularly interesting, as the diffusion of his herbal plateaus at around 5%, unlike the other simulations where ideas either reach full exposure or fade out entirely. This reflects the fact that, in roughly 95% of the simulations, Fuchs’ idea dies out quickly, keeping exposure at zero. In the other 5%, 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 twentieth.

The path shown in Figure 2 (Section 3.2) explains this fragility. The idea must leave Tübingen before the Thirty Years’ War, cross Strasbourg and Zamość, and reach the Lincei through a handful of scholars. Jakob Degen, Johannes Aeschines Sturm, Kasper Maliński, and Adriaan van Roomen are necessary for its survival. 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. 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 (7), 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 diffu-

sion 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 4, the line “No direct contribution” gives the exposure distribution when the direct contribution is shut down. Practically, we keep the vector of the individual exposures I_t^d from the benchmark but we remove academies’ exposure $S_t^{k,\varphi}$ from the computation of city exposure $S_t^{c,\varphi}$. 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 4: there are very few academies in 1600. The Ricovrati in Padua was 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 had essentially no influence on exposure to Botanical Realism at this early stage: the median exposure in 1600 remains unchanged at 0.64 in both counterfactual scenarios. Academies already played a more visible role in spreading Mathematical Astronomy, for which the median decreases by about 22% both when their direct contribution is removed and when academies are removed altogether. Even at this early stage, when academies were few and primarily informal, they therefore contributed to the dissemination of Mathematical Astronomy.

By 1650, academies had become important for both ideas. For Botanical Realism, removing their direct contribution reduces median exposure by about 17%, from 2.56 to 2.12, while removing academies altogether reduces it by more than 98%, to only 0.04. The corresponding declines for Mathematical Astronomy are about 25% and 71%, respectively. After 1700, the contribution of academies becomes increasingly substantial, both through their direct effect on nearby cities and through the additional connections they create within the academic network. The latter role is particularly important for Botanical Realism: without academies at all, its exposure falls to zero across all cities from 1700 onward. Mathematical Astronomy, by contrast, does not strictly depend on academies for its survival, but academies strongly amplify its diffusion. By 1793, removing only their direct contribution lowers median exposure to Botanical Realism by about 84%, from 40.62 to 6.59, while removing academies altogether eliminates exposure completely. For Mathematical Astronomy, the corresponding median falls from 261.77 to 37.14 when the direct contribution is removed, and to 11.64 when academies are removed altogether, a decline of more than 95% relative to the benchmark.

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

Table 4: Counterfactual experiment with and without academies.

Botanical Realism	Q1	Median	Q3
With academies in 1600	0.00	0.64	1.53
No direct contribution in 1600	0.00	0.64	1.53
No academies at all in 1600	0.00	0.64	1.53
With academies in 1650	0.93	2.56	4.24
No direct contribution in 1650	0.76	2.12	3.50
No academies at all in 1650	0.00	0.04	0.12
With academies in 1700	3.23	9.75	16.05
No direct contribution in 1700	2.12	4.86	7.57
No academies at all in 1700	0.00	0.00	0.00
With academies in 1750	6.15	20.21	31.08
No direct contribution in 1750	2.45	5.86	10.16
No academies at all in 1750	0.00	0.00	0.00
With academies in 1793	10.15	40.62	66.37
No direct contribution in 1793	2.25	6.59	11.57
No academies at all in 1793	0.00	0.00	0.00
Mathematical Astronomy	Q1	Median	Q3
With academies in 1600	0.00	3.30	9.07
No direct contribution in 1600	0.00	2.58	7.28
No academies at all in 1600	0.00	2.57	7.25
With academies in 1650	4.53	14.26	24.45
No direct contribution in 1650	3.26	10.71	19.11
No academies at all in 1650	0.00	4.13	14.24
With academies in 1700	14.63	44.64	71.48
No direct contribution in 1700	8.82	19.44	31.58
No academies at all in 1700	0.02	3.46	12.11
With academies in 1750	37.96	124.34	189.39
No direct contribution in 1750	14.15	33.72	58.29
No academies at all in 1750	2.08	10.02	18.94
With academies in 1793	69.62	261.77	428.69
No direct contribution in 1793	11.23	37.14	59.49
No academies at all in 1793	3.63	11.64	20.29

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

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 5: Counterfactual Experiment with and without European regions.

Botanical Realism	Q1	Median	Q3
No Italian Peninsula	0	0	0
No British Isles	8.99	30.74	58.48
No France	7.64	30.17	51.56
No Iberic Peninsula	10.01	40.35	66.18
No Holy Roman Empire	0	0	0
Benchmark	10.15	40.62	66.37
Mathematical Astronomy	Q1	Median	Q3
No Italian Peninsula	0	0	0
No British Isles	53.70	192.10	362.41
No France	48.09	199.54	334.35
No Iberic Peninsula	68.02	261.19	427.57
No Holy Roman Empire	67.78	250.17	400.61
Benchmark	69.62	261.77	428.69

Quartiles 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,²² one without the Iberian peninsula, and one without the Holy Roman Empire (as defined in 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 5. Each number is a summary statistic of the exposure $S_{1793}^{c,\varphi}$ of the cities’ distributions, together with the relative exposure distribution in the benchmark. The Italian Peninsula is necessary for both Botanical Realism and Mathematical Astronomy: when Italian institutions are removed, exposure falls to zero throughout the distribution for both ideas. For Mathematical Astronomy, the universities of Rome and Bologna were

22. 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).

critical hubs, allowing scholars previously exposed to Mathematical Astronomy in Vienna or Bratislava to continue disseminating it among their colleagues. For Botanical Realism, the result is consistent with the important role played by Italian institutions in the diffusion path described above, in particular the Accademia dei Lincei. Moreover, the Holy Roman Empire is also necessary for Botanical Realism, as expected given that the idea originates with Fuchs in Tübingen, but not for Mathematical Astronomy.

No other region appears necessary for Mathematical Astronomy to survive, although removing some regions substantially slows its diffusion. Without the British Isles, median exposure falls by about 27%, while without France it falls by about 24%. The corresponding declines for Botanical Realism are about 24% and 26%, respectively. Thus, the British Isles and France contributed substantially to the intensity of diffusion, but neither was indispensable for these examples of propositional knowledge. This is consistent with the distinction between the propagation of propositional knowledge considered here and the important role of the British Isles in the development and implementation of useful knowledge: Hallmann, Hanlon, and Rosenberger (2022), for example, show that British inventors worked on technologies that were more central within the innovation network (Mokyr 2011b). By contrast, the contribution of the Iberian Peninsula appears particularly limited: removing it lowers median exposure by less than 1% for Botanical Realism and by less than 0.3% for Mathematical Astronomy.

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 213 universities and colleges of some renown, and more than 6800 scholars (Jesuit priests)—approximately 8% of all recorded scholars between 1000 and 1800, a figure that rises to 11% 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. 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 6: Counterfactual experiment with and without Jesuits

Botanical Realism	Q1	Median	Q3
Benchmark	6.15	20.21	31.08
No direct contribution	5.64	18.58	28.24
No Jesuits at all	5.52	18.22	27.74
Mathematical Astronomy	Q1	Median	Q3
Benchmark	37.96	124.34	189.39
No direct contribution	32.68	107.61	161.77
No Jesuits at all	32.46	106.86	160.78

Quartiles of cities’ exposure distributions to ideas in the counterfactual network without Jesuits and the benchmark in 1750.

Table 6 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 some reduction in exposure, especially in peripheral regions largely neglected by non-Jesuit institutions (such as Sicily, Andalusia, and Romania). Given the widely recognized contributions of Jesuits to science—particularly astronomy—as evidenced by the many lunar craters named after Jesuit astronomers and the observatories they built (Udías 2003), this result is unsurprising. For Mathematical Astronomy, removing the direct contribution of Jesuit institutions reduces median exposure by about 13.5%, while removing Jesuits altogether reduces it by about 14%. The effect is smaller for Botanical Realism: removing their direct contribution lowers median exposure by about 8%, from 20.21 to 18.58, while removing Jesuits altogether lowers it by about 10%, to 18.22. Moreover, for both ideas the difference between removing only the direct contribution of Jesuits and removing Jesuits entirely from the network is relatively small. This suggests that much of their contribution operated through their direct presence in particular locations, while their additional role in connecting the broader academic network was more limited. One possible explanation is that Jesuits operated within a relatively isolated network, separate from the rest of academia. Appendix L supports this interpretation: the inbreeding homophily index of Jesuits (Coleman 1958) remains between 0.6 and 0.8 for most of the period 1556–1767 (Figure 12), indicating that Jesuit scholars were densely connected among themselves but only weakly connected to the rest of the network.

6 Conclusions

We have studied how academic networks in the premodern era provided support to 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 highlighted 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 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 treats the observed affiliation network as given. This is a limitation of our approach. In practice, the network arises from individuals' location choices, which are shaped by agglomeration forces and positive sorting. These forces are thus integral to the broader process we study. Mobilizing network formation theory would be a challenging next step.

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