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Enlightenment, Industrial Revolution, and the Knowledge Economy

Essays in (Macro-)Economic History

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Introduction

This dissertation researches the questions of what caused the Industrial Revolution and why did modern economic growth first commence in the West?

The first part on the causes of the Industrial Revolution starts from what appear to be two fundamental views in the economic history literature. One view seeks to explain it by comparing what happened in the "leader" Britain, the country where the new industrial technology supposedly originated, to what happened in the "follower" country France, which was more or less successful in adopting the industrial technology from Britain (e. g. Landes, 1969; Crouzet, 2003; Allen, 2009). Another view focuses on determinants of technological progress that are shared among (mostly Northwestern) European countries and contrasts them with technological developments in other regions of the world like China (e. g. Needham, 1969; Mokyr, 1990, 2016).

Chapter 1 documents novel stylized facts comparing the rate of inventive activity in Britain and France. Quantifying the technological leadership in invention at the sectoral level, as revealed by the relative propensity of France to imitate British inventions, the paper shows that the view of 'Britain leader, France follower' is too simplistic because both countries were leading in some industries. Moreover, it documents that inventive activity accelerated simultaneously in Britain and France across sectors, which only Europe vs. rest views can plausibly explain.

The result that something fundamental happened during the Industrial Revolution in Britain and continental Europe raises another question: Why did Britain's industry nevertheless grow faster than the French during the first half of the nineteenth century? Chapter 2 argues that, below the aggregate acceleration of inventive activity, Britain's inventors focused on technologies that were more central in the technology space (also called innovation network) and thus had a greater impact on technological progress and industrial productivity. Besides other innovations, the paper introduces a novel method to measure knowledge spillovers from patents without patent citation data to recover the technology space and the location of British and French inventors in it. Quantifications though the lens of a growth model suggest that the different allocations of inventors can fully explain difference in industry growth, summarizing the impact of all factors that shift research allocation into one statistic.

The second part of the dissertation focuses on the Enlightenment as one explanation for why modern economic growth first commenced in the West. One of several intellectual strands of Enlightenment, the "Industrial Enlightenment" arguably was most consequential for the creation and diffusion of useful knowledge of science and technology (Mokyr, 2002, 2016).

In addressing the diffusion aspect, chapter 3 studies the role of encyclopedias in accelerating technological progress by providing better access to useful knowledge. In particular, it considers two pivotal enlightenment encyclopedias, the *Encyclopédie* by Diderot and d'Alembert and *Déscriptions des Arts et Méties*, a monumental description of industrial technology prepared by the French Academy of Sciences. Based on sales data of these encyclopedias, the chapter shows that they had a causal impact on city growth by isolating plausibly exogenous variation in the supply of encyclopedias due to a combination of the local presence of booksellers and their wholesale access to the publishers.

In addressing the creation aspect, chapter 4 asks what created the human capital that mattered for developing the knowledge base of technological progress—the perhaps small but critical knowledge elite from which the "Cortesian army" was recruited (Mokyr, 2002)?[1] The novel—though perhaps not surprising—answer that emerges is science education. Based on a novel dataset in France ca 1500–1789 on secondary schools, philosophy tracks, and teachers/professors across disciplines, the paper documents a robust positive gradient of human capital (measured by encyclopedia readership) and the degree of science education. Furthermore, the paper shows that the establishment of science education in French secondary schools can be traced back to the Jesuits, who, in an environment of religious competition between Protestants and Catholics, firmly established math and science as part of the philosophy curriculum.

Evaluating the intellectual fruits of the time invested in researching these and related questions, I am certain that Newton's aphorism applies: "If I have seen farther, it is by standing on the shoulders of giants" (Merton, 1965). Have I actually seen farther? I think I have—even if some of my understanding of what actually happened is still too tacit to be explicitly formulated in the chapters of this dissertation. Who were the intellectual

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[1] "There hath not been wanting in all ages and places great numbers of men whose genius and constitution hath inclined them to delight in the inquiry into the nature and causes of things…But their Indeavours having been only single and scarce[ly] ever united, improved, or regulated by Art, have ended only in some small inconsiderable product hardly worth naming…wholly unfit & unable to conquer the difficultys of natural knowled[ge,] …this newfound world must be conquered by a Cortesian army, well-Disciplined and regulated, though their numbers be but small." —Robert Hooke, 1666 (cited after Mokyr, 2002, epitaph).

giants whose shoulders I climbed? Among them, I would like to highlight Davide Cantoni, who first introduced me to these questions; Oded Galor, who has been formative for what answers to seek; Joel Mokyr, whose influence goes beyond the many citations found in the following pages; and Uwe Sunde, whose support, guidance, and encouragement were but essential.

Furthermore, I would also like to thank explicitly my co-authors whose work has directly contributed to the thesis—Carl Hallmann, Walker Hanlon, Uwe Sunde, and Emre Yavuz—as well as my co-authors whose work is not included but has still contributed, Guillaume Blanc, Sebastian Öttinger, Alexander Patt, and Assaf Sarid. I have learned a great deal and enjoyed the time. Moreover, I would like to thank Tobias Roetheli for insisting that I should study for my master's at a very good university like LMU Munich. Finally, I would like to thank inspiring university teachers during my master's and doctorate; fellow students, colleagues, and almost advisors who provided feedback, suggestions, encouragement, or just a stimulating conversation; secretaries who helped to navigate administrative shallows; my academic hosts at Brown University and Northwestern University for enabling delightful and productive academic visits; Carsten Eckel for managing the doctoral training group (GRK) that provided much academic freedom; Joachim Herz Stiftung for financial support; and last but not least, my friends, family, and partner for their support!

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1 Invention and Technological Leadership during the Industrial Revolution

with Carl Hallmann and Emre E. Yavuz

This paper provides the first empirical cross-country evidence on inventive activity during the Industrial Revolution. Idiosyncrasies in the French historic patent law allow us to compare invention rates in Britain and France across sectors based on French patent data from 1791 to 1855. Our key result is a significant, quantitatively large, and robust positive association of invention rates in Britain and France at the sectoral level. Furthermore, we construct a quantitative measure of technological leadership in invention at the sectoral level. The evidence informs a debate about whether the acceleration of technological progress during the Industrial Revolution mainly was a British or a European achievement, which has implications for theories of growth and innovation.

1.1 Introduction

The Industrial Revolution is the watershed in human history that unleashed exponential income growth driven by technological progress, ultimately resulting in today's standard of living (Galor and Weil, 2000; Mokyr, 2002; Galor, 2011; Clark, 2014). This technological progress was fueled by an acceleration in the rate of inventive activity, which multiplied during the Industrial Revolution relative to the slow rate of pre-industrial times (Ashton, 1948; Landes, 1969; Mokyr, 1990, 1999). Commonly, Britain is perceived as the technological leader during the Industrial Revolution (Broadberry, 1994; Crafts, 1998). However, there is no empirical evidence of how large the British *technological leadership in invention* was.[1] Moreover, there is no consensus whether British technological leadership in invention can explain the aggregate acceleration in the rate of invention, or whether the rate of invention accelerated simultaneously in Britain and other European countries as France (Crafts, 2021).

Existing evidence cannot empirically distinguish the hypotheses proposed in the literature. On the one hand, it has been argued that invention was primarily constrained by demand (market size). As it was more extensive in Britain than elsewhere in sectors like coal, cotton, or steam, invention accelerated first in Britain, making her the technological leader. Then, ideas diffused to the European continent, which became a technological follower that imitated Britain (Landes, 1969; Allen, 2009a, 2017; *leader–follower hypothesis*). On the other hand, it has been argued that invention was primarily constrained by the supply of knowledge. Once this knowledge became available across Europe, invention accelerated across Europe, in particular in sectors as chemistry or machines where Britain and the European continent were technologically neck-on-neck (Mokyr, 1990, 2002, 2009a; *simultaneity hypothesis*). Both hypotheses have first-order predictions on invention and technological leadership in a setting with two (or more) countries and multiple sectors.

This paper uses a unique setting to compare invention rates across countries and sectors during the Industrial Revolution by observing domestic invention and the imitation of foreign inventions in France. During the period of the (first) Industrial Revolution, France was the main economic rival of Britain. The large majority of foreign inventions that were imitated in France originated in Britain. Using data on the universe of French patents 1791–1855, we are able to distinguish between invention and imitation patents and calculate invention and imitation patenting rates for almost all sectors of the economy.[2] Given that most imitation patents came from Britain, imitation patenting plausibly reflects invention in Britain. When comparing invention and imitation patents across sectors within France, we can account for country fixed effects and analyze how invention in France and Britain covaried between and within sectors.

Based on the British and French invention measures, we document novel stylized facts on technological progress and leadership during the Industrial Revolution. First, we provide the evidence on the association between the invention rate in Britain and the European continent across sectors. We find that invention and imitation patenting rates exhibit a significant, quantitatively large, and robust positive correlation. Second, we construct a quantitative measure of technological leadership in Britain compared to the European

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[1] We define technological leadership as an absolute advantage in invention, following the literature economic growth (e. g. Barro and Sala-I-Martin, 1997; Acemoglu, 2009).

[2] The only sectors which are not covered by the patent data are finance and pharmaceuticals.

continent. We find substantial variation in leadership across sectors in terms of how much France imitated from Britain relative to how much France invented domestically. The findings are consistent with the hypothesis that, on the aggregate, invention accelerated simultaneously in Britain and the European continent. Despite a sizable technological lead of Britain in some sectors and France in others, technological leadership mattered little for the aggregate acceleration in invention during the Industrial Revolution.

The first stylized fact is a significant, large, and robust positive association of invention and imitation across sectors. We document it at all three different levels of aggregation: Industries, sub-industries, and technologies. At the industry level, for example, the pairwise correlation of log imitation and log invention is 0.832 (p-value < 0.000) and the regression coefficient is 0.998 (std. err. $= 0.139$, $R^2 = 0.69$), implying that a one percent increase in invention is associated with a one percent increase in imitation. The positive association is robust to including fixed effects for industry or sub-industry, which rule out (sub-)industry composition effects as an explanation. Furthermore, the (sub-)industry fixed effects rule out alternative explanations that vary at the (sub-)industry level, for example, secrecy instead of patenting (Moser, 2012, 2013). The positive association also holds within sub-periods and before the acceleration of GDP per capita growth ("take-off") around 1830.

The second stylized fact is a pronounced variation of technological leadership across sectors, with Britain leading in some sectors, France leading in others, and Britain and France being neck-on-neck in yet others. The key metric is the revealed relative technological lead, which we calculate as the sectors' imitation intensity relative to the average imitation intensity. As we do not observe total invention in France and Britain directly, the measure does not by itself inform about absolute differences in inventiveness across countries. Nevertheless, we can quantify the absolute technological lead between France and Britain by combining the measure with historical case studies. First, we validate the leadership ranking with available case studies of absolute technological lead in France or Britain and rule out that one country was absolute leader in every sector. Second, we back out the absolute lead for all sectors based on a case study evidence on technological equality between France and Britain in applied sciences and applied mathematics. For example, at the technology level, we estimate Britain was about three times as inventive as France in spinning and steam engines, France was about twice as inventive as Britain in hydraulic pumps and watches, while they were equally inventive in chemical products and motors other than steam engines.

In sum, the evidence supports predictions of both hypotheses yet clearly distinguishes which hypothesis can explain what. As we explain in section 1.3.1, the simultaneity hypothesis predicts a positive association of the invention rate in Britain and France but no technological leadership. In contrast, the leader–follower hypothesis predicts a negative association of invention rates and significant technological leadership. Hence, the first stylized fact speaks clearly in favor of the simultaneity hypothesis as an explanation for the aggregate acceleration of the invention rate. In contrast, the second stylized fact of variation in technological leadership confirms a prediction of the leader–follower hypothesis, suggesting that both hypotheses are necessary to explain all data features.

The key feature of our setting that makes it possible to distinguish invention and imitation patents is distinct patent categories. The baseline category for invention is the “patent of innovation,” which could be obtained by the French inventor, whose priority was protected, for an idea that was novel and related to production. The baseline category for imitation is the “patent of importation,” which could be obtained by anyone who first patented a foreign idea in France, irrespective of priority or whether it was already patented abroad. In all other regards, the “innovation” and “importation” patents were the same. This idiosyncratic setting with imitation patents makes the French patent data a registry of domestic and foreign ideas present in France because it (a) documented stealing of ideas by imitators, which might otherwise have taken place clandestinely, and (b) incentivized the actual foreign inventors to register their ideas in France despite relatively high patent prices.

Beyond the patent categories, we adjust the invention and imitation measures with additional information to obtain more accurate measures of French invention and British invention. We define invention as the set of (technological) ideas invented in France, and imitation as the set of ideas invented abroad and transmitted to France.[3] We classify “patents of innovation” as imitation if they have a foreign (British) connection, which we see as an indication that the idea was potentially invented abroad and transmitted to France. In particular, we identify the country location of all addresses given by the patentee and classify patents as imitations if they had a foreign (primarily British) address. Moreover, we predict the nationality of all patentees based on their last names (British vs. French last name) and classify patents as imitations if they had a British last name. Finally, we measure invention and imitation as total patenting expenditure to capture systematic variation in the economic value of patents. The expenditure variation resulted from a mix of ex-ante patent duration choice (longer patents were more expensive than shorter ones) and ex-post patent renewal choice, both of which reflect the patentees’ private information about their patent’s (expected) economic value.

The paper relates to several literatures that span the fields of economic history, macroeconomics, and innovation. The paper contributes to studies of the rate of invention and

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[3] The definition follows the literature on international technology diffusion (Keller, 2004; Comin and Mestieri, 2014).

technological progress in Britain and the European continent during the Industrial Revolution by providing the first quantitative comparison of British to continental—here, French—invention rates. The empirical evidence on invention in Britain is relatively abundant. The first contributions which evaluated patent data were by Dutton (1984), MacLeod (1988). Sullivan (1989) showed that patenting in Britain accelerated in all major sectors of the British economy. Temin (1997) showed that technological progress must have accelerated in all (manufacturing) sectors of the British economy. Meisenzahl and Mokyr (2012) analyzed the determinants and characteristics of inventors, and Hanlon (2020b) showed how engineers became the dominant group of inventors over time. However, this evidence is isolated from the (comparatively scarce) evidence on invention in other countries. Among the few studies for France, Khan (2016) studies the role of female inventors, Galvez-Behar (2019) presents several statistics on French patents, and Nuvolari, Tortorici, and Vasta (2020) study the connections of French to British patents.[4] Our paper connects this literature by documenting the rate of invention in France and Britain within the same legal and economic environment. By observing British invention indirectly in terms of imitation patents in France, which can readily be compared with invention patents in France, we overcome problems associated with direct comparisons of national invention registers, including selection—which ideas are included—and quality—how valuable are included ideas.

Furthermore, the paper contributes to studies of international technology diffusion and of technological leadership during the Industrial Revolution by providing the first systematic, quantitative evidence on idea diffusion from Britain to the European continent and technological leadership of Britain relative to the continent across almost all industries and technologies. There exist case studies for some sectors that document anecdotal evidence on idea diffusion, imitation by France, and British technological leadership (Landes, 1969; Harris, 1998; Allen, 2009b). Several recent papers study the diffusion and adoption to the production of British technologies within France, notably of spinning machines and steam engines (Juhász, 2018; Franck and Galor, 2021, 2022).[5] Our quantitative evidence on imitation and technological leadership puts these case studies into context by providing the first quantitative evidence on how imitation varied across industry and technology and the first quantitative evidence on the size of technological leadership based on invention measures. Indeed, we confirm that spinning and steam engines were among the technologies Britain was most technologically ahead of France, but the finding also implies that these

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[4] For invention in other countries as Germany, see Donges and Selgert (2019) who study patent data from Württemberg and Dittmar and Meisenzahl (2020) who provide quantitative evidence based on a scholarly catalog of important inventions. Sáiz (2014) studies importation patents for Spain.

[5] Juhász, Squicciarini, and Voigtländer (2020) study within France firm-level dynamics in the spinning industry as compared to paper and metal industry.

sectors are different regarding technological lead and do not represent the aggregate. There is one previous study that documented industry-level specialization and leadership in terms of output per worker (O'Brien and Keyder, 1978). Here, we provide evidence on specialization and leadership in terms of technological creativity (invention), which is closer to the definition of technological leadership in the growth literature (Barro and Sala-i-Martin, 2003; Acemoglu, 2009), and disaggregate industries into sub-industries and technologies. Furthermore, our results are affected by limited data availability and questionable data quality of sectoral output and labor force in Britain and France before 1840.

We follow the macroeconomic literature in distinguishing between invention or idea growth (e. g. Romer, 1990; Jones, 2005; Jones and Romer, 2010; Jones, 2016), imitation or idea diffusion (e. g. Eaton and Kortum, 1999; Lucas Jr, 2009; Buera and Lucas, 2018), and adoption or idea implementation (e. g. Benhabib and Spiegel, 2005; Comin and Mestieri, 2014, 2018). In this paper, we focus on invention and imitation. Technological leadership has been analyzed, among others, by Grossman and Helpman (1991); Barro and Sala-I-Martin (1997); Acemoglu, Aghion, and Zilibotti (2006); Benhabib, Perla, and Tonetti (2014); König, Lorenz, and Zilibotti (2016); Buera and Oberfield (2020); Benhabib, Perla, and Tonetti (2021). That idea diffusion results from imbalances in invention among economies close to the technology frontier has been documented by Eaton and Kortum (1999) and Peri (2005) based on data of cross-national patent registration or patent citations, respectively.

Our finding of the invention rate's simultaneous acceleration in France and Britain is consistent with several economic mechanisms. One group of mechanisms highlights complementarities and knowledge spillovers between ideas, for example due to sequential innovation (Scotchmer, 1991; Bessen and Maskin, 2009), general purpose technologies (Helpman and Trajtenberg, 1996; Helpman, 1998), or combinatorial growth (Weitzman, 1998). Another group of mechanisms highlights that invention and imitation arise simultaneously in a given sector because they require the same knowledge or human capital as inputs (Cohen and Levinthal, 1989; Griffith, Redding, and Van Reenen, 2003; Griffith, Redding, and Reenen, 2004; Aghion and Jaravel, 2015), in the sense that "good innovators make good imitators" (Landes, 1969, 28). Either group of mechanisms points to idea diffusion among countries as critical, either for the realization of knowledge spillovers or for sharing a joint knowledge base as input. As a result, the invention rate would accelerate jointly in Britain and France in the same industries and technologies.

Our finding that there was variation in technological leadership at the sectoral level but that it mattered relatively little for the aggregate acceleration in the rate of invention during the Industrial Revolution relates to a debate whether relative prices explain both rate and direction of technological change. Differences in relative factor prices influence the direction of invention (Acemoglu, 2002; Hanlon, 2015), yet it is theoretically ambiguous whether they also cause a higher aggregate rate of invention (Acemoglu, 2007). In the context of the Industrial Revolution, Allen (2009a,b, 2017) argues that relative prices of energy—coal—varied between Britain and France (and the rest of the world), causing Britain to invent more in coal intensive technologies.[6] Reversely, Mokyr (2009a) argues that in France, water power was relatively cheaper than coal, causing France to invent more water-power intensive rather than coal intensive technologies. Indeed, the pattern of technological leadership we find is consistent with these arguments, as coal-intensive sectors are among those with the largest lead of Britain, and water-intensive sectors are among those with the largest lead of France. The finding of a positive association of invention in France and Britain does not preclude that directed technical change contributed to accelerating invention in some sectors. However, it clearly shows that directed technological change cannot explain the aggregate acceleration—unless it simultaneously affected both Britain *and* France compared to the rest of the world, contrary to the argument by Allen (2009a, 2017) that it explained why Britain would industrialize earlier than France.

1.2 Historical evidence

1.2.1 Invention and technological leadership

Anecdotal evidence on breakthrough inventions suggests a pattern that technological leadership varied between Britain and France across sectors. The famous British breakthrough inventions came from the industries of machines, textiles/spinning, and metals. In machines, the breakthroughs were Newcomen's atmospheric engine in 1712 and Watt's separate condenser and other improvements during 1780s (Mokyr, 1990, 85-7).[7] In spinning, they were Hargreaves' spinning jenny in 1764; Arkwright's water frame during the 1770s; and Crompton's mule in 1779 (Mokyr, 1990, 96-7). In metals, they were Darby's coke smelting process in 1709 and Cort's puddling iron making process in 1784 (Mokyr, 1990, 93). The famous French breakthrough inventions came from the industries of chemicals, textiles/weaving, food, and paper. In chemicals, the breakthroughs were Berthollet's invention of chlorine bleaching (bleaching water) in 1784 and Leblanc's artificial soda making in

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[6] Allen (2009a,b, 2017) also argues that labor was more expensive in Britain due to high wages, yet the factual basis of this argument has recently been questioned (Humphries and Weisdorf, 2019).

[7] Newcomen's atmospheric engine was the first functioning steam engine and based on the concept of a fire engine developed by the French scientist Denis Papin Cohen (2004). Watt's improvements allowed the application of the steam engine outside of coal mining.

1787 (Mokyr, 1990, 107); in weaving, the Jacquard loom in the 1800s (Mokyr, 1990, 100);[8] in food, the invention of food canning by Appert in 1795 (Mokyr, 1990, 140); and in paper, the continuous paper-making machine by Robert in 1798 (Mokyr, 1990, 106). These examples are consistent with economic mechanisms that predict British inventors specialize in some sectors and French inventors in others.

While this contraposition of examples suggests clear technological leadership in invention of either Britain or France in a given sector, the actual size of leadership is unclear because British and French inventors also contributed to sectors where the first breakthroughs originated in the respective other country. In textiles/spinning, the spinning machine of Hargreaves was anticipated by two French machines (McCloy, 1952, 91-2).[9] Also, another breakthrough in spinning, the wet spinning of flax, was invented in France by de Girard in 1810 (Mokyr, 1990, 103). In machines, some of the earliest applications of steam engines to transportation originated in France, including the first steam tractor in 1770 and the first (successful) steamboat in 1783 (McCloy, 1952, 28-9, 36-7).[10] Reversely, bleaching powder, which had superior industrial qualities to the original French invention, was invented in Britain by the Scot Tennant in 1799 (99 Mokyr, 1990). Also, the continuous paper-making machine was improved and made practical and economical by in London (Mokyr, 1990, 106). These anecdotes suggest that both countries could have contributed to invention in many sectors, independent of the question of which country was leading and how large the technological lead was.

Indeed, anecdotal evidence suggests that invention in Britain and France could have been positively related due to knowledge spillovers and complementarities between ideas. Instead of specialization of British inventors in some sectors and French inventors in others, ideas could have been combined across borders to create new and better ideas. For example, the invention of gas lighting resulted from an international collaboration among German,

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[8] The Jacquard loom was a programmable loom that used punch cards to store information, "one of the most sophisticated technological breakthroughs of the time." Bouchon and Falcon pioneered the use of punch cards to store information in the 1720s, and de Vaucaçcon improved the punch card reader in 1775 (Mokyr, 1990, 100-1).

[9] One machine the French Academy of Sciences approved of as novel and useful in 1745 (it spun three threads simultaneously, Hargreaves' spinning jenny spun eight). For the other machine invented in 1755, the Academy awarded the inventor a grant of 5000 Francs.

[10] The steam truck was invented by Cugnot and is said to have inspired Trevithick's locomotive. The steamboat by Jouffroy d'Abbans was the first successful one because angry boatmen scuppered an earlier steamboat by D'Auxiron before the first test boating. Jouffroy d'Abbans applied for a royal privilege (proto-patent) but was required to transport the steamboat from Lyon to Paris that it would be evaluated there. However, without covering the expenses, he was effectively denied the proto-patent as there was no river or canal connection of Rhône and Seine rivers, and the boat was unsuitable for high sea circumnavigation of the Iberian peninsula (McCloy, 1952, 31-36). The first commercially successful steamboat was operated by the American Fulton in 1807 (Mokyr, 1990, 88).

French, and Anglo-Saxon inventors. The potential use of gas as a light source was first pointed out in the late 1780s by the Belgian Minkelers and the German Pickel. The first lamp which used gas was invented by Lebon in 1799 (so-called thermolamp), based on a lamp invented by the French Argand in the early 1780s.This invention used gas derived from wood, which was unpopular because burning wood gas created an unpleasant smell. Thus, coal gas, first derived by the Scot Murdock in 1798, was superior because it did not smell disagreeable. Later, the English Clegg and Malam respectively perfected gas distribution and invented the gas meter, which allowed substantially better commercial operation of the technology.

The notion that ideas diffused across borders to cross-fertilize invention is embedded in several statements of contemporaries. For example, a Swiss printer observed upon visiting Britain in 1766 that "[the English] cannot boast of many inventions but only of having perfected the inventions of others . . . for a thing to be perfect it must be invented in France and worked out in England" (cited after Mokyr, 1990, 240). To the same effect reported in 1829 "an eminent engineering consultant of London" to a parliamentary committee that

> "we have derived almost as many good inventions from foreigners, as we have originated among ourselves. The prevailing talent of English and Scotch people is to apply new ideas to use, and to bring such applications to perfection, but they do not imagine so much as foreigners; . . . " (cited after Musson and Robinson, 1969, 63-4).

In sum, the anecdotal evidence suggests that national specialization and technological leadership could be less relevant for a high rate of invention. Instead, it could be the case that the larger the available stock of knowledge and ideas, and the more inventors in both countries working on the same problems, the larger the total rate of invention. In this interpretation, the diffusion of ideas across borders would make ideas available everywhere, cross-fertilizing inventiveness and preventing double research efforts. Our empirical evidence will show whether the rate of invention was higher in industries and technologies where both countries contributed inventions and where the technological lead was small.

1.2.2 International diffusion of inventions

Through which routes did inventions diffuse among countries? Among the multitude of routes were periodicals and journals (Mokyr, 2005), private and business correspondences (e.g., Musson and Robinson, 1969, 216-31), the bilateral migration of inventors to Britain (e.g., Musson and Robinson, 1969, 61-4) and to France (e.g., Buchanan, 1986, 509-10), or travels for industrial espionage (e.g., Crouzet, 1996, 39). Before the French revolution, the French state supported the systematic imitation of British technology. Masters, skilled workers, and engineers were poached to relocate to France, introduce new machinery and other state-of-the-art production processes, and train French workers. Even whole factories were copied and installed in France, as was the case with Arkwright's spinning factory, which used water-powered machinery to card cotton fibers and spin cotton yarn (Harris, 1998, ch. 15). After the French revolution, "[g]overnment had given up industrial espionage, but private enterprise stepped in: there were agencies which obtained from England machines which it was prohibited to export and also procured English workmen" (Crouzet, 1996, 39).

As for the diffusion of inventions from France to Britain, one illuminating example of the multitude of channels of diffusion is the case of chlorine bleaching of textiles. Chlorine bleaching of textiles was invented by the French Berthollet, who shared his discoveries with others both through personal contact and communication and through publications in scientific journals. One of Berthollet's direct contacts was James Watt, to whom he demonstrated his bleaching experiments when Watt visited Paris in 1786 and who had an interest in applying the invention as his father-in-law McGrigor was a bleacher. Subsequently, Watt and McGrigor set out to experiment with industrial-scale textile bleaching while Watt and Berthollet kept up their correspondence and exchanged information about experiences and subsequent improvements (Musson and Robinson, 1969, 262-98). Berthollet had also demonstrated the process to the Frenchmen Alban and Vallet, who ran the Javel chemicals firm. They set up company in Liverpool around 1787 to produce and manufacture bleaching water (Musson and Robinson, 1969, 273-85). Berthollet's invention also diffused to Britain through other private and public channels. For example, the French inventor Argand, a common friend of Berthollet and Watt, shared information directly with British entrepreneurs in London (Musson and Robinson, 1969, 264). Further, as Berthollet published his experiments and results in scientific journals, readers in Britain who were familiar with foreign and especially French scientific publications also knew about it (Musson and Robinson, 1969, 287-88). Finally, earlier experiments by the Swedish chemist Scheele, which had already suggested the potential of applying chlorine to bleaching, were known to scientists in Britain who passed it on to entrepreneurs (Musson and Robinson, 1969, 289).

The main barrier to idea flows was the war between Britain and France, which started with the French Revolution in 1792 and continued basically through the end of Napoleon's reign in 1815.[11] For British technologies that were already present in France at the outbreak of the war, like cotton spinning machines, the disruption of trade and protection from British competition, particularly during the Continental Blockade in 1806–13, provided incentives for widespread adoption of British technology (Juhász, 2018). For other technologies and new ideas generated between 1791 and 1815, the war obstructed idea flows across country. It became more difficult for French entrepreneurs to transfer tacit knowledge and hire British workers (cf Crouzet, 1996, 38). Likewise, it became more difficult for British industrialists to acquire new ideas despite being "well equipped to profit from international friendships" (Musson and Robinson, 1969, 230).

In sum, there is much anecdotal historical evidence for idea flows *in both directions* between Britain and France during the Industrial Revolution. Certainly after the removal of the diffusion barrier in 1815, the diffusion of invention from Britain to France, which we define as imitation, will represent inventions in Britain that had not yet been discovered in France (reversely for the diffusion of invention from France to Britain). Our empirical analysis will use patent data to document the diffusion of invention to France and indirectly measure invention in Britain.

1.3 Empirical framework

1.3.1 Predictions

In a two-country, two-sector setting, the simultaneity and leader–follower hypotheses can be illustrated as follows. Denote countries by B (Britain) and F (France), and suppose there are two sectors, one dynamic with a large acceleration of the rate of invention (e. g. steam engines), the other traditional with a small acceleration of the rate of invention (e. g. ceramics/glass). Figure 1.1, panel (b) illustrates the simultaneity hypothesis. Invention in both countries B and F are roughly balanced and, as a result, imitation and idea flows between them. In the dynamic sector, invention and imitation are large, while in the traditional sector, invention and imitation are small. Neither country is a technological leader in any sector. Figure 1.1, panel (a) illustrates the specialization hypothesis. In the dynamic sector, B has a high invention rate, leading to large idea flows and imitation of B in F. In the traditional sector, F has a somewhat lower invention rate, leading to a somewhat

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[11] The French Revolution and subsequent wars also negatively affected invention in France, which is observable in the patent data, where patenting drops to zero in the years of terror 1793-4. The effect probably worked both through economic channels (price controls and occasional expropriation of businesses) and the execution of influential scientists and inventors, among which the most famous was the chemist Lavoisier.

lower imitation of F in B. There will be reverse idea flows in any empirical application, but if they are smaller than the main flow, then B is the technological leader in the dynamic sector and F leader in the traditional one.

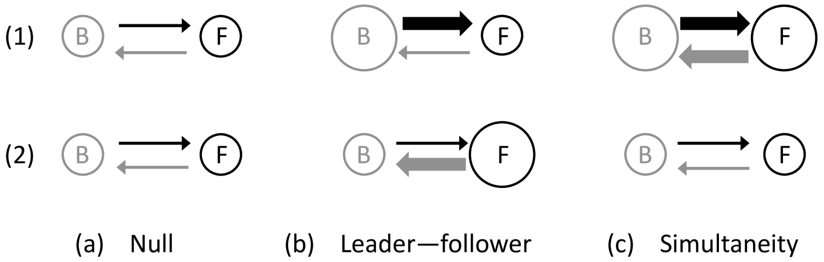

Figure 1.1: Hypotheses in two country, two sector setting. Circle size proportional to invention rate. Arrows denote idea flows (international technology diffusion), with arrow size proportional to rate of imitation.

The hypotheses differ in their predictions regarding the covariance of invention across sectors and regarding technological lead. Our empirical approach is to take the perspective of one country in which we can observe local invention and foreign invention indirectly through incoming idea diffusion (imitation). In this setting, the simultaneity hypothesis predicts that domestic invention and imitation covary positively across sectors. Within sectors, it predicts that the ratio of imitation to invention does not significantly differ from the average ratio of imitation to invention, implying no technological leadership. In contrast, the simultaneity hypothesis predicts that domestic invention and imitation covary negatively across sectors. Within sectors, it predicts that the ratio of imitation to invention will differ significantly from the average ratio of invention to imitation, implying large variation in technological leadership.

1.3.2 Ideas and patents

We define ideas as productivity improvements of technologies.[12] We posit the following reduced form idea production function, which is symmetric for France and Britain $c \in \{F, B\}$

$$N_{c,i} = A_c \, A_i \, \eta_{c,i} \tag{1.1}$$

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[12] For our empirical setting, it does not matter whether the productivity improvements result from quality ladders or expanding varieties. In fact, it could be a mix of both.

where A_c are country shifters, A_i are sector shifters, and $\eta_{c,i}$ are “inventiveness” parameters for France and Britain in sector i.[13] Each idea is represented by one patent, and can be patented only once. In our data, we observe French invention patents $N_{F,i}$ and imitation patents M_i for sectors i. Imitation patents represent a share $\alpha \in (0,1)$ of British inventions,

$$M_i = \alpha N_{B,i} . \tag{1.2}$$

In appendix 1.A.2, we justify this assumption and explain further implications, which do not affect our empirical strategy.

1.3.3 Association of invention and imitation

The core prediction that we test is whether invention in France and Britain covary positively or negatively across sectors, that is, whether $\mathrm{Cov}(N_F, N_B) > 0$ or $\mathrm{Cov}(N_F, N_B) < 0$. To implement the hypothesis test, we rewrite it as the following linear regression,

$$\ln M_i = \beta_0 + \beta_1 \ln N_{F,i} + \epsilon \tag{1.3}$$

where the prediction is $\beta_1 > 0$ if the simultaneity hypothesis is more important and $\beta_1 < 0$ if the specialization hypothesis is more important. [14] The reduced form idea production function tells us that equation (1.3) estimates

$$\ln A_i \eta_{B,i} = \widehat{\beta}_0 + \beta_1 \ln A_i \eta_{F,i} + \epsilon , \tag{1.4}$$

where $\widehat{\beta}_0 = \beta_0 + \beta_1 \ln A_F - \ln A_B$ controls for the country fixed effects.

Hence, we do not know whether the result $\beta_1 > 0$ was caused by the sector shifters A_i or by $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) > 0$. (In contrast, $\beta_1 < 0$ must be due to $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) < 0$.) Nevertheless, the result will inform which hypotheses can explain the acceleration in invention during the Industrial Revolution. Suppose that $\beta_1 > 0$ and that $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) < 0$. Then, the positive covariance of invention in France and Britain must be due to the sector shifters A_i. Therefore, whatever the differences in market size between France and Britain, be they caused by directed technological change towards coal intensive technology or some other factor, such cross-country differences are less important than a common

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[13] Endogenous growth theory typically models the inventiveness $\eta_{c,i}$ as a combination of the quantity of researchers and their research efficiency (Romer, 1990, e. g.).

[14] To see why it is equivalent, start from $\beta_1 = \frac{\mathrm{Cov}(\ln N_F, \ln M)}{\mathrm{Var}(\ln N_F)}$. Then, using (1.2), it follows because $\mathrm{Cov}(\ln N_F, \ln M) = \mathrm{Cov}(\ln N_F, \ln \alpha N_B) = \alpha\, \mathrm{Cov}(\ln N_F, \ln N_B)$ is proportional to $\mathrm{Cov}(N_F, N_B)$ (linear positive transformation), and $\mathrm{Var}(\ln N_F) > 0$.

sector shifter which increased invention in both countries simultaneously.

Nevertheless, we can go deeper and ask whether “inventiveness” was positively or negatively associated between France and Britain, i.e. whether $\mathrm{Cov}(\eta_{B,i}, \eta_{F,i}) \lesseqgtr 0$. Put differently, we would like to estimate

$$\ln A_i \eta_{B,i} = \gamma_0 + \gamma_1 \eta_{F,i} + \gamma_2 \ln A_i + \epsilon \tag{1.5}$$

and know whether $\gamma_1 \lesseqgtr 0$. This result would inform the relative strength of economic mechanisms that predict a positive or negative covariance of “inventiveness” across countries. For example, if knowledge spillovers from complementarities between invention across countries were more powerful than directed technical change, we should find that $\gamma_1 > 0$.

Our strategy is to estimate equation (1.5) at the level of a more disaggregated sector (technology) using fixed effects for more aggregate sectors plus additional controls. To do so, we first rewrite the reduced form idea production function as $N_x = A_x\, A_i\, A_j\, \eta_{x,i,j}$, where i denotes (sub-)industries and j technologies. Then, we can estimate

$$\ln A_i A_j \eta_{B,i,j} = \gamma_0 + \gamma_1 \eta_{F,i,j} + \phi_i + X_j \delta + \epsilon \tag{1.6}$$

where ϕ_i are industry or sub-industry fixed effects and X_j additional controls for technology characteristics.

1.3.4 Technological leadership

To measure technological leadership, we introduce the concept of revealed relative technological lead.[15] For sector $i \in 1, \ldots, I$, it can be calculated as

$$\mathrm{RRTL}_i = \frac{\frac{M_i}{N_{F,i}}}{\frac{1}{I} \sum_I \frac{M_i}{N_{F,i}}}\,. \tag{1.7}$$

Given the reduced form idea production function (1.1), the revealed relative technological lead measures

$$\mathrm{RRTL}_i = \frac{\eta_{B,i}/\eta_{F,i}}{\overline{\eta_B}/\overline{\eta_F}}\,, \tag{1.8}$$

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[15] The concept is inspired by the revealed comparative advantage from the trade literature (Proudman and Redding, 2000).

where $\eta_{c,i}$ is the country c inventiveness in sector i and $\overline{\eta_c}$ the aggregate (average) inventiveness of country c. Note that, different to the cross-sectional regression (1.3), the sector shifters A_i cancel out due to the within sector comparison of British to French invention.

The revealed relative technological lead compares, for a given sector, the observed inventiveness of Britain to that of France relative to the observed ratio of aggregate inventiveness. It ranges from zero (maximal French lead) to $+\infty$ (maximal British lead), with 1 denoting equality. Thus, a $\text{RRTL}_i = 0.5$ will mean that France was twice as inventive as Britain compared to the aggregate relative inventiveness, and a $\text{RRTL}_i = 2$ that Britain was twice as inventive as France compared to the aggregate relative inventiveness. As the revealed relative technological lead is non-linear when computed by (1.7), we will rescale it for empirical applications by using the natural logarithm. In logs, negative values correspond to a relative French lead, zero to relative equality, and positive values to a relative British lead. Additionally, the absolute distance from zero will symmetrically measure the size of the technological lead.

The revealed relative technological lead refers to a relative advantage in inventiveness. What can we learn from it about absolute advantages? The problem is that the ratio of aggregate inventiveness in Britain and France, $\overline{\eta_B}/\overline{\eta_F}$, is not identified. As a result, it could be the case that one country had an absolute advantage in every sector i. Fortunately, this case is implausible given historical case-study evidence that at least one sector with $\text{RRTL} < 1$ had an absolute technological lead in France and at least one sector with $\text{RRTL} > 1$ had an absolute technological lead in Britain. Furthermore, because the available case-study evidence on absolute technological lead in France or Britain generally aligns well with $\text{RRTL} \lesseqgtr 1$, we can conclude that the ranking of sectors in terms of technological leadership is meaningful. However, we will still not know the value of RRTL for absolute technological equality. We will discuss the historical case-study evidence, which allows us to draw these conclusions after presenting the main result on the revealed relative technological lead, in section 1.5.2.

Moreover, the revealed relative technological lead can be used to estimate the absolute technological lead based on the absolute lead for one single sector. Suppose we have historical case-study evidence for sector k that Britain was about as inventive as France, $\eta_{B,k} \approx \eta_{F,k}$. Then, we can estimate the absolute technological lead for other sectors $\eta_{B,i}/\eta_{F,i}$, $i \neq k$ as follows

$$\frac{\eta_{B,i}}{\eta_{F,i}} = \frac{\text{RRTL}_i}{\overline{\eta_B}/\overline{\eta_F}} = \frac{\text{RRTL}_i}{\overline{\eta_B}/\overline{\eta_F}} \frac{\overline{\eta_B}/\overline{\eta_F}}{\text{RRTL}_k} \frac{\eta_{B,k}}{\eta_{F,k}} \approx \frac{\text{RRTL}_i}{\text{RRTL}_k} \tag{1.9}$$

where the first equality is the rearranged equation for RRTL_i and the second equality follows from expanding and dividing by RRTL_k. Again, we will discuss historical case-study evidence for one such sector k after the main result in section 1.5.2.

1.4 Data

Our principal data set covers the universe of French patents from 1791 to 1855 and is provided by the French National Patent Office (INPI).

1.4.1 Background on French patents

The patent law was enacted in 1791 and remained essentially unchanged until 1844.[16] It replaced an earlier institution of proto-patents and state-granted financial rewards that existed since the seventeenth century. Patents could be obtained for novel ideas related to production in all areas except finance, pharmaceuticals, science, or unlawful things.[17] They were granted based on the requirement to pay a fee and deposit a technical documentation. Patent duration varied between 5 and 15 years. After expiry, the invention entered the public domain. The patent office did not verify the information given, nor did it evaluate novelty or usefulness. Instead, courts validated the patent claim and the technical documentation ex-post during disputes about priority or infringement suits. If the information given was found faulty, the court could invalidate the patent as a whole.

There were two principal categories of patents: First, the "patent of innovation" (*brevet d'innovation*), the standard category for inventions, which was essentially the same as it is today. Second, the "patent of importation" (*brevet d'importation*), the category for the first introduction of a foreign invention. Such importation patent could be granted to anyone, be they imitator or true inventor, if they were the first to patent the idea in France and if the idea was not already present in France. Thus, the copying and stealing of foreign technology were legal for the first person who documented the act of imitation by registering a patent. The category existed until the reform of the patent law in 1844.[18] The patent categories were non-exclusive, and some patents were both "patent of innovation and importation."[19]

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[16] The following history is based on Beltran, Chauveau, and Galvez-Behar (2001) and Galvez-Behar (2008). Galvez-Behar (2019) provides a valuable summary in English.

[17] In the patent law of 1791, it was not clearly defined what constituted a patentable idea. The 1844 reform defined it more precisely as a new product or a new method or a new application of a known method in industrial production (Beltran et al., 2001, 31).

[18] The reform reserved the foreign inventor the exclusive right to apply for a patent in France and created the new category "foreign patent."

[19] There was an additional category, the "patent of improvement" (*brevet d'amélioration*, after 1844 *certificats d'addition*). It allowed the inventor to modify the patent of invention or importation and add improve-

The patent duration was determined by a patent expenditure choice along two dimensions. First, patents could be obtained for five, ten, or fifteen years at the cost of 300 Franc, 800F, or 1500F, respectively, plus a registration fee of 50F. This choice was made with the registration of the patent. Second, the patent fee was paid in two installments, the first half at registration and the second half six months later. If the patentee defaulted on the second installment, the patent was in a protection gray-zone for up to two years until the default was officially publicized.[20]

Patents were not exactly cheap considering that the cheapest patent cost 200F whereas, in 1847, the median daily wage for male non-agricultural workers was 1.8F, but the fees were probably not prohibitive.[21] Hence, the patent fee worked as a screening device in an open registration system and provided an incentive for patentees to form an expectation about the economic value of their idea.[22]

1.4.2 Distinguishing invention and imitation patents

Following the literature on international technology diffusion (Keller, 2004; Acemoglu, 2009; Comin and Mestieri, 2014), we define *imitation* as the set of (technological) ideas that were invented abroad and transmitted to France. This definition of imitation is appropriate given our goal to measure the international idea diffusion from Britain to France. We consider

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ments and extensions to an existing patent without taking out another one. Improvements were linked to the original patent, did not prolong its duration, and would expire with it. We do not consider improvements in the baseline analysis because it is not clear whether they constituted a new idea.

[20] Defaults were publicized in lists of expired patents about every other year in the official government law paper (*Bulletin de lois*). (The lists excluded regular patent expiries after 5, 10, or 15 years.) Until the next edition of the expiry list, only the patentee and persons who consulted the patent document in the patent office would know about the default.

The INPI dataset reports whether patents expired but not whether the reason was a default or a court invalidated it. Nevertheless, defaults constituted most likely the large majority of expired patents, as evidenced by the large spikes in the number of expired patents in the INPI data in years when such expiry lists were publicized in the *Bulletin de lois*. Based on this evidence, we estimate that the expiries in our data were true defaults within a margin of error below 10 percent.

[21] The median daily wage is calculated from Chanut, Heffer, Mairesse, Postel-Vinay, Boccara, Sicsic, Strauß, and Verley (2000). Concerning the question of whether the patent fee was prohibitive, what matters is the income and access to capital of *inventors*. Inventors came by and large from the upper end of the income distribution based on patentees' occupation titles. However, we observe inventors only conditional on patenting, which leaves open the possibility of selection into patenting based on capital access. To address this issue, one can consider as a metric of accessibility the frequency of one-off inventors, who plausibly had, on average, worse access to capital. Nuvolari et al. (2020) find it to be similar to the USA, where patents were much cheaper relative to the median wage, which suggests that the French fees were not prohibitive.

[22] MacLeod, Tann, Andrew, and Stein (2003) argue similarly for the case of Britain where patents cost $100 plus registration fees. (One pound was about 25 Francs. Both currencies adhered to the gold standard, $1 was 7.3g fine gold, 1F was 0.29g fine gold.)

patents as invention if there is neither definite nor potential evidence that they could be an imitation. In total, we observe 11387 patents in the period 1791–1844.

The definite evidence for imitation is the patent category "importation." The category can include both imitation in the narrow sense by a proper imitator and imitation in the broader sense by an original inventor who is foreign. In the period 1791 to 1844, there were 1,512 importation patents. For 605 of them, a French name and address (see next paragraph) indicate that they were most likely imitations in the narrow sense. For the rest, we do not know whether the foreign-based or foreign national patentee was an imitator in the narrow sense or the actual inventor. Nevertheless, as our definition clarifies, both should be considered as evidence for imitation.

The evidence for potential imitation is that patentees of "innovation" category patents have some foreign connection. Foreign actual inventors could use either innovation or importation category. Thus, we need to identify actual foreign inventors within the innovation category, for otherwise, we will likely underestimate imitation by France. We consider foreign nationality and foreign address as the primary indicators of a foreign connection. As the historical patent office did not record the nationality of patentees, we infer nationality from their last names based on a two-step procedure that combines dictionary approach and machine learning algorithm to classify names as French or British.[23] The addresses of patentees were fully recorded by the historical patent office, even if a patent agent was involved.[24]

In total, we classify as imitation 1026 innovation patents with an indication of a foreign connection. For 700 innovation patents, we find a British named patentee with a French address, which is consistent with the historical evidence that there was migration of British inventors, engineers, and mechanics to France (Buchanan, 1986; Harris, 1998; Bensimon, 2011). For 109 innovation patents, we find a British named patentee with a British address, indicating an actual foreign inventor who protected their idea in France by taking out a standard patent instead of an importation patent. For 217 innovation patents, we find a French named patentee with a foreign address. This group includes, but is not limited to,

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[23] First, we create a dictionary of French and British last names from the sample of all people on Wikipedia (Wikidata) born in France or Britain during the eighteenth or nineteenth century and classify the unambiguous names. Then, we train a random forest on this data, classifying names as British and French with an out-of-sample accuracy of more than 95%. We use the algorithm to classify missing and ambiguous last names and reject implausible dictionary entries. Appendix 1.A.3 provides more details.

[24] In the British data until 1850, only the addresses of the patent agent are known in many cases. We identified the exact location of the addresses using Google Map API. For France, we matched latitude–longitude to historical mainland départements in the borders of 1830 (Friendly and Dray, 2020). That means we exclude Corsica, the Savoy départements, which came to France around 1860, the colonies, and regions in Belgium and Germany that were occupied and belonged to Napoleonic France at the time of patenting.

British nationals with Huguenot emigrant ancestry[25] and French emigrants to Britain from the heyday of the French Revolution (Franck and Michalopoulos, 2017). In appendix 1.B.2, we show that our results are quantitatively robust when we instead drop the innovation patents with a foreign connection.

1.4.3 Aggregating patents to sectors

We aggregate invention and imitation patents to the nested sectors of industry, sub-industry, and technology. We create 30 industries by re-grouping the industry classification from INPI. The goal is to create a technologically and economically sensible industry classification that is not too fine (at least 100 patents per industry) and can be matched to the French industry census of 1839–46 (Chanut et al., 2000).[26] For sub-industries, we use the classification provided by INPI that gives 94 sub-industries in total, of which 21 are small and have less than 30 patents in total during the observation period. Technologies are unique keywords assigned to the patents at registration until 1852 by the historical patent office based on the technical documentation. We obtain 587 technologies in total, of which 251 are small and have less than ten patents per technology.[27]

When aggregating patents to sectors, we adjust for variation in the patents' economic value—in short, patent quality—to get more accurate measures of invention and imitation. In general, it is well known that the quality of patents varies widely across patents (Schankerman and Pakes, 1986; Griliches, 1990; Nuvolari and Tartari, 2011 for Britain during the Industrial Revolution). This variation might not get averaged out when counting the total number of patents per sector. Therefore, we adjust for variation in quality by weighting patents with patent expenditure. This quality measure exploits the inventor's willingness to pay for patents. It assumes that inventors have private information on the expected economic value of patentable ideas and are willing to spend more on patents if they expect a higher value.[28] The French patent system provides two margins of willingness to pay, the patent duration choice at registration and the renewal/expiry choice after six months.

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[25] Harris (1998) documented many cases where Huguenot emigrant's connections to France were used for technology transfer from Britain.

[26] The industry census provides information on output and value added (output minus value of raw materials and energy) in Francs.

[27] The INPI applied the industry classification of 1904 retrospectively to the data from 1791 to 1852 based on the keywords. INPI harmonized the historic keywords during digitization to reduce redundancy, which results from using different words for the same concept or from different spelling. We use the harmonized version of the keywords provided by INPI and corrected a few further such redundancies in the harmonized keywords.

[28] Mokyr (2009b) argued for Britain that the median actual economic value of patented ideas could have been below the patent price, which was about 2500F in Britain (compare footnote 22).

The resulting quality-adjusted invention and imitation measures provide a lower bound estimate of ideas' true expected economic value. Within the 3×2 expenditure categories, we effectively price the patents at the marginal value. The obtained ranking of sectoral invention and imitation patenting will reflect the distribution of the true economic value of ideas accurately under the following condition. Let $F(\cdot|g)$ denote the distribution of expected patent values within sector g. If for any two industries their respective $F(\cdot|g)$s can be ranked according to the criterion of first-order stochastic dominance, then the ranking will preserve the true expected economic value of ideas.

1.4.4 Descriptive evidence

We first document patenting rates over time. Figure 1.2 compares the time trends of invention and imitation patenting in France to that of Britain. Note that the British imitation patenting is proximate because it is not possible to adjust for address or nationality as in France. (For British patents, we do not know the inventor if a patent agent registered the patent.) Nevertheless, the figure shows that invention patenting rates accelerated in parallel in both countries, as did imitation patenting rates. The acceleration was particularly fast around 1820–1830, which coincides with the acceleration of GDP per capita growth rates (the "take-off" in economic growth). Figure 1.3 zooms in on France and documents that invention and imitation patenting accelerated in parallel within France, such that their shares in total patenting were broadly constant over time. This evidence motivates us to sum patenting rates over the entire period 1791–1844 in the baseline analysis and only consider the cross-sectional variation. In the robustness analysis, we show that we obtain quantitatively similar results for sub-periods.

1.5 Main results

1.5.1 Association of invention and imitation

We begin by documenting the association of invention and imitation rates in the imitation–invention-space. As argued in section 1.3.1, the simultaneity hypothesis predicts a positive correlation, whereas the leader–follower hypothesis predicts a negative association. To interpret the hypotheses geometrically, plot the "average line" whose slope equals total imitation over total invention (the denominator of the revealed technological lead). If invention and imitation rates are strongly positively associated across sectors, observations will be scattered closely around the average line. Inversely, if invention and imitation rates are strongly negatively associated across sectors, observations will be scattered far away from the average line (orthogonal to its slope).

Figure 1.4 graphs our main result of a strong, positive association of invention and imitation expenditure at the industry level. The pairwise correlation coefficient in logs is 0.832 (p-value < 0.0001). Graphically, one can observe that the variation in the direction of the average line, leading to a positive association, is much more considerable than the variation in the orthogonal direction, which would lead to a negative association.

A significant concern with the industry level result is that it could be an artifact of aggregation to industries. Any assignment of patents to unique industries is necessarily imperfect (Griliches, 1990). Furthermore, it could be driven by a composition effect of summing over negative correlations within industry at different levels or of grouping technologies in a way such that the negative correlation is obscured.

Disaggregated evidence at the technology level shows that the positive association of invention and imitation is no artifact of aggregation. Figure 1.5 shows the same strong, positive association of invention and imitation at the technology level. The pairwise correlation coefficient in logs is 0.674 (p-value < 0.0001). Moreover, figure 1.6 shows that the result holds equally within industries. It appears that invention and imitation are positively associated within every single of the 30 industries. In sum, the geometrical evidence plausibly rules out aggregation and composition effects as an explanation.

We next move to regression analysis because it allows us to infer the sign of the association while controlling fixed effects and covariates. Table 1.1 presents OLS regressions of log imitation on log invention at different levels of aggregation.[29] All regression coefficients on log invention are statistically different from zero at the one percent significance level. At the industry level (column 1), the regression coefficient is 0.998. Thus, at the mean, a one percent increase in invention is associated with a one percent increase in imitation, implying a linear, positive association of invention and imitation. At the sub-industry level, the regression coefficient is 0.851 without industry fixed effects (column 2), 0.761 including industry fixed effects (column 3), and 1.075 if we drop small sub-industries with less than 30 patents. Furthermore, the adjusted R^2 increases by less than 5% from columns (2) to (3). At the technology level, the regression coefficient is 0.694 without fixed effects (column 5), 0.699 including industry fixed effects (column 6), 0.749 including sub-industry fixed effects (column 7), and 0.924 if we drop small technologies with less than ten patents. The inclusion of fixed effects improves the adjusted R^2 by about 10 percent.

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[29] Using logs is appropriate here because invention and imitation patenting follow a log-normal distribution. However, it implies that we lose some observations, particularly technologies, with zero invention or imitation.

The regression results have two implications. First, they show that the positive association of invention and imitation—that is, of the invention rates in France and Britain—is a granular feature of the data that holds both at all levels of aggregation, including the most disaggregated level of technology. Second, they show that while industry and sub-industry shifters have some explanatory power, they are not a first-order determinant of the positive association. As seen through the lens of our empirical framework, if sector shifters were relevant, they must have primarily operated at the level of technology but not at the level of industry or sub-industry. Furthermore, it appears likely that the covariance of the inventiveness in France and Britain, η_F, η_B, was positive. This would suggest that invention in both countries cross-fertilized each other because of complementarities between ideas or the sharing of a joint knowledge base.

Robustness: Technology characteristics One concern with this conclusion is that the positive association of invention and imitation could be a spurious outcome of some technology level characteristic that drives up invention and imitation mechanically but should not be considered a sector shifter of the idea production function. One such characteristic could be the age of technologies because younger technologies could have on average less of both invention and imitation while older technologies could have more of both. We measure age as years since the first patent within technology in 1855. Another characteristic could be the complexity of technologies because more complex technologies may have lower "technological opportunities," implying that it is generally more challenging to improve existing ideas by creating new inventions. We classify technologies as complex if they require engineering knowledge (Hanlon, 2020a) or scientific knowledge (Mowery and Rosenberg, 1989) for invention and adaptation.[30] Finally, one such characteristic could be foreign and principally British origin because British origin technologies will probably have more imitation on average and might also have more invention as a result of spillovers from imitation on invention. We measure foreign origin by whether the first patent within technology was an imitation.

Table 1.2 shows that the positive association of invention and imitation is highly robust to controlling for technology characteristics that could drive it mechanically. We first show that the technology characteristics predict a higher imitation patenting rate individually (conditional on industry fixed effects). The coefficient of 0.04 on the age of technologies (column 1) implies that a ten years older technology does have, on average, 40 percent more imitation patenting. (It also has more invention patenting, not reported.) The coefficient of

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[30] We code as complex all technologies in the fields of steam and motors, transport (railways, vehicles, ships, aviation), chemicals, electricity, precision instruments, printing, and photography.

0.41 on the complexity indicator (column 2) implies that a complex technology does, on average, also have about 40 percent more imitation patenting, though the coefficient is not precisely estimated. Similarly, the coefficient on the foreign origin indicator implies that such technologies have, on average, significantly more imitation patenting. Then, we include the technology characteristics jointly with log invention and industry fixed effects, one by one (columns 5 to 7) and all together (column 8). We find that the coefficient on log invention is highly robust as it varies between 0.653 and 0.721, which is well within the range of the baseline estimate without technology characteristics of 0.699 (std.err. 0.047). As for the technology characteristics, the coefficient of age becomes a precisely estimated zero, that of complexity stays positive but drops by half and becomes insignificant, whereas that on foreign origin doubles and predicts significantly more imitation, yet without affecting the coefficient on invention. Only the indicator for foreign origin appears to improve the regression fit (by about 10 percent). In sum, we find evidence of more imitation in technologies of foreign origin and some such evidence for more complex technologies, yet no evidence that technology characteristics would explain the association of invention rates in Britain and France.

Robustness: Sub-periods One concern is that the positive association between invention in Britain and France emerged only after the major acceleration in the aggregate rate of invention. As shown in figure 1.2, patenting accelerated around 1820/1830 in both Britain and France. In table 1.7, we split the sample in 1830 and replicate the regressions of log imitation on log invention at industry, sub-industry, and technology level, including fixed effects for more aggregate levels where applicable. We find that all estimated coefficients stay significant before and after the acceleration of the aggregate invention rate. Also, the magnitude of coefficients is similar for the two sub-periods and the whole period, with the only exception for the technology level estimate before 1830, which is about 1/3 smaller. We also find that the standard errors are smaller after 1830, which is as expected given the increase in patenting rates that allow observing invention and imitation more precisely. In sum, the evidence shows that the positive association existed already before the acceleration of invention.

1.5.2 Technological leadership

Figure 1.7 documents the revealed relative technological lead at the industry level. Britain had the largest relative lead in the maritime, mining, railways, and textile/spinning industries. The coefficients imply that Britain was 2.1 times as inventive in the maritime industry as France relative to the average relative inventiveness, in mining 1.9 times, and 1.7 times in railways and textile/spinning. France had the largest relative lead in the watchmaking, furniture, music, and health industries.[31] Here, the coefficients imply that in watchmaking, France was 2.4 times as inventive as Britain relative to the average relative inventiveness, in furniture 2.2 times, in music two times, and in health (which includes medical and hygiene inventions, but no pharmaceuticals) 1.9 times. Between those industries with the largest lead in Britain or France, many industries are close to the average ratio of relative inventiveness, including machines (Britain 1.26 times as inventive), chemicals (Britain 1.02 times as inventive), and paper (France 1.16 times as inventive).

Figure 1.8 documents the revealed relative technological lead at the technology level for the 30 most dynamic technologies (those with the highest total patenting expenditure). The overall gradient from relative British lead to relative French lead appears similar, though the revealed relative technological lead variation is magnified. Britain had the largest relative lead in tulle (3.7 times),[32] spinning technology (3.02 times),[33] steam engines (2.88 times), and shipbuilding (2.2 times). France had the largest relative lead in distillation (2.5 times), watchmaking technology narrowly defined (2.17 times), shoes (2.1 times), and hydraulic pumps (2 times). However, the relative technological lead appears minor for most technologies, as in 20 out of 30 technologies, the relative lead is within 1.5 times (marine machines down to hydraulic motors).

The technology level evidence also reveals heterogeneity of technological leadership at the industry level. The machine industry, for example, includes steam engines with a notable British lead, but also diverse motors where Britain and France are effectively equal (France leading 1.03 times), and technologies where France is leading, hydraulic motors (1.33 times) and hydraulic pumps. This variation is consistent with geography as a determinant of the direction of technological change, given that water power was relatively cheaper in France and coal energy relatively cheaper in Britain (Mokyr, 2009a). In the chemical industry, there was also substantial heterogeneity. Britain and France were equal in chemical products (Britain was leading 1.06 times), but France led in distillation. Similar heterogeneity existed in the textile industry, the largest industry in France in terms of output, value added, and labor force. In the sample of top 30 technologies in textiles (tulle, spinning, carding, looms, cloth, and silk), Britain was leading in many technologies but not all.

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[31] We discuss below in the robustness section "differential demand" why the coefficients for agriculture and entertainment might overestimate the relative French lead.

[32] While the name "tulle" derives from a French city, the key breakthrough was the bobbinet lace machine, invented in Britain by John Heathcoat in 1808 (https://en.wikipedia.org/wiki/Bobbinet).

[33] Spinning technology differs from the textile/spinning industry because the industry also comprises different steps of pre-processing of fibers, including cleaning and carding.

The revealed relative technological lead ranks industries and technologies according to relative leadership of Britain or France, but what about absolute technological leadership? The first question is whether it could be the case that one country was an absolute leader everywhere. If that can be ruled out, the second question will be for what value of revealed relative technological leadership Britain and France are equal. Given that value, we can calculate the size of absolute technological leadership for all industries and technologies.

Anecdotal and qualitative case-study evidence confirms that Britain or France's most outstanding observed values of revealed relative technological lead align with British or French absolute technological leadership. For example, the estimated British lead in maritime and shipbuilding is consistent with the evidence on absolute leadership as discussed by Kelly and Ó Gráda (2019) and Hanlon (2020a). In mining and railways industries and steam engines technology, it is consistent with the evidence on absolute leadership in coal-related sectors (Landes, 1969; Harris, 1998; Allen, 2009a). Similarly, the lead in spinning (industry and technology) is consistent with the qualitative evidence on absolute leadership in Allen (2009b); Juhász (2018). For France, the estimated lead in watchmaking is consistent with the qualitative evidence on absolute leadership of the French industry (though many watchmakers were, in fact, francophone Swiss nationals based in Paris, Landes, 1979).[34] Based on this evidence, we can rule out the possibility that one country was the absolute leader everywhere. Thus, there must be a value of revealed relative technological lead for which Britain and France are equal between the values for spinning (.53 log points at industry level) and watchmaking (-.77 log points at technology level).

Anecdotal evidence on the technological equality of Britain and France in sectors where invention was most constrained by scientific knowledge suggests that the revealed relative technological lead plausibly approximates the absolute technological lead between Britain and France. Anecdotally, Britain had no clear-cut advantage over France in terms of practical science and applied mathematics. This knowledge was crucial for invention, in particular in technologies related to chemicals and engineering (Mokyr, 2002). In our setting, this argument applies to "chemical products" and "diverse motors" technologies.[35] If invention was most constrained by knowledge in these sectors, and the same knowledge was available

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[34] Kelly and Ó Gráda (2016) argue there were much more watchmakers in Britain than in France and that their mechanical skills contributed to the British advantage in human capital over France, allowing Britain to implement more inventions, and implement them more intensely. There is no contradiction to a simultaneous French lead in invention because different skills may be necessary for the rate of invention, and thus the quantity of workforce may be less relevant.

[35] The same knowledge could have been crucial for steam engines and hydraulic motors, yet the revealed relative technological lead of either Britain or France varies with the geographic endowments of coal and water power. We need to consider technologies that are not affected by (differential) directed technological change for the argument made here.

in both countries, then the genuine inventiveness should be approximately equal. We find that their revealed relative technological lead is close to zero, with Britain 1.06 times more inventive than France in chemical products and France 1.03 times more inventive than Britain in diverse motors. Thus, it appears that a revealed relative technological lead of zero is a reasonable estimate of (absolute) aggregate technological equality between Britain and France. In turn, this would imply that we do not have to rescale the revealed relative technological lead levels because they already approximate the levels of absolute technological lead.

Robustness: Over time By and large, the revealed relative technological lead persisted over time. Figure 1.9 plots the revealed relative technological lead for the later period from 1830 to 1843 against that of the earlier period until 1829.Most industries cluster around the 45-degree line, which denotes that the relative technological lead did not change. For example, industries as spinning or machines were consistently leading in Britain while industries as construction, food, and watchmaking were consistently leading in France. Only in a few industries, the revealed relative technological lead change notably. On the one hand, France caught up relative to Britain in mining and perhaps overtook Britain in leather and printing. On the other hand, Britain forged ahead in maritime, where it cemented an initial technological lead of the early period of Industrial Revolution (Kelly and Ó Gráda, 2019) during the middle of the nineteenth century (Hanlon, 2020a).

Robustness: Differential demand One concern is that the documented pattern of revealed relative technological lead is biased by differential demand for French rather than British ideas. The demand differences could result from differential preferences as, for example, a taste for French fashion in clothing and furniture rather than British fashion.[36] Alternatively, the demand differences could result from different appropriateness of British inventions given the French economic environment as, for example, in agriculture (different climate and soil), food (different ingredients due to different agriculture), fuel (different supply of energy sources), or maritime (Britain being an island).[37]

The home-biased preferences for French rather than British inventions do not affect our main result of evident variation in leadership across sectors. True, such preferences could lead to an underestimation of the technological lead in the affected sectors. However, if we excluded the sectors potentially affected by fashion tastes as clothing, furniture, or entertainment, the main finding of variation in the leadership from mining to watchmaking by about a factor of four remains valid. Similarly, if we considered only sectors in which

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[36] On the development of British tastes in consumer goods during the eighteenth century, see Berg (2004).

[37] For the concept of appropriateness of technology, see Basu and Weil (1998); Acemoglu and Zilibotti (2001).

inventions from Britain are less appropriate than the French ones, as in agriculture, food, fuel, and maritime, we could again confirm the main finding of variation in the leadership by about a factor four within these sectors. Moreover, home biased preferences will not affect our estimates of revealed relative technological lead if they affected all sectors similarly. To see this, denote the home preference $\phi > 0$. Then, $M_i = \tilde{\alpha}\, N_i^B$, with $\tilde{\alpha} = (\alpha - \phi)$. As $\tilde{\alpha}$ appears both in the numerator and denominator of RRTL, it will cancel out. Relatedly, if ϕ_i varied across sectors but orthogonally to the technological lead, it would cause measurement error in the individual estimates of RRTL_i but not affect our main result. Thus, we can conclude that home-biased preferences are a minor concern in our setting.

Robustness: Differential superstar inventions Another concern is that the patent expenditure measures may not account for high economic impact "superstar" inventions. The expenditure measures assume that the ranking of high-impact inventions is preserved when patents are priced at the marginal expected value and aggregated to invention–sector or imitation–sector observations. If the distribution of high-impact inventions differed from the distribution of patent expenditure, the expenditure measures would be biased measures of true technological creativity.

To address this concern, we study whether we obtain a similar ranking of revealed relative technological lead when using a different measure that better reflects high-value inventions. For our empirical exercise, we use the first patents within their technology, which plausibly captures patents of high technological creativity, as a proxy for high-impact inventions. Indeed, we find a similar pattern of revealed technological lead at the industry level when considering this proxy for high-impact inventions. Figure 1.10 plots by industry the share of technologies whose first patent is an imitation patent from Britain, weighting technologies by importance (total patents). As before, there is a considerable variation in technological leadership across industries as measured by the origin of high-impact inventions. Furthermore, the same industries as before have the highest and lowest first imitation shares. For example, most high-impact inventions in railways and maritime industries originated in Britain, while in watchmaking, the majority originated in France. In sum, this evidence supports the assumption that high-impact inventions and (aggregate) patent expenditure follow a similar distribution.

Robustness: Differential spillovers from imitation on invention Finally, there is a concern that French inventions could be copies or minor variations of British superstar inventions. The revealed relative technological lead would be biased if such spillovers from imitation on invention varied across sectors. This bias could go in either direction and lead to overestimating or underestimating the relative technological lead. To evaluate the direction of bias, we assume that spillovers from imitation are plausibly the largest in technologies introduced from Britain (those whose first patent is an imitation patent).

We find that the omission of spillovers from imitation to invention leads, if anything, to an underestimation of comparative advantage in invention. To provide an upper bound of spillovers from imitation, we count as "British technology" all patents in technologies with first imitation patent (invention or imitation) in addition to all other imitation patents. Figure 1.11 shows that if we re-calculate the imitation–invention–ratio in such a way, the observed revealed relative technological lead gets magnified.

Given the finding that the distribution of high-impact patents is similar, the new ranking of the technological lead across industries is, as expected, similar. As before, railways, maritime, spinning, fuel, other textiles, and metals are leading in Britain; and industrial arts, music, and watchmaking are leading in France. Nevertheless, in some details, the ranking changes. In particular, it appears that we have previously underestimated the British technological creativity in fuel, health, and precision instruments; and previously underestimated the French technological creativity in mining, ceramics, and paper.

1.6 Conclusions

This paper provides the first empirical evidence on invention and technological leadership in a two-country, multi-sector setting during the Industrial Revolution. The evidence is based on patent data in France, where it is possible to distinguish between invention and imitation patents. As imitation patents predominantly reflect British inventions, the patent data provide quantitatively comparable measures for the French and British invention rates. The indirect comparison within France allows us to effectively control for country fixed effects when comparing the invention rate across or within sectors.

Based on the novel measures, we provide two principal stylized facts on invention and technological leadership during the Industrial Revolution. First, we document that French and British invention rates covary strongly positively across sectors, which holds robustly at different levels of aggregation, conditional on more aggregate sector fixed effects, and within sub-periods. Second, we document the heterogeneity of technological leadership in invention of the British relative to French sectors. Our evidence documents in which sectors Britain was ahead of the continent and by how much, in which sectors the continent was ahead of Britain and by how much, and in which sectors Britain and continent were technologically neck-on-neck.

The stylized facts distinguish empirically leading hypotheses of technological progress during the Industrial Revolution. Fact one, the positive association of invention in France and Britain, is consistent with hypotheses that predict the simultaneous acceleration of invention rates in both countries. In contrast, it rejects hypotheses that predict that invention rates accelerated in some sectors mainly in Britain but in others mainly in France, resulting in a negative association of invention in France and Britain. Fact two, the heterogeneity in technological leadership, shows that economic mechanisms that predict a negative association of invention on the aggregate are nevertheless present in the data and valuable for explaining technological leadership.

The key questions that remain open are what economic mechanisms caused the positive association of invention in France and Britain and the technological leadership. The baseline finding of positive association is consistent with sector shifters that affected invention in both countries equally, for example, if the market for inventions was the same. Furthermore, we find the same positive association on the finest level of aggregation (technologies) when conditioning on industry or sub-industry fixed effects and additional controls. This finding suggests that complementarities (another form of knowledge spillovers) between inventions in France and Britain could have played a role in creating the positive association of inventiveness across countries. Regarding technological leadership, proposed explanations explain the heterogeneity by demand factors like variation in energy and labor prices and by supply factors like skills of inventors and implementors. Future work shall identify and distinguish these economic mechanisms empirically.

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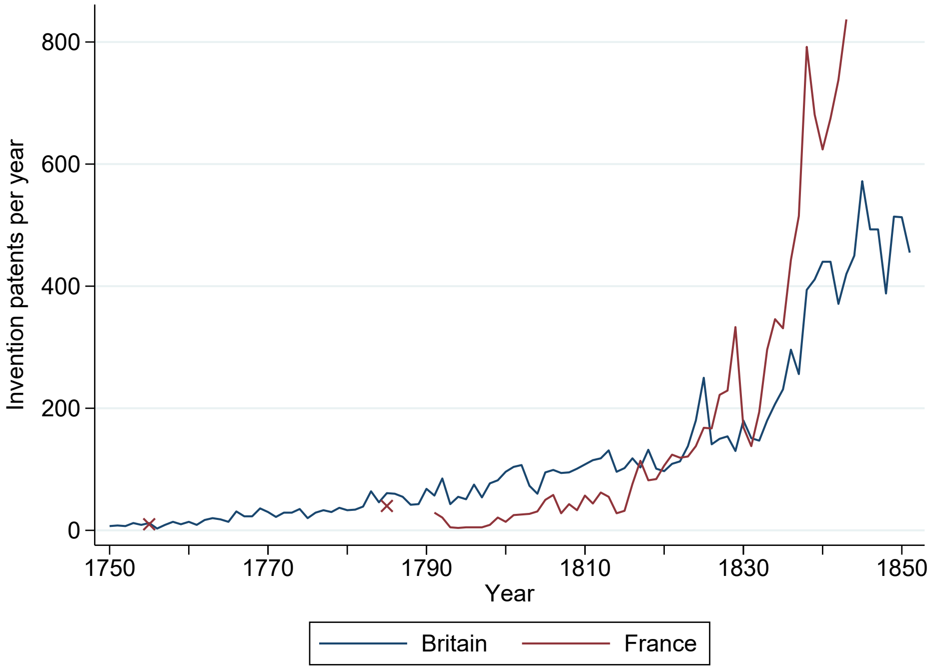
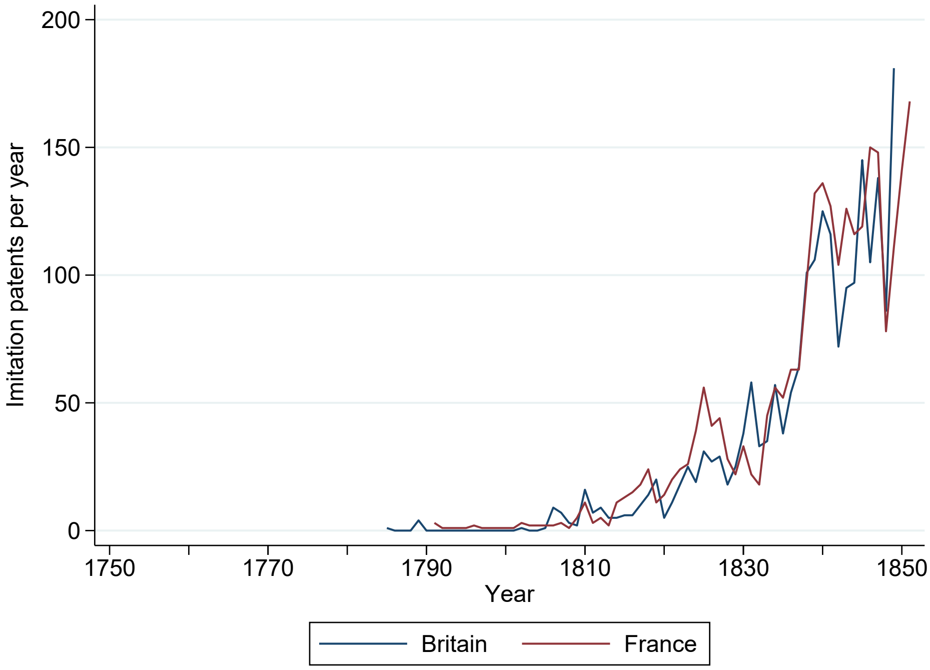


(a) Invention



(b) Imitation

Sources: Invention patenting in Britain: Dutton (1984). Invention patenting in France from 1791: Own calculation, based on *base de brevets historique* by Institut National de la Propriété Industrielle (INPI). Invention patenting in France in 1755 and 1785 (X): Decadal averages of proto-patent applications, Hilaire-Pérez (2000). Imitation patenting in Britain: Data communicated from Walker Hanlon. Imitation patenting in France: Own calculation, based on INPI.

Figure 1.2: Acceleration of invention and imitation during the Industrial Revolution

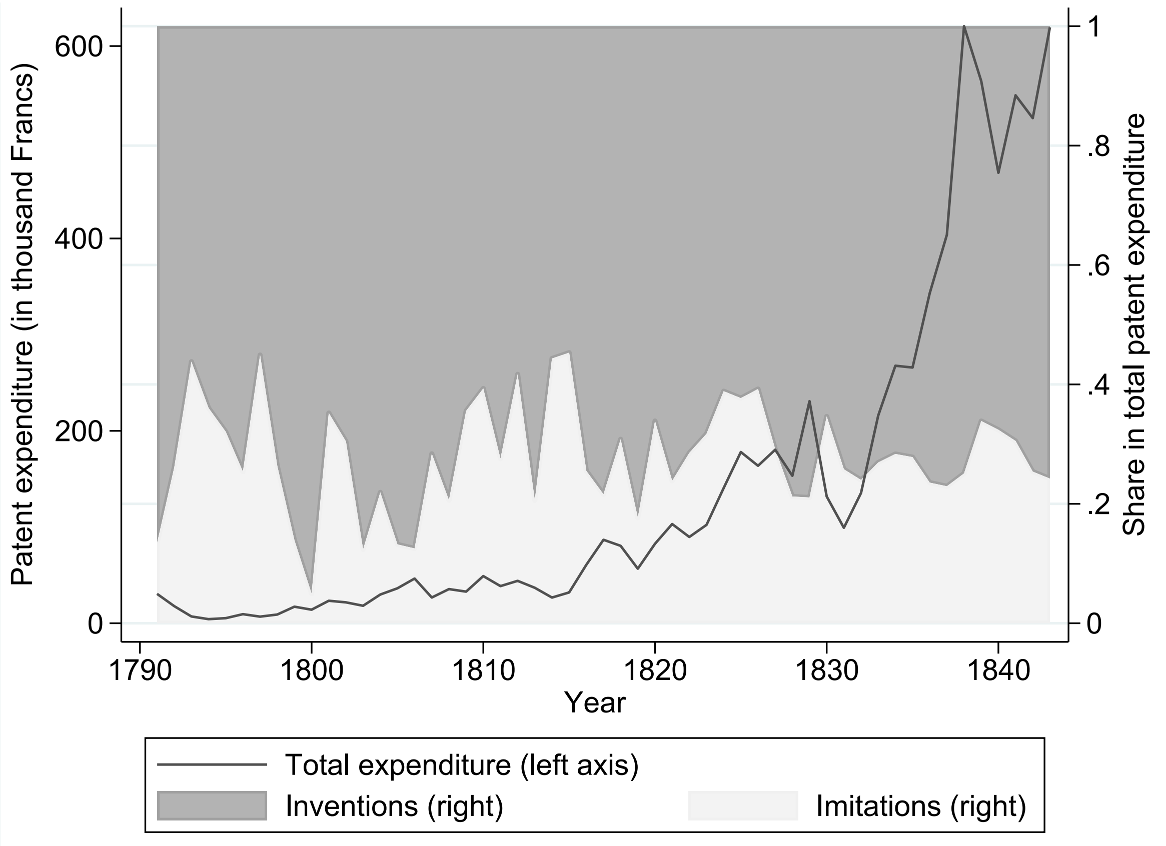
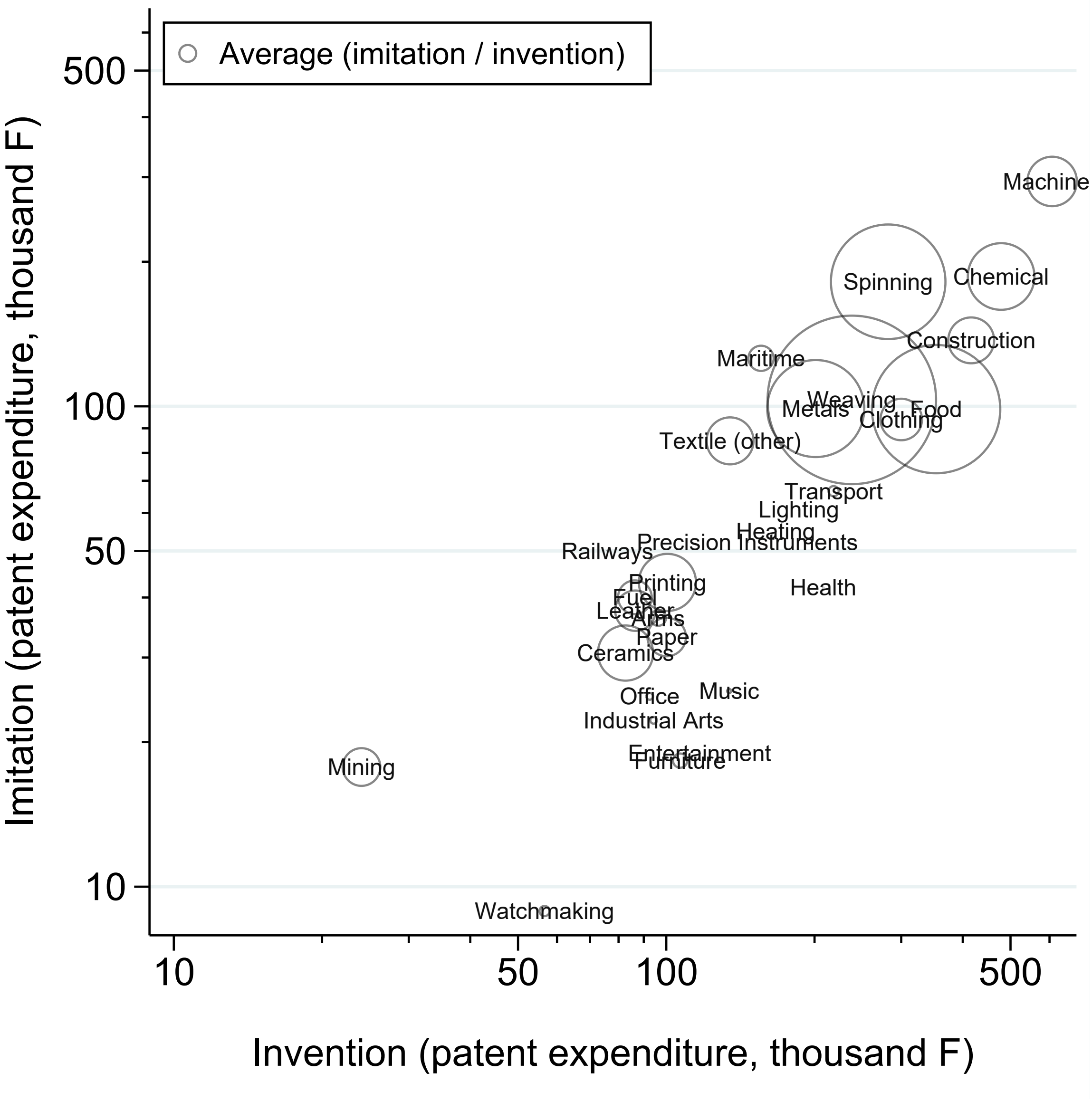
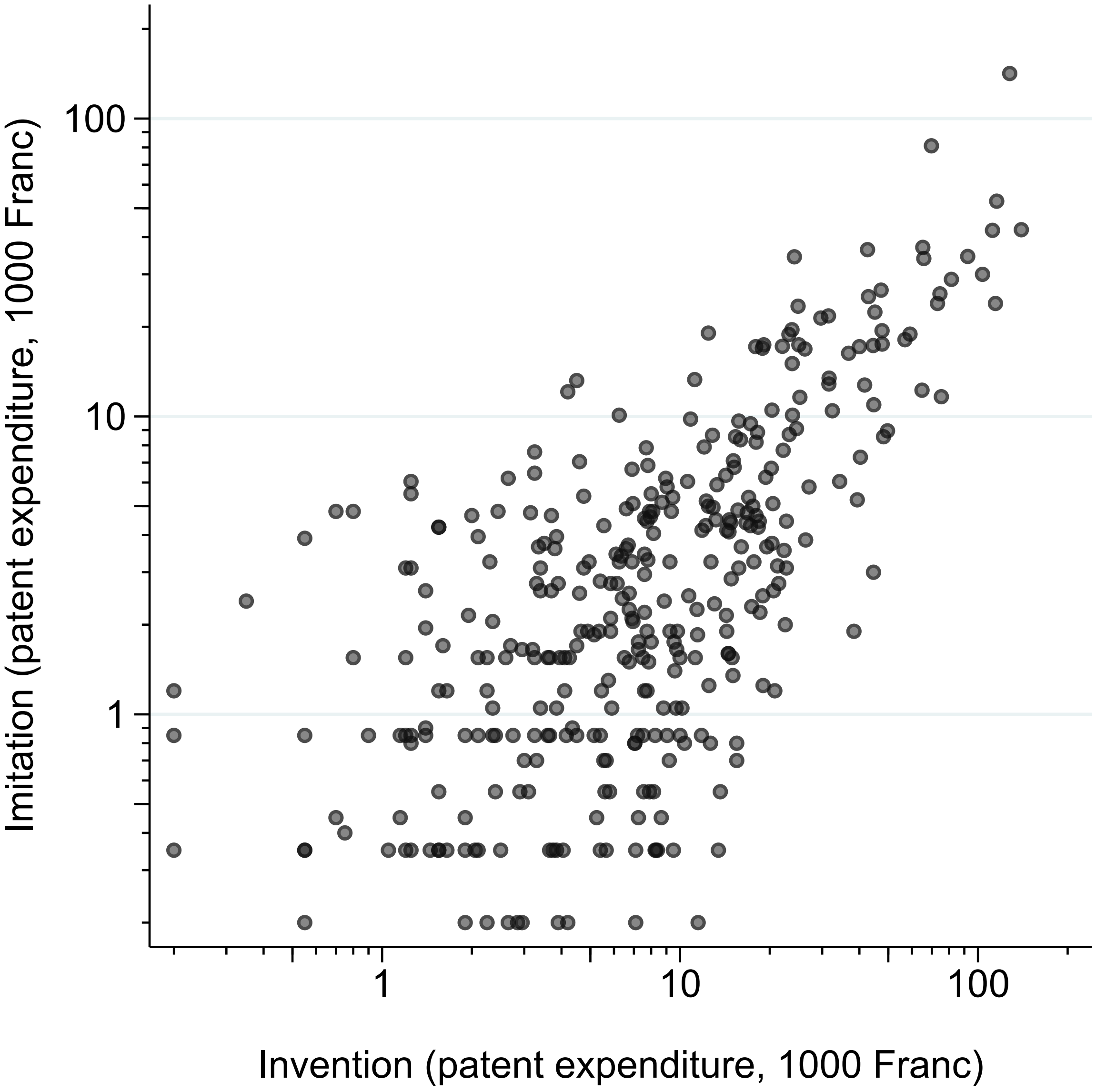


Figure 1.3: Patenting shares of invention and imitation over time



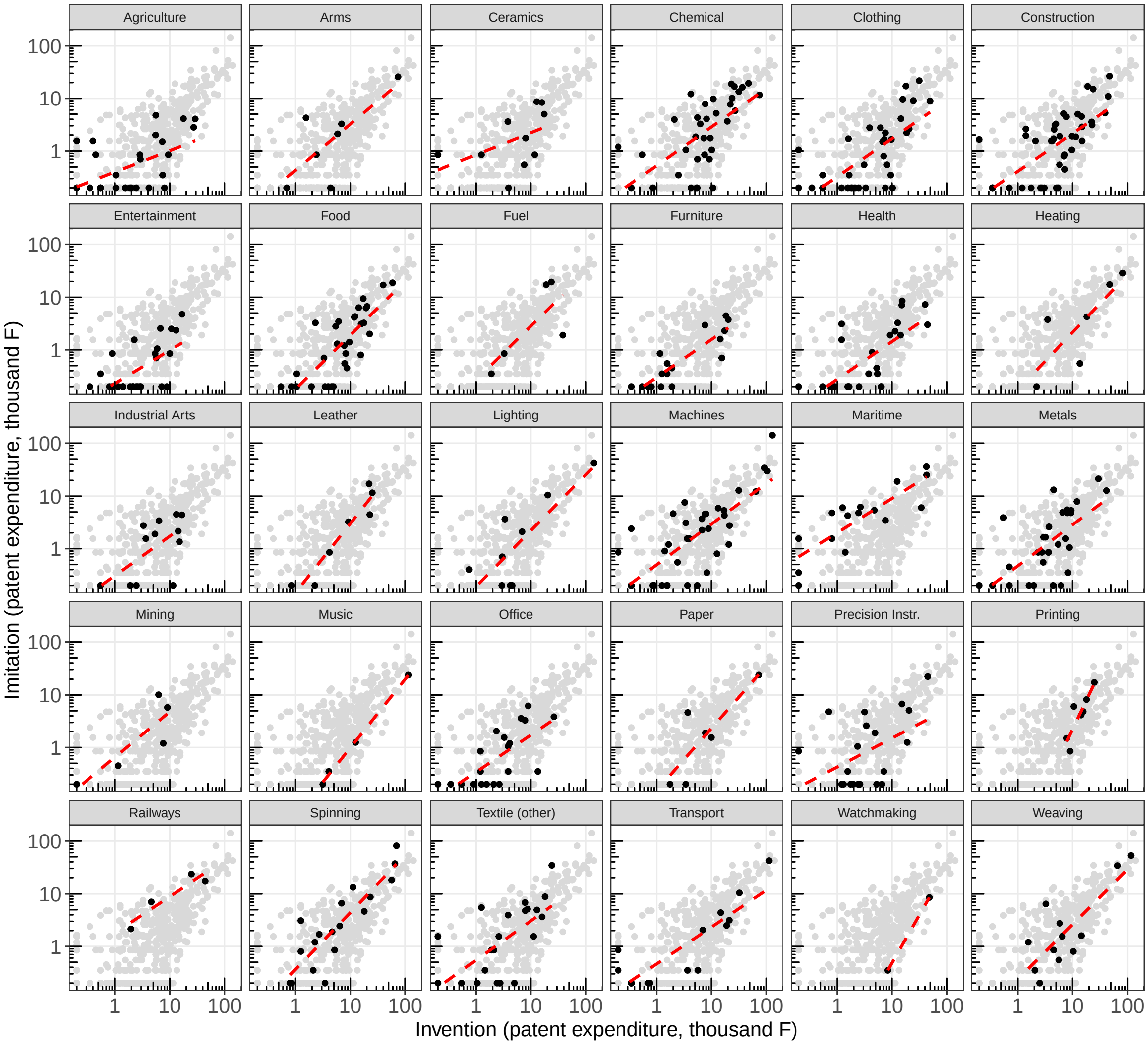
Note: Each circle is one industry. Circle size is proportional to industry value added ca. 1840. The pairwise correlation coefficient of log invention and log imitation is 0.832 (p-value < 0.0001). The bold line plots the average imitation–invention ratio.

Figure 1.4: Association of invention and imitation at industry level



Note: Each dot is a technology. The bold line plots the average imitation–invention ratio. The correlation coefficient of log invention and log imitation is 0.674 (p-value < 0.0001). Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 143 cases), the same for technologies without invention patent (10 cases).

Figure 1.5: Association of invention and imitation at technology level



Note: Each box is one industry and each dot is a technology. The dashed line is a linear regression of log imitation on log invention. Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 143 cases), the same for technologies without invention patent (10 cases).

Figure 1.6: Association of invention and imitation at technology level within industries

Table 1.1: Association of invention and imitation at different levels of aggregation

	Dep. var.: Ln imitation					
	Industry	Subindustry		Technology		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln invention	0.998	0.851	0.761	0.694	0.699	0.749
	(0.139)	(0.072)	(0.079)	(0.047)	(0.047)	(0.053)
Industry FE			Yes		Yes	
Subindustry FE						Yes
Observations	30	90	81	364	364	345
adjusted R^2	0.681	0.694	0.721	0.414	0.476	0.475

Observation = industry (column 1), sub-industry (columns 2 trough 4), technology (columns 5 through 9). Invention & imitation measured as total patent expenditure 1791–1843. Sample size drops from column (2) to (3) because some industries have a single sub-industry and from column (6) to (7) because some sub-industries have a single technology. In column (4), we drop small sub-industries with less than 30 patents in total. In column (8), we drop small technologies with less than 10 patents in total. Robust standard errors in parentheses. All coefficients on ln invention are significant at the 1%-level.

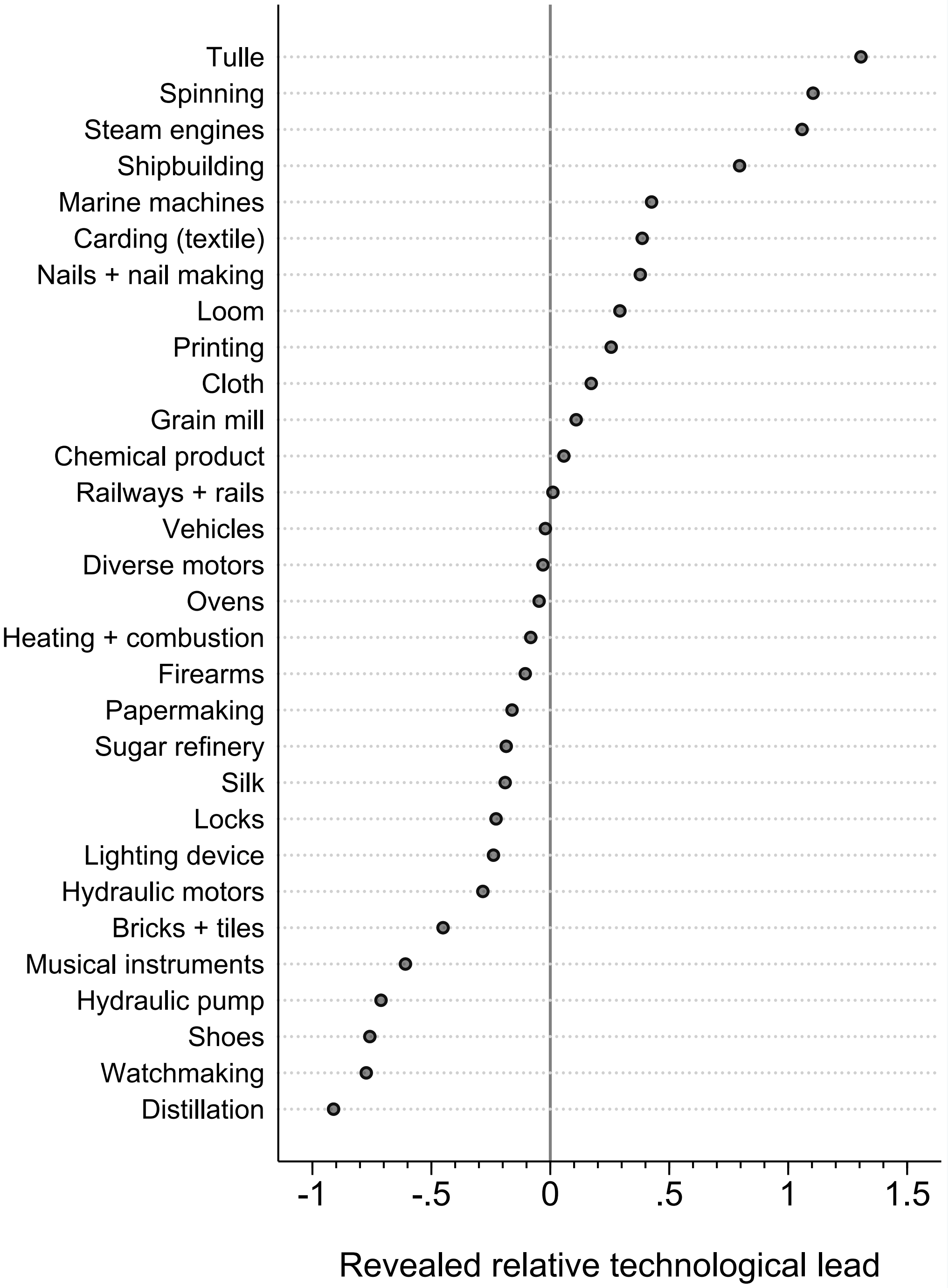
Table 1.2: Robustness to technology level characteristics

	Dep. var.: Ln imitation						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Ln invention				0.653 (0.056)	0.697 (0.047)	0.721 (0.046)	0.680 (0.053)
Age	0.040 (0.004)			0.008 (0.005)			0.006 (0.005)
Complexity		0.410 (0.422)			0.231 (0.230)		0.333 (0.200)
Foreign origin			0.332 (0.143)			0.633 (0.099)	0.643 (0.099)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	374	374	374	364	364	364	364
adjusted R^2	0.219	0.052	0.061	0.479	0.476	0.523	0.526

Observation = technology. Invention and imitation are measured as total patent expenditure from 1791 to 1843 (in 1k Francs). Age is years since the first patent within technology (in 1855). Complexity equals one if technologies required engineering knowledge (Hanlon 2020) or scientific knowledge (Mowery–Rosenberg 1989) and includes all technologies in the fields of steam and motors, transport (railways, vehicles, ships, aviation), chemicals, electricity, precision instruments, printing, and photography. Foreign origin equals one if the first patent within a technology was an imitation. Robust standard errors in parentheses.

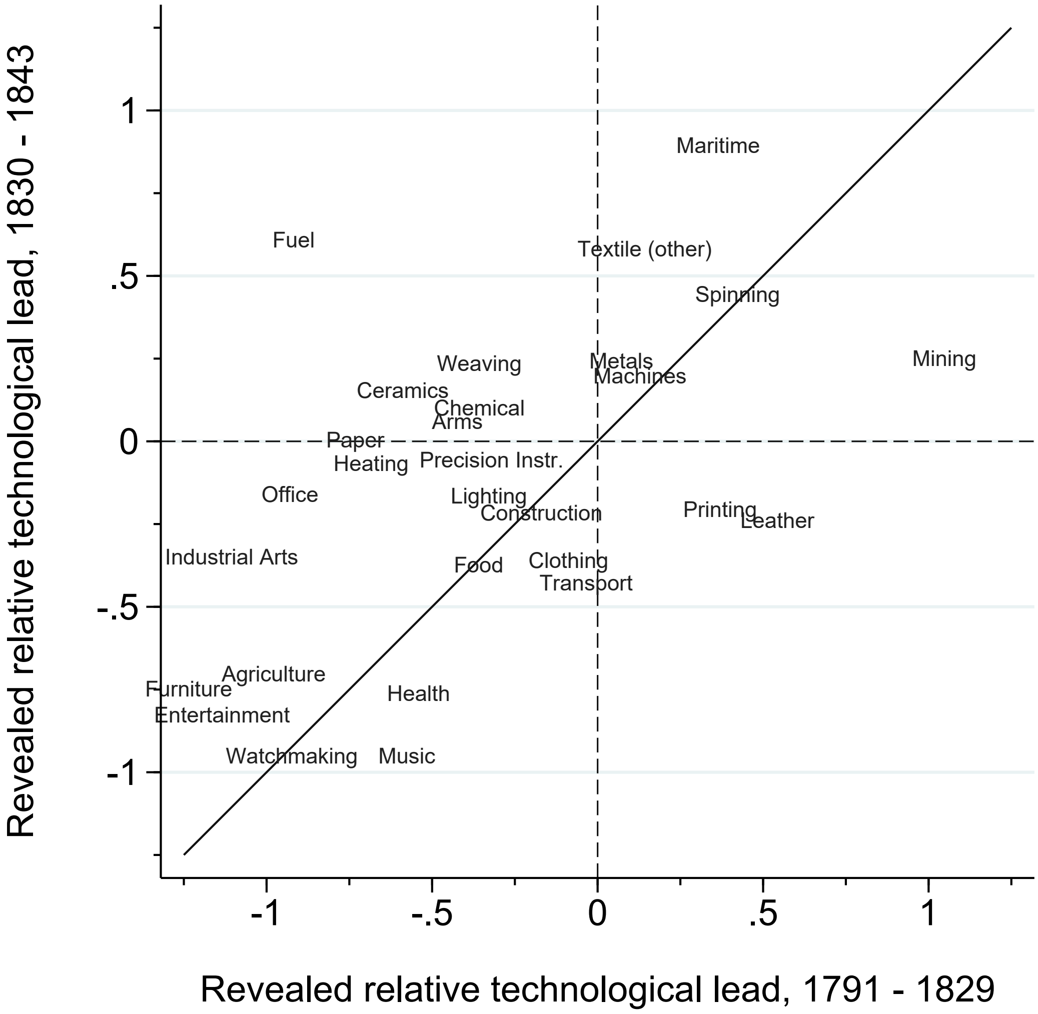
Note: Calculated as ln (imitation–invention ratio in industry / average ratio of total imitation to total invention). For positive revealed relative technological lead, Britain is leading relative to France. For negative revealed relative technological lead, France is leading relative to Britain.

Figure 1.7: Relative technological lead of Britain or France at industry level



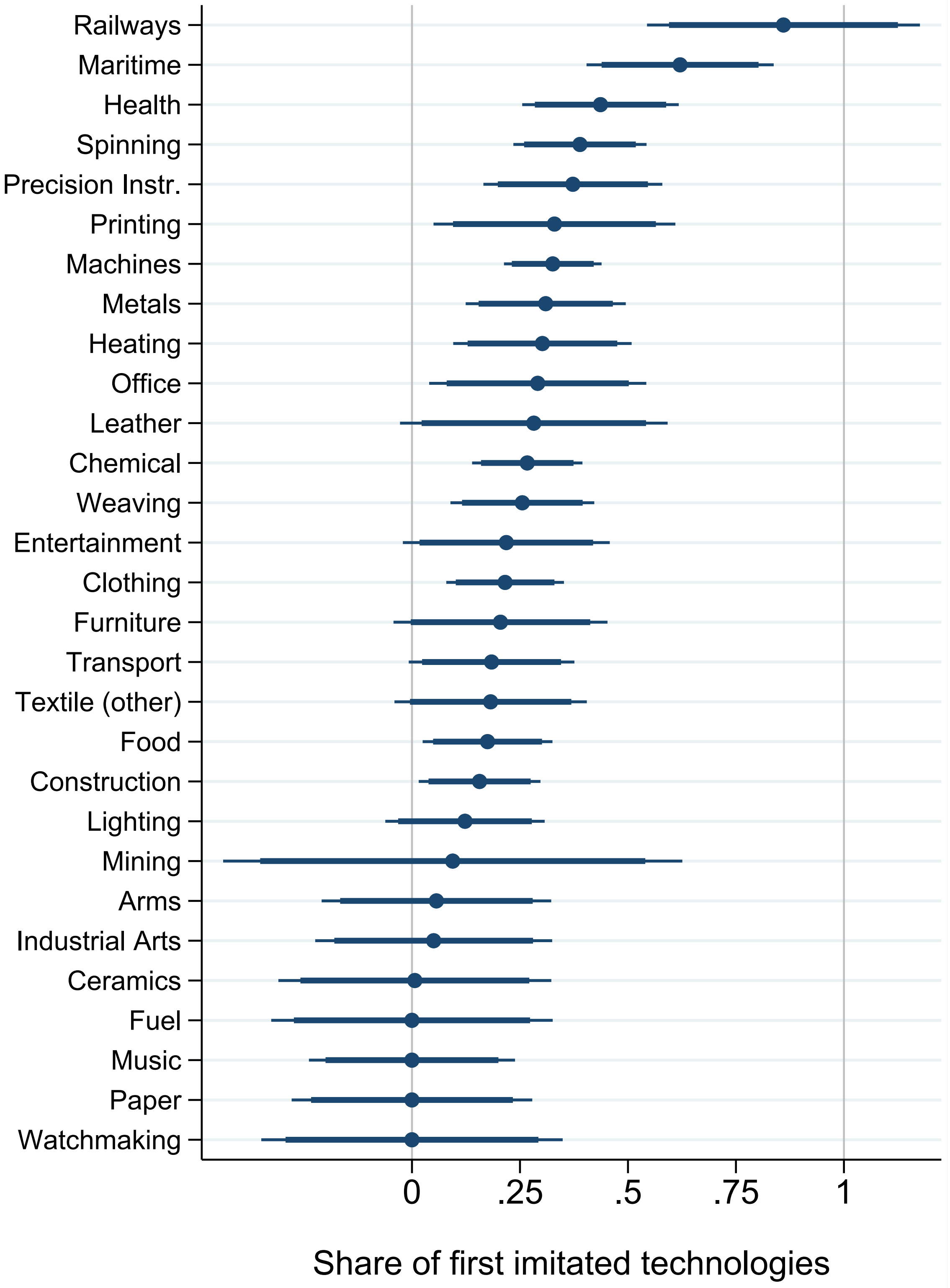
Note: Calculated as ln (imitation–invention ratio in technology / average ratio of total imitation to total invention), for the top 30 most dynamic technologies with largest total patent expenditure. For positive revealed relative technological lead, Britain is leading relative to France. For negative revealed relative technological lead, France is leading relative to Britain.

Figure 1.8: Relative technological lead of Britain or France at technology level



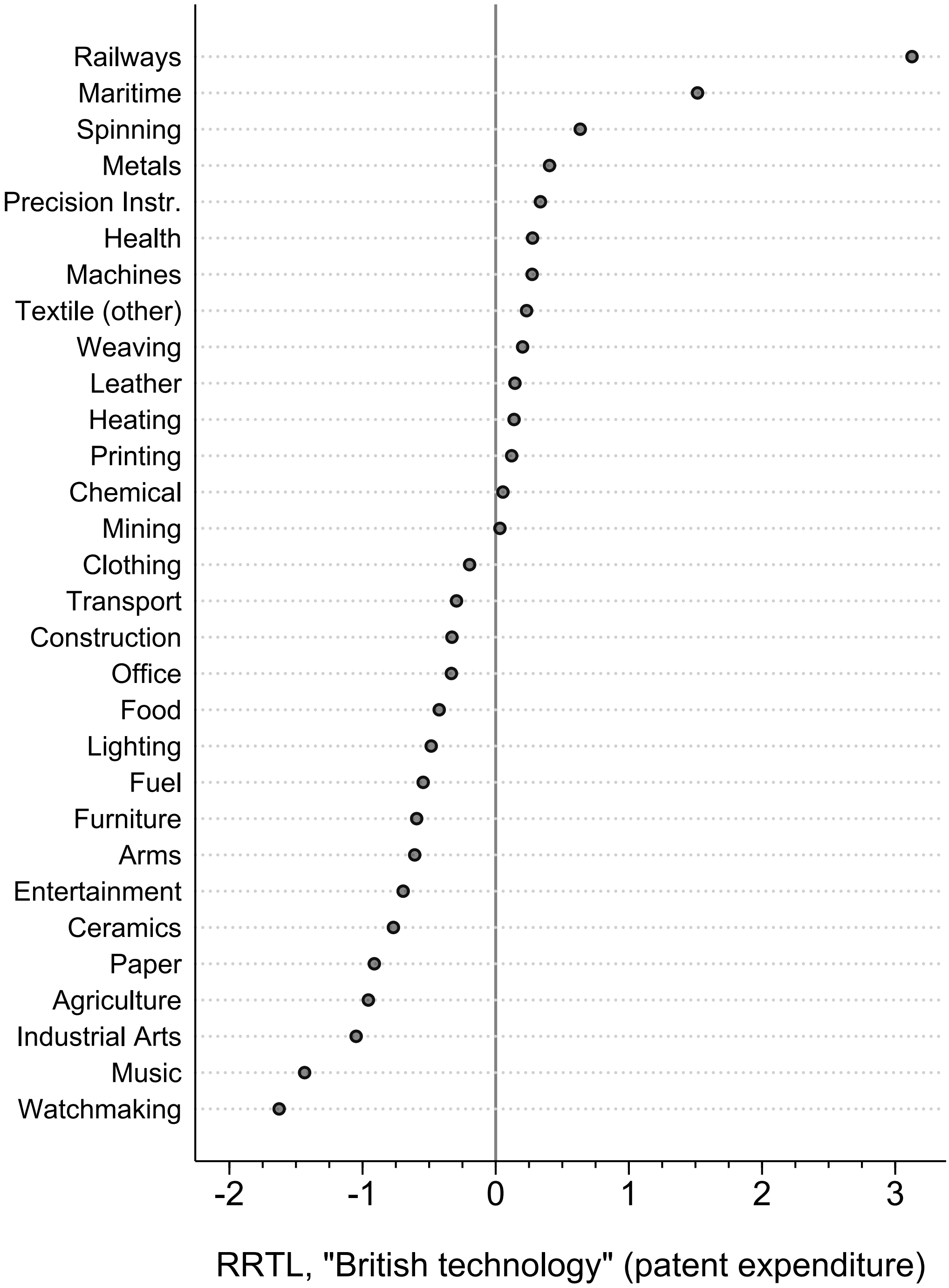
Note: Scatterplot of revealed relative technological lead in later period against earlier period. Bold line is 45-degree line. Industries left of dashed line initially leading in France, right of dashed line initially leading in Britain, below dashed line eventually leading in France, above of dashed line eventually leading in Britain.

Figure 1.9: Persistence of revealed relative technological lead



Note: The graph plots by industry the share of technologies within industry whose first patent was an imitation patent from Britain. First patent within technology is a proxy for inventions of high economic value. Technologies are weighted by the total number of patents per technology until 1853. The thick horizontal line provides a 90% and the thin horizontal line a 95% confidence interval. In total, 24% of all technologies were first imitated (96 out of 401).

Figure 1.10: Alternative measure of revealed relative technological lead



Note: Based on patent expenditure, 1791 to 1843. Alternative measure of imitation, counting additionally as imitation all patents in technologies whose first patent was an imitation patent. This wider concept of imitation includes patents invention patents which plausibly profited from spillovers from initial imitation.

Figure 1.11: Revealed relative technological lead when accounting for potential spillovers from imitation on invention

1.A Data Appendix

1.A.1 Summary statistics

Table 1.3: Summary statistics on patent origin

	Type: Innova./inven.		Type: Importa./imita.		Diff.	
	mean	sd	mean	sd	beta	t
Panel A: Patent category						
Foreign address	0.033	0.179	0.489	0.500	0.456	35.1
British address	0.016	0.127	0.409	0.492	0.392	30.9
British name	0.082	0.274	0.420	0.494	0.338	26.0
British address or name	0.089	0.285	0.540	0.499	0.451	34.3
Observations	9875		1512		11387	
Panel B: Our classification						
Foreign address	0.000	0.000	0.420	0.494	0.420	42.8
British address	0.000	0.000	0.307	0.461	0.307	33.5
British name	0.000	0.000	0.569	0.495	0.569	57.9
British address or name	0.000	0.000	0.669	0.471	0.669	71.5
Observations	8849		2538		11387	

Observation = patents 1791–1843. Panel A: Innovation and importation patent categories. Panel B: Invention patents are innovation patents by non-British patentees with French address. Imitation patents are importation patents plus innovation patents by British patentees and patentees with foreign address. Note that patents can have more than one address, mainly as a result of multiple patentees. The incidence of a foreign or British address indicates that at least one of several addresses was from there. There are 1065 patents with foreign addresses in total (9.35%). Among foreign address patents, 779 are British (United Kingdom; 73.15% of foreign, 6.84% of total).

1.A.2 Validation of quality adjustment

Predictions from empirical framework

The assumption that only a fraction of British ideas $\alpha \in (0, 1)$ is patented in France can be justified as follows. Suppose that the economic value of ideas—in short, quality—is drawn from a distribution $q \in (0, \infty)$~Φ *after* obtaining a patent (the inventor may receive a signal about the quality). Further, suppose that obtaining a patent is costly, $c > 0$. Then, patented ideas will be selected on their expected value, such that only ideas with $E(q) > \tilde{q}$ are patented. Now, suppose that for some British ideas, the quality can be observed before they are patented in France, for example, because they were already patented in Britain some time ago. Then, $M_i < N_{B,i}$ because for some British ideas, a quality below the cutoff $q < \tilde{q}$ could be observed before the patenting decision in France.

Two implications for the empirical setting follow. First, the average quality of patented ideas $\bar{q}$ will differ such that the average quality of imitations is higher than that of inventions $\bar{q}_M > \bar{q}_N$. Our empirical measures will account for this quality variation by considering the expenditure on patents. (Actually, in our empirical setting, only heterogeneity in average quality across sectors and heterogeneity in relative quality of imitation to invention across sectors can be problematic for our results.) Second, given that the quality of some British ideas was observed before they were patented in France, but less is known about the quality of French ideas before patenting, there will be more invention patents with $q < \tilde{q}$ than imitation patents. In other words, more invention patents than imitation patents will ex post turn out not to be worth the patenting cost. Our empirical measures of patenting expenditure cannot remove these worthless patents. Thus, after adjusting for patent expenditure, it can still be the case that $N_{F,i} > M_i$ despite potentially $N_{F,i} < N_{B,i}$. Put differently, our adjustment for patent expenditure cannot recover the true ratio of $N_{F,i}$ to $N_{B,i}$.

Evidence

Several patent characteristics indicate that imitation patents are indeed positively selected on quality. Table 1.4 panel B compares the patent characteristics by patent type "invention" versus type "importation" (our main indicator for imitation; imitation patents also include inventions by foreigners). Importation patents have an average 45% higher patent expenditure, driven by a longer patent duration of either 10 or 15 years, with the likelihood of a short 5-year patent roughly halved and defaults on the second installment about half as likely. Further, importation patents were on average 25% less likely to be modified or extended by addition certificates. Conditional on at least one addition certificate, importation patents do have on average 0.24 fewer additions (1.73 versus 1.49). In sum, these differences underscore that imitated inventions were more valuable and probably more mature at the time of introduction to France compared to the average French invention at the moment of patenting.[38]

Our empirical strategy holds constant aggregate differences between invention and imitation in France and indirectly between invention in France and Britain. Hence, selection on quality would be unproblematic for our results if both strengths of selection of ideas from

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[38] Obviously, these quality differences imply nothing about the underlying distribution of idea quality in Britain and France.

Britain and source distribution of invention quality in France and Britain were similar across industries and technologies. To control for the case that selection (and source distribution) might vary differentially across industries and technologies, we measure invention and imitation as total patent expenditure. For example, if imitation were of systematically higher quality in machines than in ceramics, we would underestimate Britain's revealed relative technological lead in the machines industry and add a measurement bias to the estimated correlation between invention and imitation.

We evaluate whether patent expenditure adjusts for quality differences in practice by studying patent sales as an alternative indicator of idea quality. The exercise is based on the notion that patents of high economic value are more likely to be sold than patents of low value. Patent sales had to be documented by a notary, and lists of traded patents were published in the official law publication (*Bulletin de Lois*). According to the INPI data, 5% (573 in 11387) of patents registered until 1843 were sold at least once.

Table 1.5 shows that the patent expenditure measures do correct for observable quality differences between patents. In columns (1) to (4), we first confirm that patentees are willing to pay substantially more for imitation patents: On average, patent expenditure is about one third larger, longer duration than five years is about 50% more likely, and defaults are about 25% less likely compared to invention patents. In columns (5) to (7), we instead use patent sales to measure patent quality. Unconditionally, imitation patents are 20% more likely to be sold, consistent with higher quality. Conditional on patent expenditure, however, imitation patents are not statistically different from invention patents regarding the patent sale measure of quality. The quality indicators themselves—duration categories and patenting expenditure—are all significant predictors of patent sales, supporting the validity of patent sales as an alternative quality measure.

1.A.3 Nationality prediction

In order to teach our algorithm to recognize British names, we need a large dataset of historical British and non-British names. We rely on two sources. First, we use the famous people dataset already used in economic history literature (De la Croix and Licandro, 2015). Second, we obtain all European names of people born between 1700 and 1900 from Wikipedia. We use the place of birth as an indicator of nationality. Alternatives are "nationality" and "ethnicity" variables available in Wikipedia. Those seem less reliable because the definition of a person's nationality and ethnicity is not reliable when a person moves. For instance, famous Europeans emigrating to the US are often labeled as American, which may be accurate but is not the information we are looking for. Furthermore, the

Table 1.4: Summary statistics on patent quality

	Type: Innova./inven.		Type: Importa./imita.		Diff.	
	mean	sd	mean	sd	beta	t
Panel A: Patent category						
Patent expenditure (Franc)	629.630	447.408	914.947	478.542	285.317	21.8
Duration 5 years	0.559	0.497	0.250	0.433	−0.309	−25.3
Duration 10 years	0.254	0.435	0.397	0.489	0.143	10.7
Duration 15 years	0.187	0.390	0.351	0.478	0.164	12.7
Defaulted on 2nd installment	0.242	0.428	0.133	0.340	−0.109	−11.2
Prob (additions > 0)	0.259	0.438	0.192	0.394	−0.067	−6.1
Number of additions	0.447	1.114	0.285	0.764	−0.162	−7.2
Patent sold	0.048	0.214	0.064	0.245	0.016	2.4
Observations	9875		1512		11387	
Panel B: Our classification						
Patent expenditure (Franc)	620.313	442.989	832.092	488.132	211.779	19.7
Duration 5 years	0.570	0.495	0.336	0.472	−0.235	−21.8
Duration 10 years	0.249	0.432	0.357	0.479	0.108	10.2
Duration 15 years	0.181	0.385	0.306	0.461	0.125	12.5
Defaulted on 2nd installment	0.243	0.429	0.174	0.379	−0.069	−7.9
Prob (additions > 0)	0.263	0.440	0.205	0.404	−0.058	−6.2
Number of additions	0.459	1.143	0.309	0.791	−0.151	−7.6
Patent sold	0.048	0.214	0.058	0.234	0.010	2.0
Observations	8849		2538		11387	

Observation = Patent. Sample: Raw patent categories (innovation and importation) 1791 to 1843. Invention patents are innovation patents by non-British patentees with French address. Imitation patents are importation patents plus innovation patents by British patentees and patentees with foreign address.

Table 1.5: Validation of quality adjustment

	Patent expenditure				Altern. quality measure		
	(1) expenditure	(2) 10 year	(3) 15 year	(4) defaulted	(5) sold	(6) sold	(7) sold
Imitation patent	0.212	0.108	0.125	−0.069	0.010	−0.004	−0.004
	(0.010)	(0.010)	(0.009)	(0.009)	(0.005)	(0.005)	(0.005)
Patent expenditure (1k Francs)						0.068	
						(0.004)	
Duration 10 years							0.037
							(0.005)
Duration 15 years							0.064
							(0.005)
Defaulted on 2nd installment							−0.039
							(0.005)
Constant	0.620	0.249	0.181	0.243	0.048	0.006	0.037
	(0.005)	(0.005)	(0.004)	(0.004)	(0.002)	(0.004)	(0.003)
Observations	11387	11387	11387	11387	11387	11387	11387
R^2	0.036	0.010	0.016	0.005	0.000	0.020	0.021

Observation = Patent. Sample: All invention and imitation patents 1791 to 1843. Imitation patent compares against baseline of invention patent (constant). Standard errors in parentheses.

place of birth is the most widely available variable.

Our algorithm is a simple random forest with 100 trees. As features for the classification, we use the frequency of ASCII signs in last names and the 15 percent two and three-letter syllables for which the frequency is most different between French and British names. The INPI dataset of historical patents necessitates the use of ASCII signs. Apostrophes and other characteristically French signs are not reliably reported, so we cannot rely on them. When learning the three with 80 percent of the Wikipedia data and using the remaining 20 percent as test data, we can achieve 97 percent accuracy. Relying on two and three-letter frequencies is the key for this result, as our classification algorithms using only letter frequencies achieved accuracy rates around 80 percent at best.

Since the ratio of British to French names is about 1 to 10, we were delighted to see that the rate at which we misclassify French names as British is much lower than the rate at which we misclassify British names as French. An example helps to illustrate why this is important. If we have 1000 French inventors and 100 British, and we misclassify 10 percent of the French as British, half of the inventors we classify as British are French. This would make our measure of British inventors extremely noisy. If, on the other hand, we classify 10 percent of British inventors as French, then only 1 percent of French inventors are British, and we catch 90 percent of British inventors.

We can identify British names using a second method as well. Here we create a dictionary of names and nationalities based on all historical names available in either of our two datasets. Then we classify names as British if they are in the dictionary.

In the last step, we then combine the random forest with the dictionary. When the two agree that a name is British, it is considered British. If a name does not appear in the dictionary, the assignment of the random forest is used. If the dictionary and the classification algorithm disagree, we classify the origin of the inventor as unknown. At first, it may seem surprising that we do not trust the dictionary more than the random forest. We take this approach because when inspecting cases when the two disagree, no clear pattern emerges which one is better.

1.B Additional Results and Robustness

1.B.1 Dropping small technologies

Here, we show that the strong, positive association at the technology level, between technologies and between technologies within industries, is robust to the exclusion of small technologies. We drop small technologies with less than ten patents, as they might cause a positive association by fixing the anchoring the regression line at zero in terms of technologies with scant invention and scant imitation. In figure 1.12, we reproduce the basic graph at the technology level because it will be the backdrop for the individual industries. As already shown in table 1.1, column (8), the regression coefficient of log imitation on log invention increases to one if we exclude the small technologies. In figure 1.13, we reproduce the graph within industry for each of the 30 industries. The association between invention and imitation stays strikingly positive. The association becomes negative only in two industries (fuel and mining) and flat in one (industrial arts). In all other industries, it is essentially unaffected by the exclusion of small industries.

1.B.2 Alternative classification of invention versus imitation

Table 1.6 provides an overview of how many patents there are within the different groups of invention and imitation. It breaks down patents by category (innovation vs. importation), address (French or foreign), and nationality (French or British). In our baseline analysis, we include 8849 patents as invention (innovation category, French name, and address) and the rest (2538) as imitation, which includes importation patents (1512), British migrant inventors (700), and other likely foreign actual inventors (326).

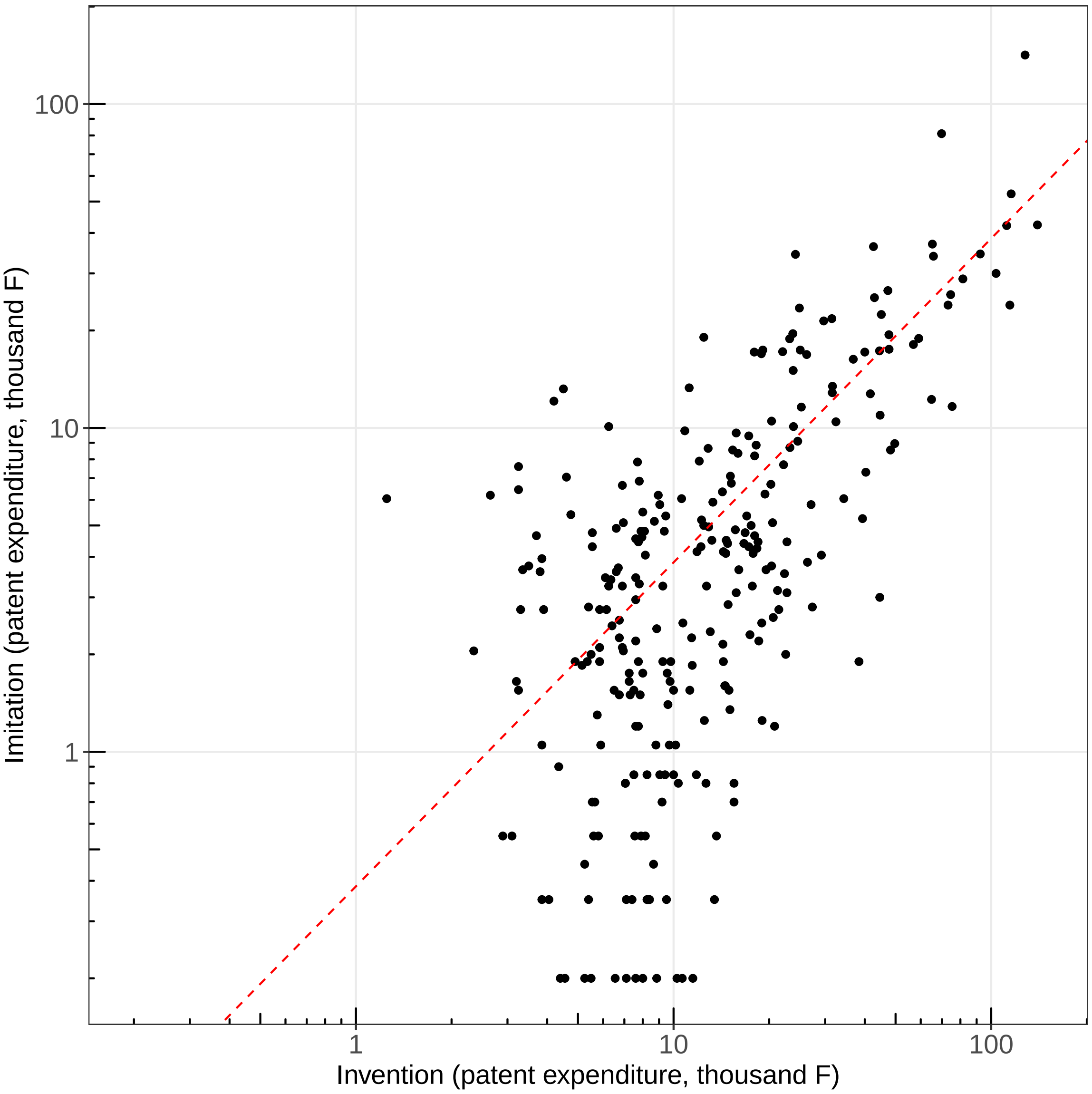
Table 1.6: Breakdown of invention and imitation into patent groups

	French name			British name		
French address	Innov	8849		Innov	700	34.5%
	Import	605	22.9%	Import	168	
Foreign address	Innov	217	19.2%	Innov	109	23.4%
	Import	272		Import	467	

There were 11387 patents until reform 1844, out of which we classify 2538 as imitation. Importation is the principal category for imitation patents. The most common foreign address is Britain. British nationality is predicted from last names.

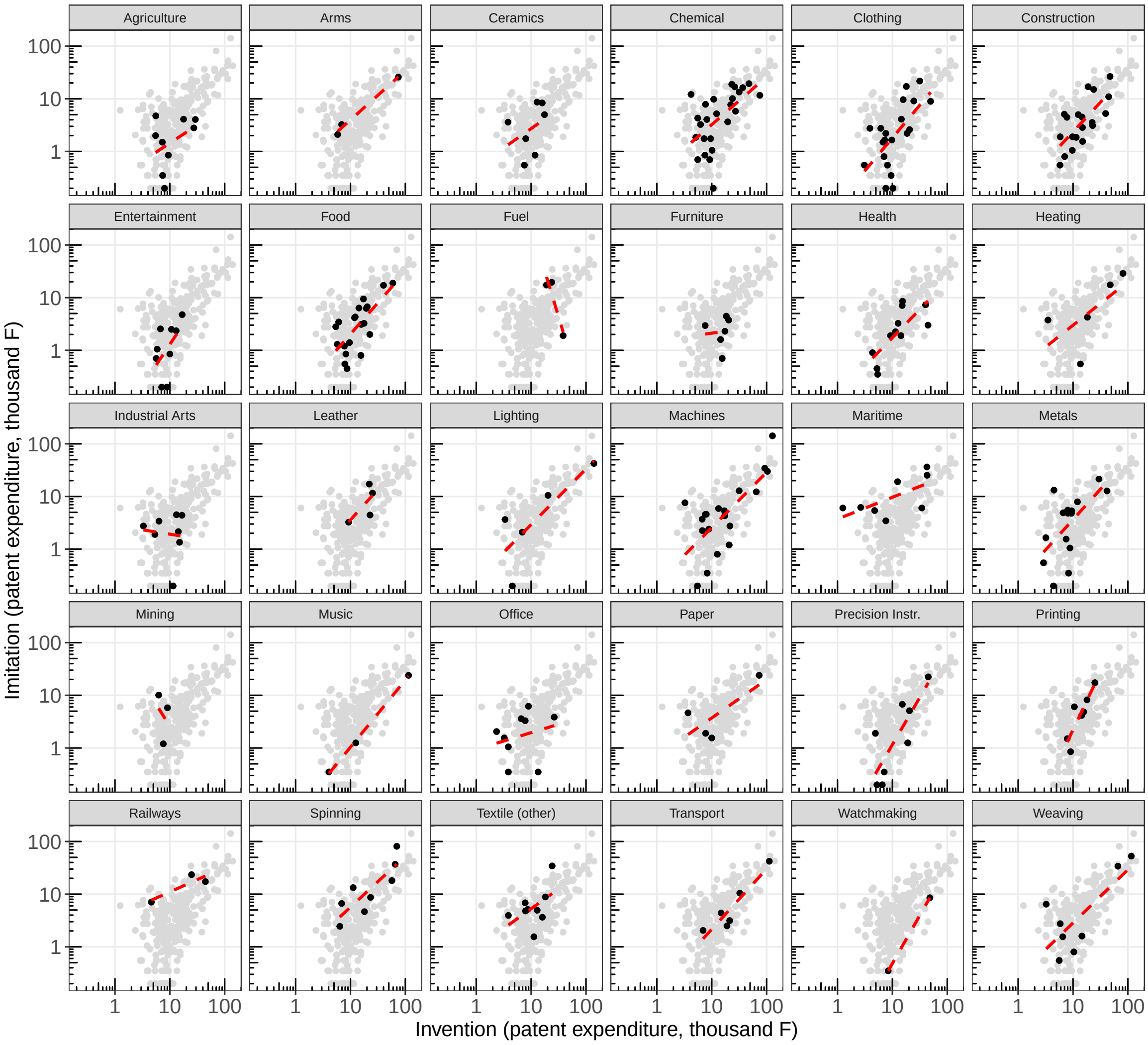
1.B.3 Before and after growth take-off

This section shows that our main results are qualitatively robust in the sub-periods before and after the take-off of modern economic growth. Thus, we split the sample from 1791 to 1830 and 1830 to 1843 (the patent law reform).



Note: Each dot is a technology. The dashed line plots the linear regression line of log imitation on log invention. Technologies with less than 10 patents until 1843 are excluded. Technologies without imitation patent are assumed to have 200F patent expenditure (the smallest possible amount; 9 cases).

Figure 1.12: Association of invention and imitation at technology level



Note: Each box is one industry, each dot is a technology. The dashed lines plots separate regressions of log imitation on log invention within industry. Technologies with less than 10 patents until 1843 are excluded.

Figure 1.13: Association of invention and imitation at technology level within industries

Table 1.7: Robustness for sub-periods

	Dep. var.: Ln imitation							
	1791 to 1814		1815 to 1829			1830 to 1843		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ln invention	1.097	0.515	0.814	0.880	0.347	0.972	0.807	0.638
	(0.216)	(0.125)	(0.259)	(0.119)	(0.090)	(0.105)	(0.096)	(0.061)
Industry FE				Yes			Yes	
Subindustry FE					Yes			Yes
Observations	28	54	29	60	162	29	75	287
adjusted R^2	0.412	0.196	0.431	0.570	0.211	0.661	0.651	0.403

Observation = industry (columns 1, 4), sub-industry (columns 2, 5), technology (columns 3, 6). Invention and imitation are measured as total patent expenditure within the sub-period (in 1k Francs). Robust standard errors in parentheses. All coefficients on ln invention are significant at the 1%-level.

2 Why Britain? The Right Place (in the Technology Space) at the Right Time

with Carl Hallmann and Walker Hanlon

Why did Britain attain economic leadership during the Industrial Revolution? We argue that Britain possessed an important but underappreciated innovation advantage: British inventors worked in technologies that were more central within the innovation network. We offer a new approach for measuring the innovation network using patent data from Britain and France in the 18th and early 19th century. We show that the network influenced innovation outcomes and then demonstrate that British inventors worked in more central technologies within the innovation network than inventors from France. Then, drawing on recently-developed theoretical tools, we quantify the implications for technology growth rates in Britain compared to France. Our results indicate that the shape of the innovation network, and the location of British inventors within it, can help explain the more rapid technological growth in Britain during the Industrial Revolution.

2.1 Introduction

One of the enduring questions of the Industrial Revolution is: why was Britain able to achieve more rapid economic growth than other European countries? There is now a substantial list of potential British advantages, including the country's uniquely practical Enlightenment tradition (Mokyr, 2009), its well-developed apprenticeship systems (Kelly, Mokyr, and Ó Gráda, 2014), the stable institutions established in the wake of the Glorious Revolution of 1688 (North and Weingast, 1989; Acemoglu, Johnson, and Robinson, 2005), higher wages (Allen, 2009), and its advantageous natural resources (Pomeranz, 2000; Fernihough and O'Rourke, 2014). Despite the substantial body of ongoing research on this topic, the debate remains largely unsettled.

In this study, we argue that there is one important British advantage that has been largely overlooked: the possibility that British inventors may have been working "at the right place" in the *technology space*. Our idea builds on emerging literature in growth economics which finds that innovation in some technologies generates more spillover benefits than innovation in others (Acemoglu, Akcigit, and Kerr, 2016; Cai and Li, 2019; Huang and Zenou, 2020; Liu and Ma, 2021). As a result, a country's allocation of researchers across technologies can substantially impact the overall rate of economic growth. In particular, this literature shows that technological progress will be faster in economies where more research effort is focused on technologies that generate more spillovers for other technologies; in other words, technologies that are more *central* in the technology space.

Translating these ideas into the context of the Industrial Revolution, we ask: did Britain experienced more rapid technological progress because British inventors were more focused on technologies, such as steam engines, machine tools, or metallurgy, that generated stronger spillover benefits for other technologies and were therefore more central in the technology space? In contrast, could it have been the case that Continental economies like France experienced slower technological progress because they specialized in developing technologies, such as apparel, glass, or papermaking, which were more peripheral in the technology space?[1]

Put another way, we aim to examine whether Britain's differential growth during the eighteenth and early nineteenth centuries can be explained by the distinct position of British inventors in the technology space. By starting with ideas from modern growth economics, our analysis is less subject to the type of "post hoc, proper hoc" concerns that have been raised about some other explanations (Crafts, 1977, 1995). Moreover, we offer a theoretically-grounded quantification describing exactly how much of Britain's differential growth experience can be attributed to this mechanism. These two features differentiate our study from most existing work that aims to understand Britain's growth lead during the Industrial Revolution.

To structure our analysis, we begin with a growth model, from Liu and Ma (2021), that incorporates an innovation network. In this network, each node is a technology

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[1] Hallmann, Rosenberger, and Yavuz (2021) show that technological leadership in invention of Britain relative to France varied across technologies, with Britain leading, besides others, in steam engines and textile technologies, and France leading, besides others, in papermaking and shoemaking. Mokyr (1990, Chapter 5) provides a historical overview on British technological lead or lag in invention relative to Continental Europe.

type, while each edge reflects the extent to which innovations in one technology type increase the chances of further innovation in another. This model provides a framework for thinking about how the distribution of researchers across technology sectors relates to the growth rate in the economy. It also generates specific expressions that, given the matrix of connections across sectors, allow us to quantify how different allocations of researchers across technology sectors will affect growth. The upshot is that allocations in which more researchers are working in technology sectors with greater spillovers will generate higher overall growth rates than others. Therefore, the growth maximizing allocation of researchers will feature more researchers working in more central technology sectors: specifically, those sectors with higher eigenvalue network centrality. Furthermore, the model delivers precise analytical relationships that allow us to quantify the implications of different allocations of research effort for the rate of economic growth.

To examine whether these forces operated during the Industrial Revolution, we utilize patent data for Britain, from 1700 to 1849, and for France from 1791-1844.[2] These historical patent data cover a large number of inventors and their inventions, providing a rich source of information on innovation during the Industrial Revolution.[3] We follow a long line of work, dating back at least to Sullivan (1989), using patent data to better understand innovation patterns during this period.

A key challenge in our setting is measuring spillovers across technology categories. The innovation literature typically uses patent citations, but these are not available in our historical setting. Instead, we introduce a new approach based on the idea that if there are spillovers between two technology categories, then inventors working primarily in one area will occasionally file patents in the other. In particular, we measure the extent of spillovers from technology category j to i based on the propensity of inventors who patent in j to subsequently patent in i.

Since our approach is new, we validate it using modern data. Specifically, using U.S. patents from 1970-2014, we construct innovation networks using our approach as well as the citation-based approach used in modern studies. Comparing these networks shows that the two approaches generate networks that are extremely similar. This suggests that our method does a good job of recovering the underlying innovation network. Developing and validating this new approach to measuring innovation networks is one contribution of our study.

Using our approach, we document technology networks in Britain and France that fea-

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[2] Both of these were periods during which the patent systems were largely stable. We end just before the major British patent reform of 1852 and the French patent reform of 1844.

[3] Of course, not every useful invention was patented, as (Moser, 2012) has shown.

ture a dense central core of closely related—and mainly mechanical—technologies. One important question about our estimated networks is, do they reflect fundamental features of the underlying technologies or simply reflect the local innovation environment in each country? One way to test this is to compare the networks obtained from the two countries. If they are similar, they likely reflect fundamental technological features rather than idiosyncratic conditions. Conducting a direct comparison, however, is challenging because the two countries use very different technology categorizations. Therefore, it is necessary to construct a mapping of technology categories from one country's categorizations to the other. To do so, we carefully identify a set of inventions that were patented in both countries. We can then use the categorization of these inventions in each system to construct a crosswalk between the technology categorizations used in the two countries.

Using this mapping, we construct technology spillover matrices from French patents but in terms of British technology categories, or from British patents but expressed in French technology categories. This allows us to regress the entries of the technology matrices of one country on the entries of the other country. We find they are strongly positively related, despite the noise that is inherent in any mapping between different systems of technology categorization. This indicates that our innovation matrices not just reflect the local economic environment, but that a significant part of each represents an underlying 'global' network of technology spillovers.

Next, we establish that the shape of the technology spillover network matters for innovation outcomes. As a first step, we follow existing work on modern patent data by analyzing how patenting rates vary across technology categories depending on the lagged knowledge stock in other categories, weighted by the strength of connections through the innovation matrix. Consistent with the theory, and the results in previous studies of modern data, we find a significant positive associations of patenting with the lagged network weighted knowledge stock, shrinking toward zero as lags increase. However, the lack of exogenous variation in the lagged knowledge stock means that this result could be due to common shocks that affect connected technology categories.

Thus, in the second step, we provide evidence based on a source of quasi-exogenous variation in the timing of increases in the knowledge stock at some nodes of the innovation network. Specifically, we use the unexpected arrival of "macroinventions." These are inventions which Mokyr (1990) describes as "a radical new idea, without a clear precedent, emerges more or less ab nihilo." We take three approaches to identifying macroinventions. In one, we use a a list of 65 macroinventions from Nuvolari, Alessandro, Tartari, and Tranchero (2021). In a second, we focus on inventions that were the first listed in a particular technology subcategory. Our third measure is the intersection of the first two, which identifies patents that were both important and new.

We then examine whether the arrival of a new macroinvention in one technology category leads to a subsequent increase in patenting in downstream technology categories within the innovation network. Here, the identifying assumption is *not* that the location of macroinventions were random, but that the timing of their arrival at a given location was unpredictable within the time frame of analysis. Using pooled difference-in-difference and event study analyses for a time frame of ten years before and after the arrival of each macroinvention, we show that macroinventions are followed by significant increases of the patenting rates in technology categories sharing stronger (downstream) connections from the technology category of the macroinvention. In addition, we find no evidence of an increase in technology categories as a result of being upstream from the macroinvention technology category within the innovation network. This second result provides a useful placebo check on our analysis.

Next, we look at whether there are notable differences in the allocation of British and French inventors within the innovation network. In particular, we focus on whether British inventors were patenting in technology categories that were more central within the innovation network than French inventors. We do this by studying, within the sets of British and French patents whether foreign inventors (of British or French origin) were patenting in more central technology categories than domestic inventors.[4] We find that among French patents, patents by British-based inventors were significantly more central compared to the average patents by French domestic inventors—and all other foreign inventors—, whereas among British patents, patents by French-based inventors were less central compared to the average patent by British domestic inventors. The pattern indicates that British inventors were more likely to work in central technology categories than French inventors. As more central nodes have stronger spillover connections to other technology categories, the more central locations occupied by British inventors are consistent with a greater "bang for the buck" of British innovation on the aggregate rate of technological progress.

Finally, we quantify the growth implications of the observed innovation network and different allocations of inventors in Britain and France through the lens of the model. Existing estimates for Britain suggest that industrial production grew by between 3 and 3.5% during the first half of the nineteenth century (Broadberry, Campbell, Klein, Overton, and van Leeuwen, 2015). In France, estimates indicate growth rates of between 1.7 and

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[4] We also attempted to study whether British vs. French inventors were more central within the innovation network of a third country, using U.S. patent data. Unfortunately, this analysis is not possible because U.S. patents only become available starting in 1836 (earlier patent information was lost due to a fire) and there are too few British and French inventors patenting in the U.S. in the two decades after that to draw any clear conclusions on their relative centrality within the U.S. network.

2.5% in the same period (Crouzet, 1996; Asselain, 2007). (Preliminary) Results from our quantification exercise show that differences in the allocation of inventors across technology categories led to a technology growth rate in Britain that was between 0.5 and 2.9 percent higher than the French technology growth rate. Thus, our results indicate that Britain's more advantageous position in the innovation network can explain a substantial fraction, and possibly the entire difference, in growth rates between the British and French economies during the first half of the nineteenth century.

In sum, the evidence presented in this paper shows that Britain benefited from an advantageous distribution of inventors across technology sectors during the Industrial Revolution, and that this difference meaningfully contributed to Britain's more rapid industrialization. Our analysis takes as given the differences in the distribution of inventors across sectors. Thus, our mechanism complements explanations for the British advantage during the Industrial Revolution, in particular those that can explain why British inventors were more likely than the French to work on technologies that happened to be more central within the innovation network, in particular mechanical technologies. For example, it could be that Britain's practical Enlightenment tradition and well-developed apprenticeship system (Mokyr, 2009; Kelly et al., 2014) contributed to the British inventors' greater ability for working on mechanical technologies, or that high wages and access to cheap coal steered British inventors to focus on labor-saving mechanical devices (Allen, 2009).[5] Put differently, the contribution of our paper lies in demonstrating *that* Britain was at the right place in the technology space at the right time, rather than explain *why* it was there but France was not.

In addition to improving our understanding of one of the most important questions in economic history, our study also contributes to work by growth economists on the importance of innovation networks. Relative to studies in this area (cited above), we offer two main contributions. First, we offer new methods that can help researchers study innovation networks further back in history, when standard tools such as systematic patent citations are unavailable. This opens up the possibility of studying the influence of innovation networks in different contexts or over longer periods. Second, our analysis of macroinventions provides additional, more causal, evidence that innovation networks matter for technology development. Third, our application demonstrates empirically the value of recent theoretical advances integrating innovation networks into economic growth

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[5] A stable institutional environment and well-developed patent system may have contributed in shifting inventors from technologies that can be protected by secrecy toward technologies as mechanical devices that are easily reverse engineered and thus profit the most from patents (Moser, 2005). However, as both Britain and France had strong patent protection, it is unclear how this mechanism could explain the *differential* focus of British vs. French inventors on mechanical devices.

models.

Our work builds on a long line of literature using patent data to examine innovation during the Industrial Revolution and into the nineteenth century. Early papers in this area include Sullivan (1989) and Sullivan (1990). More recent work includes MacLeod, Tann, Andrew, and Stein (2003), Khan and Sokoloff (2004), Moser (2005), Khan (2005), Brunt, Lerner, and Nicholas (2012), Nicholas (2011), Nuvolari and Tartari (2011), Moser (2012), Bottomley (2014b), Bottomley (2014a), Burton and Nicholas (2017), Khan (2018), Bottomley (2019), Nuvolari, Tortorici, and Vasta (2020), Nuvolari et al. (2021), Hallmann et al. (2021), and Hanlon (2022). Relative to this extensive literature, we are the first to study the role of innovation networks in influencing inventive activity during the Industrial Revolution.

The next section of this paper presents our theoretical framework. We then introduce our data, in Section 2.3 and discuss our approach to measuring the innovation network, in Section 2.4.1. Section 2.4.3 describes and compares the estimated innovation networks, while Section 2.5 provides evidence that the structure of the network has a causal effect on innovation rates. Section 2.6 shows that British inventors tended to operate in more central nodes of the innovation network. Finally, Section 2.7 uses the structure of the model to quantify the impact of these differences on each country's growth rate.

2.2 Theory: Growth with Innovation Networks

This section presents a theory of growth with innovation networks based on recent work by Liu and Ma (2021). The key feature of their model is the introduction of a matrix of spillovers across technology sectors into a continuous-time closed-economy endogenous growth framework. At the outset, it is important to recognize that our aim is to study the impact of different allocations of research effort across technology categories on the growth rate of an economy. Thus, we take the allocation of researches as given.[6]

2.2.1 Preferences and Production

The model features a representative consumer with utility at time t that is a function of discounted log consumption c_s in period t and all future periods:

$$V_t = \int_t^\infty e^{-\rho(s-t)} \ln c_s \, ds \quad .$$

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[6] These allocations may be due to a range of factors, including individual choices, market forces, government policies, or persistent historical conditions, which we do not attempt to model.

Consumption is a Cobb-Douglas aggregation of consumption of goods from K different sectors,

$$c_s = \sum_{i=1}^{K} c_{it}^{\beta_i} \quad ,$$

where the β_i parameters give the consumption shares for each sector i and $\sum_i \beta_i = 1$ (consumption is Cobb-Douglas).

Within each sector i, there is a continuum of varieties of intermediate products, denoted by ν, which can be supplied in a countably infinite set of quality levels. The highest quality level available for any variety is given by $q_{it}(\nu)$. Only the highest quality version of each variety is used in the production process. We denote the quantity of a variety of quality q produced as $x_{it}(\nu|q)$ and total production (and consumption) of goods from sector i is:

$$\ln c_{it} = \int_0^1 \ln \left(q_{it}(\nu) x_{it}(\nu|q) \right) \, d\nu$$

Given some available quality level, production in a sector depends only on the number of workers allocated to that sector: $x_{it}(\nu|q) = l_{it}(\nu)$ where l_{it} is the quantity of labor employed in sector i.

2.2.2 Innovation

Following Liu and Ma (2021), we define the knowledge stock available in a sector i at time t as q_{it}, where $\ln q_{it} = \int_0^1 \ln q_{it}(\nu) \, d\nu$. These knowledge stocks are the state variables in the model. The knowledge stock in a sector improves through the efforts of researchers, r_{it}, working on developing new technologies in that sector at time t. The innovation production function is given by:

$$n_{it} = r_{it} \, \eta_i \, \chi_{it} \quad \text{where} \quad \chi_{it} = \Pi_{j=1}^{k} q_{jt}^{\omega_{ij}} \, . \tag{2.1}$$

In this expression, n_{it} is the set of new ideas in sector i generated in time t, which in our empirical application will be represented by patents, η_i is a parameter that determines the productivity of research effort in sector i, and χ_{it} reflects the impact of spillovers across the innovation network that improve the chances of generating new innovations in sector i. These spillovers depend on the stock of knowledge in every other sector and a matrix of ω_{ij} parameters that determine the extent to which existing ideas in sector j increase the changes of producing new ideas in sector i. These will be the key parameters in our study. In order to obtain balanced growth across sectors, we need to assume that $\sum_j \omega_{ij} = 1$

for all i. We denote the $K \times K$ matrix of these parameters as Ω, which we refer to as the *innovation network*.

New ideas translate into incremental quality improvements according to the following relationship:

$$\dot{q}_{it}/q_{it} = \lambda \ \ln(n_{it}/q_{it}) \tag{2.2}$$

where the inclusion of q_{it} in the denominator on the right-hand side of this equation reflects the idea that improving quality becomes more difficult as the quality level rises. This formulation is intuitive in that it reflects the idea is that improvements become more difficult once the "low-hanging fruit" has been harvested. It also plays an important functional role in the model, because it means that the continually increasing stock of existing knowledge, which generate a corresponding increase in useful knowledge spillovers, does not generate explosive growth.

2.2.3 Resource constraints

To keep the model simple, we fix the number of production workers at $\bar{l}$ and the number of researchers at $\bar{r}$. Thus, $\sum_i l_{it} = \bar{l}$ and $\sum_i r_{it} = \bar{r}$. These assumptions abstract from the potentially important possibility that changes in the productivity of research activities may cause more workers to shift into research, but they substantially simplify the model.

2.2.4 Key results

The model provides several results that we will use in our empirical analysis. The first of these is related to how the innovation network determines the relationship between the current stock of knowledge in one sector and the rate of innovation in other sectors. We can derive this relationship from Equations 2.1 and 2.2. We obtain:

$$\ln n_{it} = \ln \eta_i + \ln r_{it} + \lambda \sum_{j=1}^{K} \omega_{ij} \left(\int_0^\infty e^{-\lambda s} \ln n_{j,t-s} \, ds \right) \tag{2.3}$$

This is a useful expression for our purposes, because it shows how the current knowledge stock in related sectors, represented by the term on the far right, influences the current pace of technology development. Later, we will use this expression to structure our investigation of whether our estimated innovation network matters for innovation outcomes.

A second key result has to do with the relationship between the distribution of research effort across sectors and the growth rate. It is useful to start by defining **a** as the dominant left eigenvector of Ω with an eigenvalue of one. As described by Liu and Ma (2021), the vector **a** exists and is unique. Let **b** be a vector of researcher allocations across sectors, so that each element $b_i = r_i/\bar{r}$. Liu and Ma (2021) then provide the following useful result:

Proposition: For a balanced growth path with researcher allocation vector **b**, the aggregate stock of knowledge and consumption in each sector grows at the rate $g(\mathbf{b}) = c + \lambda\,\mathbf{a}'\ln\mathbf{b}$ where c is a constant term that depends on the total stock of researchers, the λ and η parameters, and **a**.

From this proposition we get two useful additional results:

Corollary 1: The difference in the growth rates between implied by two different distributions of researchers across sectors, **b** and $\tilde{\mathbf{b}}$ is: $g(\tilde{\mathbf{b}}) - g(\mathbf{b}) = \lambda\mathbf{a}'(\ln\tilde{\mathbf{b}} - \ln\mathbf{b})$.

This result tells us that given **a** and λ, we can easily calculate the difference in growth rates implied by different allocations of researchers across sectors. The second useful result has to do with the growth-maximizing allocation of researchers, which we label $\mathbf{b}^*$. This is,

Corollary 2: The allocation of researchers that maximizes the rate of technology growth, $\mathbf{b}^*$, solves $argmax_b \quad \mathbf{a}'\ln\mathbf{b}$ subject to $\mathbf{b} \geqslant 0$ and $\mathbf{1}'\mathbf{b} = 1$. The solution to this problem is the vector **a**.

This result tells us that the growth-maximizing allocation of researchers is the allocation that mirrors the vector of innovation centrality **a** obtained from the innovation network.[7] Both of these results will come in handy in our empirical analysis, which we turn to next.

2.3 Data

2.3.1 Patent data

The patent data used in our analysis were digitized from the *Titles of Patents of Invention, Chronologically Arranged* collected by the British Patent Office (BPO). These data cover England and Wales, but for ease of exposition we will refer to them as "British" patents throughout the paper. These data include the patent number and date and the inventor name and occupation for over 12,500 patents from 1700 to 1849. This was a period of stability in British patent law, which ended in 1852 when a major patent reform was adopted. The printed volumes also include information on the inventor address and the patent title. We

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[7] This is not the same as the welfare-maximizing allocation, since the welfare-maximizing social planner will be willing to sacrifice some future growth in order to increase current consumption because future consumption is discounted.

add to these data technology classifications, produced by the BPO, which classify each patent into one or more of 147 technology categories.[8]

The most important feature of our patent data set is that patents by individual inventors have been linked using a time-consuming careful manual linking procedure. We form links using all of the available information in the patent data, and in some cases additional external biographical information, following a procedure that is described in more detail in Hanlon (2022). Starting from 13,972 patent-inventor observations, this procedure identifies 8,980 individual inventors. Most of these inventors were located in the U.K., though a small number filed patents from abroad. In addition, 1,350 patent-inventor observations were "communicated from abroad." In these cases, the location and name of the original inventor is unknown.

The French patent data used in our main analysis begin with the initiation of a modern patent system in 1791 and end in 1843, just before the major patent reform of 1844. These data, which come from the French National Patent Institute (INPI) and were previously used in Hallmann et al. (2021), include patent number, patent title, inventor name, inventor occupation, inventor address, and additional details such as the type of patent and the patent term. French patents are divided into three main types: patents of invention, the standard format for new inventions, patents of importation for inventions imported from abroad, and patent of improvement for improvements on existing designs. Our analysis focuses on the first two of these, as they are the categories that represent truly new inventions.[9] The French patent data also include a technology category classification for each patent. Unlike the British classifications, each French patent is matched to exactly one out of 85 technology categories.

As in the British data, we have manually linked patents by the same inventor in the French patent data using the full set of available information.[10] Starting with 14,277 patent-inventor observations based on just over 11,000 patents, this matching procedure identifies around 10,500 unique inventors.

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[8] See Hanlon (2022) for additional details about these data.

[9] Patents of improvement provided a less expensive way to modify an inventor's existing design, but they did not extend the term of the original patent. Another difference between the French and British patent systems is that in France inventors could choose to apply for patents of different lengths: 5, 10, or 15 years. Longer patent terms required higher fees.

[10] These links are likely to be even more reliable than those in the British data, because French inventors were less likely to have common names and many inventors had three, four, or five names.

2.3.2 Mapping between technology categories

An important challenge in our analysis is constructing a reliable mapping between the French and British technology categories. The difficulty is that the two nation's patent offices employed structurally different systems of classifying patents into technology categories.

We build our mapping by matching patents that were filed both in Britain and in France. Using the technology categorizations applied to the same patent in the two locations, we build a probabilistic mapping between French and British technology categories. The most challenging part of constructing this mapping is therefore identifying patents filed in both locations.

We can construct three sets of patents filed in both countries. For the first set, we begin with all patents filed in Britain with inventors reporting a French address and then search for matching French patents. For the second set, we begin with all patents filed in France before 1844 with an inventor reporting an address in Britain and then search for matching British patents. For both of these sets, we determine a match based on the name of the inventor, the patent title, and the temporal proximity of the patent date. This is done through a manual review in order to account for the fact that patents typically have somewhat different titles in the two countries, and one patent often appears one, and sometimes a few, years later than the other. A third set of matched patents were filed in France between 1844 and 1852. For this group, we take advantage of the fact that, as part of the 1844 French patent law reform, the length of protection for French patents of inventions were previously patented abroad depended on the filing date of the original foreign patent. As a result, the French patent office recorded the origin location and filing date of foreign patents. These data allow us to make a direct match between a number of French patents of British technologies filed after 1844. Combining these three groups, and eliminating any duplicate entries, we have 1,140 patents filed in both locations from which to construct our technology category mapping.[11]

This set of matched patents enables us to construct a probabilistic mapping from French to British technology categories. Specifically, if a fraction θ_{ij} of French patents filed in French category i corresponded to British patents classified into British category j, then we assign patents from French category i to British category j with a weight of θ_{ij} (see Appendix 2.B for further details and discussion). This provides a procedure through which

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[11] We get 127 matched patents in the first set, 167 in the second, and 855 from the third (where we have better information to identify unique matches). In case there are concerns about the matching procedure used for the first two sets of matched patents, we have also generated results using only the third set of matched patents to construct the mapping. This generates similar results, which shows that the patent matching procedure applied to the other two sets of patents does not have a substantial influence on our results.

we can reassign all French patents into British technology categories (or vice versa). Overall, the mapping obtained using this method gives results that appear reasonable (see Appendix Tables 2.10 and 2.11), though it is also clear that differences in the technology classifications will also introduce noise into analysis where it is necessary to convert patents from one country into the technology classifications of the other.

2.3.3 Input–output connections

When analyzing the effect of the innovation network on patenting activity, it will be important to differentiate the influence of the technology space from the influence of the product space that operates through input-output channels (Bloom, Schankerman, and Van Reenen, 2013). To do so, we need to construct a control reflecting the extent to which our technology categories are linked through input-output connections. This requires (1) data on the input-output connections between industries and (2) a mapping between industries and our input-output categories. To our knowledge, no mapping of this kind exists for the historical period we study, and even in modern settings constructing such a mapping can be challenging (Griliches, 1990).[12]

As for the data, we use the input–output (IO) table for Britain in 1907 constructed by Thomas (1984), which gives us a matrix of upstream and downstream connections between 33 industries, to measure product space connections between technology category nodes.[13] This is the earliest point for which a detailed input-output matrix for the British economy is available.[14]

We introduce a novel approach to constructing a mapping between technology categories and industries based on occupation information in patent data. In particular, we use that a substantial fraction of the occupations reported by patenting inventors can be unambiguously associated with specific industries, for example, "cotton textile manufacturer," "paper maker," or "button manufacturer." To construct our mapping, we reviewed just over 7,000 occupations found in the British patent data and manually linked them to industries in the IO matrix. We link just over 3,400 occupations to industries, providing us with 4,295 patents

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[12] One aspect that makes this mapping challenging is that it is often not clear whether a technology category should be applied to industries that produce the technology or those that use it. Another challenge is that patents in some important technology categories (e.g., "Valves") may be both produced by and used by a number of different industries.

[13] The original dataset contains 41 sectors, from which we exclude the four service sectors (*Laundry*, *Public utility*, *Distributive services*, *Other services*), aggregate the four chemical industries to one because of difficulties to match unique occupations (*Chemicals*, *Soap and candle*,*Oils and paint*, *Explosives*), and exclude the *Motor and Cycle* industry because it did not yet exist during our period.

[14] Horrel, Humphries, and Weale (1994) provide an input-output matrix for the British economy in 1841, but it is much less detailed than the matrix available from Thomas (1984).

linked to industries. As these patents are also classified into technology categories, we can use these to construct a probabilistic mapping from technology categories to industries.[15]

Based on the available IO matrix together with our novel mapping from technology categories to industries, we construct matrices reflecting both upstream and downstream IO connections between technology categories. Further details on the construction of this control are available in Appendix 2.C. As discussed in this appendix, the procedure delivers results that appear to be quite reasonable.

2.4 Measuring the innovation network

One of the contributions of this study is the introduction of a method for obtaining innovation matrices in historical settings where no systematic patent citation data are available. We start this section by describe how our measure of the network. We then provide evidence from modern data that our method can generate results that are very close to those obtained when using citation data. Last, we describe the innovation networks from Britain and France during the Industrial Revolution recovered using our method.

2.4.1 Method for measuring the innovation network

In modern settings, where citation data are available, existing studies measure the strength of spillovers from some technology category j to category i as $\omega_{ij}^{cite} = Cites_{ij} / \sum_l Cites_{il}$, where $Cites_{ij}$ is the number of patents in category i citing patents in category j (e.g. Liu and Ma, 2021). In the citation-based approach, the key assumptions are that some fraction of the useful ideas generated through research in technology j that increase research productivity in technology i are reflected in citations from i to j, and that this fraction is fairly stable across all i-j pairs.

Our approach to measuring connections between technology categories relies on a similar intuition. The basic idea in our approach is that by working on research in technology category j, an inventor may learn lessons that lead to a subsequent invention in technology category i. So, when there are more inventions in category j are followed by inventions in category i by the same inventor, that signals a higher the level of knowledge spillovers from j to i. The key assumptions in our measure are that some fraction of the useful ideas generated through research in technology j that increase research productivity in technology i lead to one or more patents in technology i by inventors who previously

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[15] Specifically, we construct a set of weights ϕ_{in} reflecting the ratio of patents in technology category i that are linked to industry n to the total number of patents in category i that are linked to an industry.

patented in technology j, and that these fractions are fairly stable across i-j pairs.

Let P_{kij} be the (weighted) count of pairs of patents by inventor k where the first patent is filed in technology category j and the next patent is filed in technology category i. By "weighted count" we mean that, for patents categorized into multiple technology categories, which only occurs in the British system, each category receives a fraction of a patent that depends on the number of categories across which the patent is listed.

Let P_{ki} be the total number of patents in technology category i by inventor k which pair with an earlier patent, which can be either in i or in another technology category. Our measure of the strength of connections from category j to i is given by:

$$\omega_{ij} = \frac{\sum_k P_{kij}}{\sum_k P_{ki}} \tag{2.4}$$

The result is a directed matrix of connections from j to i constructed using a method that is very similar to the approach used with patent citations by studies in modern data. Intuitively, our connection values ω_{ij} can be thought of as the fraction of knowledge flows into category i coming from category j, as reflected in the number of inventors who file patents in i just after a previous patent in j. Later, we will show that our method, when applied to modern data, generates an innovation network that is almost identical to the network obtained when using citation data.

Mapping network into foreign categories In some of the analysis below, it will be useful to have an innovation network based on British patents but expressed in French technology categories, or a network based on French patents but expressed in British technology categories. Constructing these networks requires us to use our mapping between the two technology categories. Let $\theta_{i\tilde{i}}$ be the weight used to map patents from, say, French technology category i to British category $\tilde{i}$. Given this, to construct an innovation matrix based on French patents but expressed in British technology categories (or vice versa) we use:

$$\tilde{\omega}_{ij} = \frac{\theta_{i\tilde{i}}\theta_{j\tilde{j}} \sum_k P_{kij}}{\theta_{i\tilde{i}} \sum_k P_{ki}}$$

Joint network Finally, in some of the analysis below we will use a joint matrix constructed using both French and British patents, where one of these sets has been mapped into the technology categories of the other country. A number of potential methods might be used to construct these joint matrices. Any method requires a judgment about the relative weight that should be granted to patents from each system in determining the joint matrix. However, because patents in the two systems are the product of different patent systems and institutional environments, there is no clear way to determine the correct weighting to be applied. Given this, we opt for a simple approach that gives each system equal weight in determining the joint matrix. Specifically, we construct joint matrices where each element is the average of the elements of the matrices constructed from the two different sets of patent data (but expressed in terms of the same technology category).

2.4.2 Validating our method

Whether the method described above provides a useful measure of the innovation network is ultimately an empirical question. To provide some confidence that our method works, before moving to our main analysis we look at how the innovation network generated using our method in modern data, where we also have citations, compares to a network based on citation links. To do so, we use data on U.S. patents from 1970-2014 from PatStat. As described in more detail in Appendix 2.F, we generate a citation-based innovation matrix using a standard approach taken from previous studies. Our inventor-based innovation matrix is obtained using the approach described above. Once we have the two matrices, we can compare either the edge values or centrality of the nodes in the two matrices.

Table 2.1 presents results comparing the centrality of nodes within the citation-based and inventor-based networks. We can see that the estimated coefficients are close to one and the centrality values from the inventor-based network explain nearly all of the variation in the nodes of the citation based network. This indicates that our inventor-based approach provides a very close approximation to the network generated using the citation-based approach commonly used in modern studies. We get the same message if we instead compare the edges of the two matrices, as is done in Appendix 2.F

The bottom line from this analysis is that our inventor-based method generates results that are very similar to those obtained using citation data and standard approaches in modern data. These findings suggest that our approach is also likely to work well in the historical setting considered in our main analysis, where citation data are unavailable.

2.4.3 Innovation networks during the Industrial Revolution

In this section, we describe and compare the innovation networks obtained when our method is applied to both British and French patent data. A first glimpse of the innovation network is shown in Figure 2.1, which provides a visualization of the innovation network based on British patents and expressed in terms of the British technology categories. In the figure, each technology category is a node, the size of node reflects the number of

Table 2.1: Comparing the centrality of nodes in the citation-based and inventor-based networks

	Dep var: Citation-based network centrality		
	(1) Eigenvector	(2) InDegree	(3) OutDegree
Eigenvalue cent. (inventor-based)	0.947^{***} (0.026)		
InDegree cent. (inventor-based)		0.986^{***} (0.018)	
OutDegree cent. (inventor-based)			0.939^{***} (0.024)
Constant	0.005^{*} (0.003)	0.006 (1.603)	0.025 (0.018)
Observations	120	120	120
R^2	0.949	0.958	0.940

Observations = 3-digit IPC technology categories (network nodes). Robust standard errors in parentheses.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

patents filed in that category, and the location of the node is determined by the strength of connections between that node and every other node in the network.

There are several interesting patterns to note. The technology space is characterized by a dense central core area. Near the center of the core area, we see categories such as Steam Engines, Water and Fluids (i.e., pumps, etc.), and Motive Power, as well as many smaller technology categories. These core technologies include a number that historians have highlighted as important for the Industrial Revolution (Landes, 1969; Mokyr, 1990), most notably steam engines. We can also see that there are clusters of related technologies. The most visible of these is the set of chemical technologies located in the northwest part of the central core. This includes Acids, Chemical Salts, Dyeing and Coloring, and Alkalis. Finally, there are a number of very peripheral categories, including such things as Pearl, Ivory, and Horn technologies, Blacking, Bell-hanging, Calculating Machines, and Hearses and Coffins.

Figure 2.2 visualizes the network obtained from the French patent data and using French technology categories. As in the British case, the French network is characterized by a dense central core surrounded by a set of more peripheral technology categories. Within the core region, we can see technologies such as Steam Engines, Spinning, Weaving, and Misc. engines. We can also see a number of more peripheral technologies, such as Umbrellas,

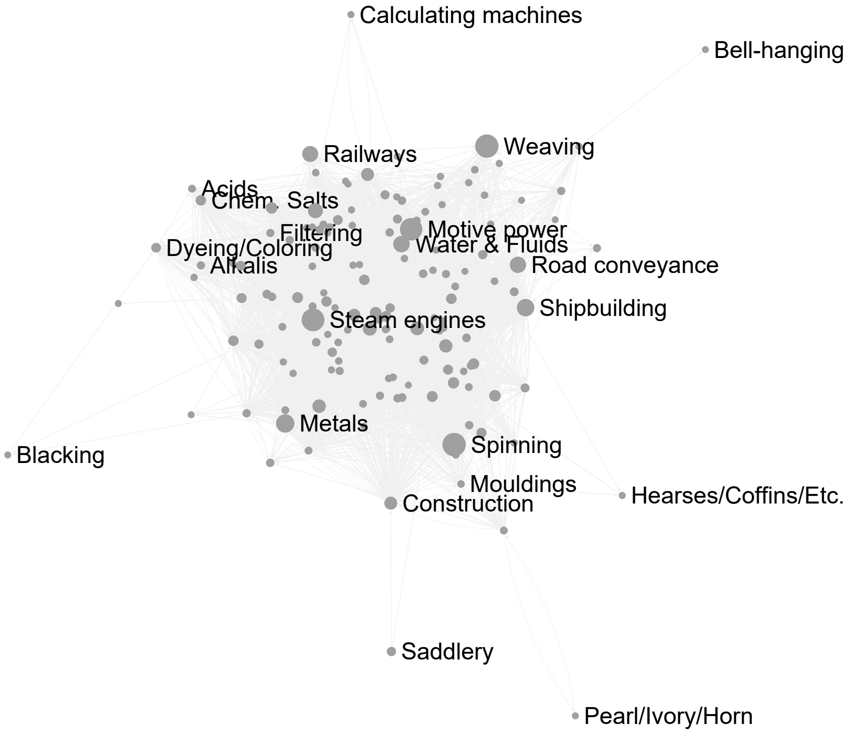

Figure 2.1: The technology network based on British data

Plot is generated using multidimensional scaling. Some labels are not reported to improve readability.

Electricity, and Cannons.

How similar are the two networks? If they show clear similarities, these similarities could reflect fundamental features of the technologies as described by our theory, consistent with an underlying ‘global’ technology network rather than idiosyncratic local conditions in the British and French innovation systems. In order to make this comparison, we begin with two separate innovation networks, one constructed using only French patents and another constructed using only British patents, but both expressed in terms of the same technology categories. We then apply the following regression specification:

$$\omega_{ij}^{FR} = \beta_0 + \beta_1 \omega_{ij}^{UK} + \epsilon_{ij}$$

where the superscripts indicate edges from either the French or UK innovation matrices. If the networks were identical, then we would estimate $\beta_1 = 1$ with an R-squared of 1. Given that the two matrices represent two different realizations of any underlying innovation network, together with the fact that we have to map patents from one system

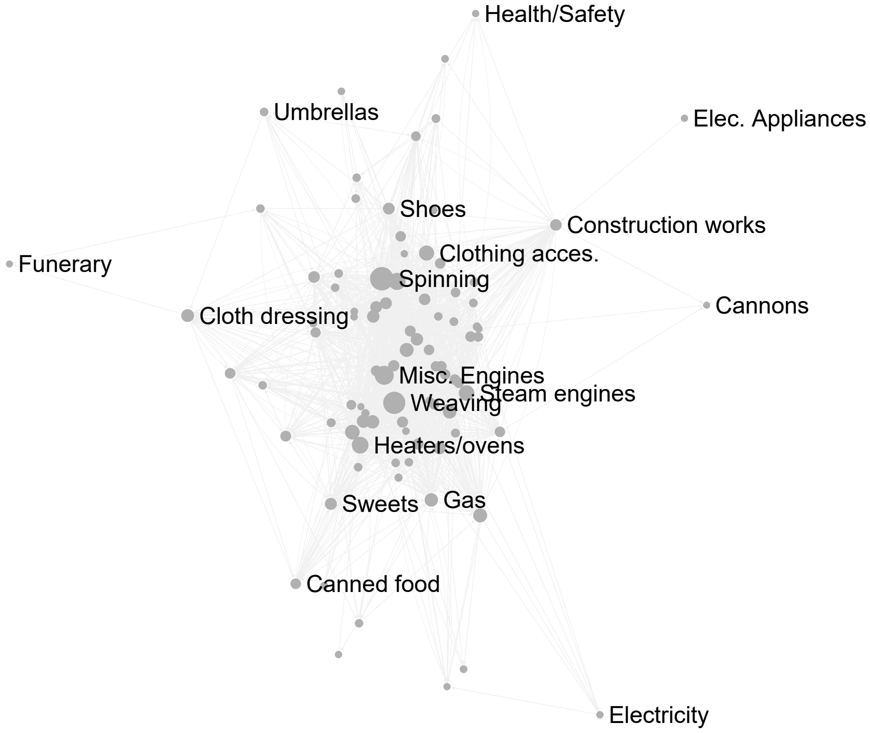

Figure 2.2: The technology network based on French data

Plot is generated using multidimensional scaling. Some labels are not reported to improve readability.

into the technology categories of the other, which will introduce substantial noise into the comparison, it is unrealistic to hope that the two matrices will correspond so closely. However, evidence of strong similarities between the two matrices is suggestive of a common underlying network structure, as assumed by the theory.

Table 2.2 presents the regression results. The first two columns present results where both matrices are expressed in British technology categories. Column 1 compares all ij elements, while Column 2 looks across only those ij matrix entries with non-zero values. Both columns provide clear evidence of similarity across the two matrices. Columns 3 and 4 follow the same structure, but using matrices expressed in French technology categories. Across all four sets of results, we observe strongly significant positive coefficient estimate as well as R-squared values indicating that the patterns observed in one matrix can explain a meaningful fraction of the variation observed in the other matrix.

An alternative approach to assessing matrix similarity is to focus on the centrality of the network nodes, which provides a useful way to summarize the shape of the network. This approach is motivated by our theoretical results, which highlight the importance of

Table 2.2: Comparing the edges of French and British innovation networks

	Dep var: French network edges			
	in UK categories		in French categories	
	(1) incl zeros	(2) excl zeros	(3) incl zeros	(4) excl zeros
UK network edges	0.182***	0.311***	0.063**	0.621***
	(0.033)	(0.043)	(0.025)	(0.193)
Constant	0.029***	0.036***	0.006***	0.027***
	(0.000)	(0.001)	(0.001)	(0.004)
Observations	21462	3401	9120	1435
R^2	0.006	0.080	0.006	0.136

OLS. Observations are network edges connecting nodes (technology categories) i and j. Observations are weighted by the sum of patents in i and j (Stata analytical weights). Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2.3: Comparing node centrality in the French and British networks

	Dep var: French network centrality (in UK categories)		
	(1) Eigenvector	(2) In Degree	(3) Out Degree
UK Eigenvector centrality	0.177***		
	(0.032)		
UK in Degree centrality		0.521***	
		(0.114)	
UK out Degree centrality			0.571***
			(0.129)
Constant	0.072***	96.051***	0.722***
	(0.003)	(4.728)	(0.034)
Observations	132	132	132
R^2	0.253	0.157	0.173

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. OLS regressions with robust standard errors. Observations are network nodes based on U.K. technology categories. A small number of technology categories are dropped (e.g., wigs) because of insufficient data to generate a mapping from French technology categories to those British technology categories.

centrality in determining outcomes. Table 2.3 presents regression results comparing the centrality of nodes based French patents to the centrality of nodes based on British patents, where both are expressed in terms of British technology categories.[16] The first column contains results for eigenvector centrality. The next two columns present results for two alternative centrality measures, indegree and outdegree centrality. Across all three, we see clear evidence of commonalities in the network structure, despite the noise induced by the need to map from one system of technology categorizations to another. This provides further evidence that there is some common underlying structure in the innovation networks in Britain and France. We interpret these estimates as indicating that there is a substantial 'global' underlying innovation network.

2.5 Effect of the network on innovation

In this section, we examine the effect of the network on innovation. In the first step, we follow existing studies on modern innovation networks by running panel regressions using lagged values of the network-weighted knowledge stock based on Eq. 2.3. Identification in this approach relies on the assumption of no common shocks to connected technology categories, which can be difficult to establish. To address this concern, we introduce in the second step a novel approach that uses the unexpected arrival of important inventions in certain technology categories to isolate variation in knowledge stocks.

2.5.1 Effect of knowledge stocks on patenting

Equation 2.3 expresses the log number of patents in a particular technology category i and year t as a function of the log knowledge stock in other categories that generate spillovers for technology i through the innovation matrix. This expression has been used by existing studies, such as Liu and Ma (2021), to provide evidence that the innovation network has an impact on innovation outcomes. Following this approach, we operationalize this relationship by regressing log patents in category i and year t, n_{it} (plus 1), on lagged patents in other technology categories j in previous years $t-s$, $n_{j,t-s}$ (also plus 1), weighted by the strength of connection in the innovation network between the categories ω_{ij}, conditional on a set of technology category fixed effects A_i and year t fixed effect B_t:

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[16] Equivalent results are obtained if we instead express the matrices in terms of the French technology categories.

$$\ln(n_{it}+1) = A_i + B_t + \beta_s \sum_{j \neq i} \omega_{ij} \ln(n_{j,t-s}+1) + \epsilon_{it} \quad \text{where } t > s \tag{2.5}$$

One notable difference in Eq. 2.5 relative to the model is that we add one to the number of patents in each technology category and year. This is necessary because at the technology category by year level we end up with a large number of cells with zero patents.

Figure 2.3 presents the estimated β_s for lags from one to ten years using British patent data and the British innovation network. The network proximity weighted lagged knowledge stock is significantly and positively associated with patenting rates. The association decreases over time, consistent with the pattern we would expect given the model. As the finding is fairly similar to those obtained by studies using modern data, it appears that our novel network measures are representing the innovation network well.[17] In Appendix 2.D, we show that similar patterns are also obtained if we include lagged patents in category i as a control. We can also estimate effects for the knowledge stock downstream of category i. Those results show that only knowledge stocks upstream from a category in the innovation affect subsequent patenting in that category, while knowledge stocks in downstream categories have no effect.

2.5.2 Effect of macroinventions on patenting

One important concern with the approach above is that there may be common shocks to connected technology categories, which would result both in greater knowledge stocks in some categories as well as higher rates of patenting in other connected technologies, but not as a result of spillovers through the innovation network.

To provide a stronger test of the role of innovation networks, in the next part of our analysis we use the arrival of unexpected macroinventions in certain technology categories as a source of quasi-exogenous variation in knowledge stocks. Macroinventions are ideal for this exercise because (1) they represent substantial increments to existing knowledge and (2) they are thought to be largely unpredictable. Mokyr (1990), for example, described macroinventions as “inventions in which a radical new idea, without a clear precedent, emerges more or less *ab nihilo*.” According to Crafts (1995) (p. 596), “Technological history suggests that seeking for socio-economic explanations of macroinventions is likely to be a fruitless pursuit.”

The key identifying assumption will be that the exact timing of arrival of macroinvention

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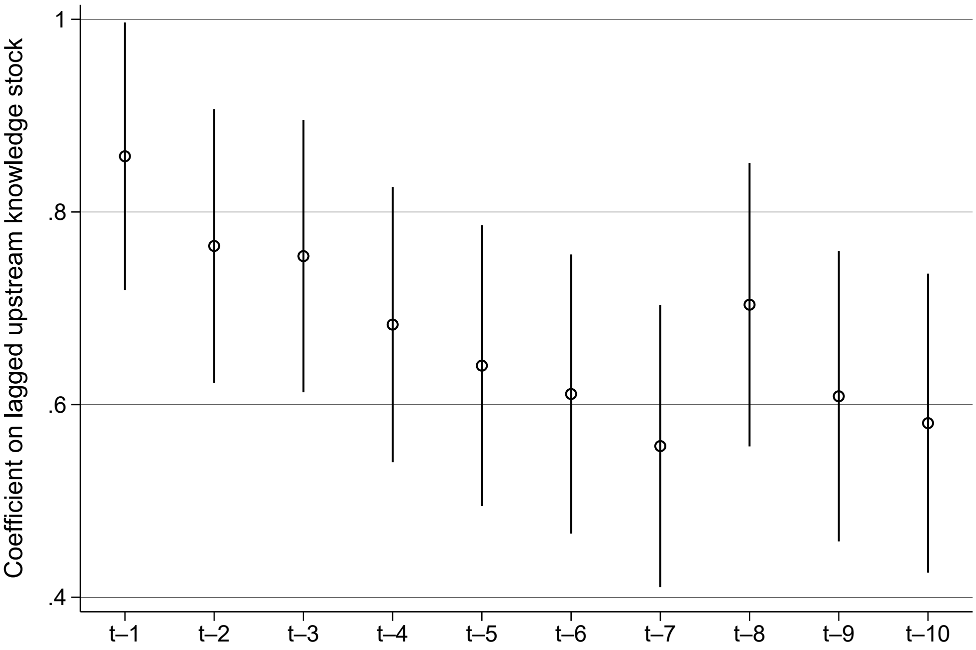
[17] See, e.g., Liu and Ma (2021) Figure 4.

Figure 2.3: The lagged effect of the knowledge stock on patenting rates



The figure presents estimated coefficients and 95% confidence intervals for PPML regressions based on Eq. 2.5 applied to all British patents and using the British innovation matrix. We include only patents by domestic inventors. Patents appearing in multiple (N) technology categories count as only a fraction (1/N) of a patent in each of category. Because there are many zeros in the data, we actually use $\ln(n_{it} + 1)$ in place of the $\ln(n_{it})$ terms shown in Eq. 2.5. Each estimate comes from a separate regression, though joint estimation yields similar results.

is unpredictable within the analysis window. The analysis does *not* assume that the technology category in which a macroinvention appeared was random. To illustrate the variation harnessed in our analysis, take the example of steam engines. After Thomas Newcomen introduced the atmospheric engine in 1712, there were consistent efforts to improve the efficiency of the design. Thus, it was likely that a major advance would occur in the area of steam engines at some point in time. However, it took until 1769 that James Watt invented the separate condenser. From the historical accounts, there is no apparent reason why that idea may not have occurred earlier—and it may well have occurred many years later if genius had not struck Mr. Watt.

We use three different approaches to identifying macroinventions. Our first approach relies on a list of 65 British macroinventions provided by Nuvolari et al. (2021).[18] Nuvolari

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[18] These are identified using a wide variety of sources, including contemporary citations to patents complied by Bennett Woodcroft and the British Patent Office, biographies of famous inventors such as the Oxford Dictionary of National Biography, and modern histories of technology such as Bunch & Helleman's *History of Science and Technology*. Nuvolari et al. (2021) define macroinventions as the top 0.5 percentile of patents in a composite citation score that is based on all of the sources they review.

et al. (2021) provide evidence that this was a particularly impactful set of patents, though there may be questions about how unexpected they were. Second, we use a set of 406 patents that were the first patent in a particular technology subcategory.[19] This set of patents is more likely to be unexpected since each patent opened up a new technology (sub-)type, but we may have questions about how impactful each of these patents was. As a third measure, we use the intersection of the two sets, which generates a small set of six patents that are likely to be both important and novel. This may seem like a small set of experiments to work with but recall that we can examine the impact across all other technology categories for each event. We call these three alternative macroinvention lists the “Nuvolari et al. list”, the “First patent list”, and the “Intersection list”.

Data and empirical specification We structure the dataset as a stacked panel. We define ‘event’ e as a year t in which at least one macroinvention occurred in technology categories $j \in J^e$. For each event, we construct a sub-panel dataset with four five-year periods τ: Two periods before the event year ($t-10$ to $t-6$ and $t-5$ to $t-1$) and two after ($t+1$ to $t+5$ and years $t+6$ to $t+10$), excluding the year of event t itself. For the cross-sectional dimension, we calculate for each sub-panel technology categories i’s upstream connection to the technology category where the macroinvention occurred, $j(e)$, as $\mathit{Proximity}_{ie} = \omega_{ij(e)}$. If there were multiple macroinventions in the year t, then we sum the proximity across all macroinventions. By sub-panel, we omit any technology category in which a macroinvention occurred. Thus, the level of observation will be macroinvention–event e by period τ by technology category i cells.

We begin by estimating a more parsimonious “stacked difference-in-difference” specification,

$$\ln(\mathit{Patents}_{ie\tau}) = \beta_{post}\, \mathit{Proximity}_{ie} \cdot \mathit{post}_{e\tau} + X_{ie\tau}\Gamma + \gamma_{ie} + \eta_{e\tau} + \epsilon_{ie\tau} \tag{2.6}$$

where $\mathit{Patents}_{ie\tau}$ is the number of patents in technology category i in time period τ of event e, β_{post} the coefficient of interest, $\mathit{post}_{e\tau}$ an indicator for the periods after the arrival of the macroinvention, $X_{ie\tau}$ a set of control variables (interacted with post indicator) defined later, γ_{ie} a set of technology categories by event fixed effects, $\eta_{e\tau}$ a set of periods by event fixed effects, and $\epsilon_{ie\tau}$ an error term that may be correlated across i. The coefficient β_{post} estimates whether patenting changed after the macroinvention differentially in technologies closer in technology space to the category of macroinvention relative to technologies further in technology space from the category of macroinvention.

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[19] We exclude patents from this list before 1750 since they may appear to be the first patent in their subcategory only because our data began in 1700.

We also estimate a more demanding "stacked event study" specification,

$$\ln(\mathit{Patents}_{ie\tau}) = \sum_{\tau} \beta_{\tau} \mathit{Proximity}_{ie} \cdot \mathbb{1}(\tau) + X_{ie\tau}\Gamma + \gamma_{ie} + \eta_{e\tau} + \epsilon_{ie\tau} \tag{2.7}$$

where, different than before, we estimate β_τ flexibly for periods $\tau \in \{1, 3, 4\}$—period $\tau = 2$ being the omitted reference period—, and also interact the controls $X_{ie\tau}$ with period indicators $\mathbb{1}\tau)$.

Both specifications 2.6 and 2.7 effectively average coefficients from separate difference-in-difference or event study regressions, respectively, by stacking the panels to obtain common β_{post} or β_τ coefficients. Given the distribution of the dependent variable, (log) number of patents, we estimate 2.6 and 2.7 using Pseudo–Poisson Maximum Likelihood (PPML) regressions.

We focus this analysis on British patents in the period 1700–1830. We do not use data after 1830 because there was a massive increase in the number of patents during that decade, a surge that has been attributed to the influence of a series of legislative and court decisions that made patenting more attractive (see Figure 2.5).[20] This change appears to have been differential across technology types, so including this period can affect our results substantially.

One potential concern with these regressions is that macroinventions may affect innovation patterns in other technology categories through input-output linkages rather than spillovers across the innovation network (Bloom et al., 2013). To address this concern, we can include controls for upstream and downstream IO linkages to the macroinvention technology category. Another potential concern is that technology categories that are more proximate to the macroinvention categories may be more central within the network. As a result, they might grow more rapidly overall. To deal with this concern, we can include a control for the eigenvalue centrality of each technology category within the network. Moreover, the directed nature of the network provides a natural placebo exercise for all specifications, namely, to use i's downstream proximity to the category of macroinvention $j(e)$, $\mathit{proximity\ downstream}_{ie} = \omega_{j(e)i}$ (the macroinvention happens downstream), instead of the upstream proximity.

Results Table 2.4 presents results for equation 2.6. Columns 1 and 2 present results using the Nuvolari et al. list, without and with our full control variables. Columns 3 and 4 present similar results using the first patent list, while columns 5 and 6 present results using the

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[20] Bottomley (2014a) describes (p. 22) how, "around 1830, when there was a 'sea change' in attitudes, that judicial hostility was replaced by a growing appreciation of patenting's role in encouraging innovation...placing patent rights on a much more secure footing."

Table 2.4: Macroinventions baseline regression results

	Dep var: Ln (number of patents)					
	Nuvolari et al		1^{st} in subcat.		Intersection	
	(1)	(2)	(3)	(4)	(5)	(6)
Proximity upstream × post	0.061^{***}	0.058^{**}	0.034^{**}	0.030^{*}	0.199^{***}	0.205^{**}
	(0.021)	(0.026)	(0.016)	(0.017)	(0.077)	(0.085)
Proximity downstream × post		−0.001		0.010		0.014
		(0.026)		(0.015)		(0.047)
EV centrality × post		−0.012		0.002		0.028
		(0.015)		(0.014)		(0.022)
Upstream I–O × post		−0.008		−0.007		−0.004
		(0.007)		(0.006)		(0.007)
Downstream I–O × post		0.001		−0.006		−0.044
		(0.013)		(0.010)		(0.041)
Category × event FE	✓	✓	✓	✓	✓	✓
Period × event FE	✓	✓	✓	✓	✓	✓
Observations	11591	11519	21595	21455	1925	1911
Estim. FE coef.	3535	3508	6643	6591	572	567
Number of clusters	138	136	139	137	129	127
Pseudo R^2	0.199	0.198	0.198	0.197	0.197	0.196

Poisson pseudo maximum likelihood (PPML) regressions. Observation = category–event–period, with four periods per event, two before the event ($[t-10, t-6]$ and $[t-5, t-1]$) and two after the event ($[t+1, t+5]$ and $[t+6, t+10]$). Standard errors are clustered at the level of technology category. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

intersection of the two lists. The results show that as a result of a macroinvention upstream, patenting increases significantly in closer connected technology categories. This effect is not explained by any of our control variables—neither upstream and downstream input-output linkages to the macroinvention technology category, a measure of the eigenvalue centrality of each technology category within the network, or the placebo downstream proximity. The coefficients are smaller for the first patent list, arguably less impactful on average than the Nuvolari list. In contrast, the intersection list has substantially larger coefficients—these macroinventions are plausibly more important breakthroughs, and we find significantly larger effects for them.

Figure 2.4 summarizes event study results based on Eq. 2.7 using the Nuvolari et al. list. The results in Figure 2.4 indicate that, prior to the arrival of a macroinvention, there

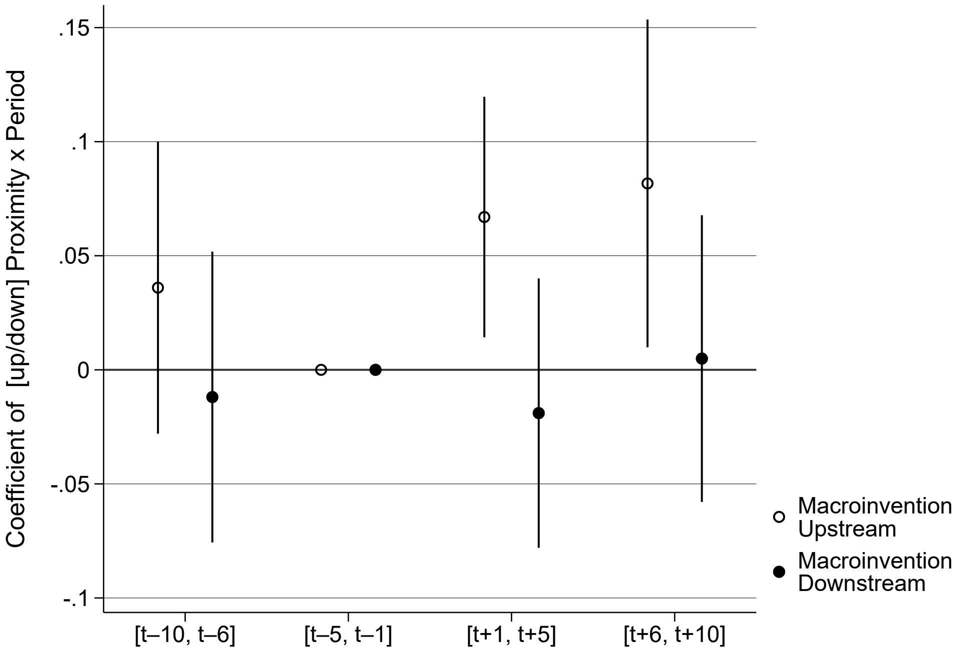

Figure 2.4: Macroinvention event study, Nuvolari et al definition

The figure presents estimated coefficients and 95% confidence intervals (robust standard errors) for PPML regressions of log patents on the interaction of proximity to a macroinvention ($proximity_{ie}$) either upstream or downstream of a technology category and indicators for every five years before and after the event. The five-year period just before the macroinvention is the omitted reference category. Additional results using this event study approach are available in Appendix 2.E. The regression includes controls for upstream and downstream IO connections to the macroinvention technology category and the eigenvalue centrality of each technology category, each interacted with time-period indicators.

was no differential patenting trends in technology categories that were more proximate to (upstream) macroinvention technology categories. After the arrival of the macroinvention, we observe a substantial increase in the number of patents in technology categories that were more proximate to the upstream macroinvention category relative to those less proximate within the same period. These patterns are apparent using either approach to identifying macroinventions.

Results obtained using the first patent or intersection list, provided in Appendix Figure 2.7, are also very similar. The only notable difference between the results in these two panels is that when using the first patent list, the effects seem to die out over time, as the model would lead us to expect, while there is some evidence of an increased effect over time when using the Nuvolari list (though the standard errors rule out drawing any clear conclusions regarding this pattern). We also observe no evidence that having a macroinvention arrive downstream in the innovation network affects patenting rates. This provides additional confidence that our directed innovation network is capturing meaningful spillovers from upstream to downstream technology categories.

In Appendix 2.E, we provide some additional robustness checks for our macroinvention analysis. Specifically, we show that similar results are obtained if we run regressions in levels rather than logs, which allows us to include those category-period bins with zero patents.

2.6 Centrality of inventors by country

The previous section provides evidence that the shape of the innovation network matters for technological progress. In this section, we look at whether there are systematic differences between Britain and France in terms of the distribution of researchers across technology categories, which could have implications for their rate of technology growth.

Motivated by the theoretical results, in this section we focus on comparing the relative centrality of British and French inventors. These results provide suggestive evidence relating to the growth outcomes that we can expect from the different distributions of research efforts (as reflected by patents) in these two economies. However, the analysis in this section, which has some advantages from an empirical point of view, will not map directly into the model. In the next section, we take the model more seriously and analyze the differential growth outcomes implied by the theoretical framework given the observed differences in the allocation of research effort between the British and French economies.

To generate a fair comparison between the centrality of British and French inventors within the innovation network, we compare in both countries foreign inventors to domestic inventors, using the domestic innovation network. If we find that foreign inventors were always patenting in more central categories, in Britain as in France, differences in centrality could be due to a foreign inventor selection effect. If, however, we find that only inventors from one country are more central, we can rule out such selection effect. For example, using French patents and the French network, we estimate

$$\mathit{Centrality}_{pkt} = \beta_{\mathrm{UK}} \mathrm{UK}_k + \beta_{\mathit{foreign}}\, \mathit{OtherForeign}_k + \phi_t + \epsilon_{pkt} \tag{2.8}$$

where $\mathit{Centrality}_{pkt}$ is the centrality of the technology category associated with patent p patented by inventor k in year t, UK_k is an indicator for whether inventor k reported a UK address when filing the patent in France, and $\mathit{OtherForeign}_k$ is an indicator for whether the inventor listed some other location outside of France as their address, for example in the USA, or the patent type is "of unspecified origin" (*communication* in British patents, *importation* in French patents). We also include a set of year-of-patent-filing fixed effects

Table 2.5: Centrality of British inventors within the French innovation network

	Dep var: French patent centrality (standardized)					
	Eigenvector		Out Degree		In Degree	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign inventor	0.080^{***}		0.076^{***}		0.092^{***}	
	(0.018)		(0.018)		(0.018)	
UK inventor		0.141^{***}		0.138^{***}		0.138^{***}
		(0.035)		(0.036)		(0.037)
US inventor		−0.065		−0.077		0.009
		(0.138)		(0.138)		(0.138)
Other foreign inventor		0.065^{***}		0.061^{***}		0.081^{***}
		(0.020)		(0.020)		(0.020)
Year FE	✓	✓	✓	✓	✓	✓
Observations	14145	14145	14145	14145	14145	14145
R^2	0.012	0.012	0.011	0.012	0.013	0.013

Observation = inventor–patent in France (French patents, French categories). The dependent variables are the centrality of the technology category associated with a patent, standardized to mean zero and standard deviation of one. Foreign inventors are identified based on the reported addresses and an indicator for unspecified foreign origin (*imported patent*). Robust standard errors in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

ϕ_t.

Table 2.5 shows that British inventors patenting in France patented in substantially more central technology categories than any other group of patentees in France, foreign or domestic. This holds for three different centrality measures, *eigenvalue centrality*—the main centrality measure from the theory—as well as both *indegree* and *outdegree* centrality. Whereas the first columns of each centrality measure (1, 3, 5) report that foreign inventors patenting in France were generally patenting in more central categories, the second columns (2, 4, 6) show that this is particularly due to British based inventors.

Table 2.5 shows that French inventors patenting in Britain did *not* patent in more central technology categories than British or other foreign patentees across all centrality measures. In fact, foreign inventors in Britain patent generally in significantly less central categories than the average British inventor (columns 1, 3, 5). Splitting up foreign inventors by origin (columns 2, 4, 6), we see that this association is driven both by French foreign inventors and other foreign inventors. The coefficient on French inventors is not significant, but it has the same magnitude (negative). Due to the irregular reporting of addresses in the British patent

Table 2.6: Centrality of French inventors within the British innovation network

	Dep var: UK patent centrality (standardized)					
	Eigenvector		Out Degree		In Degree	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign inventor	-0.111^{***} (0.024)		-0.069^{***} (0.024)		-0.064^{***} (0.023)	
French inventor		−0.066 (0.076)		−0.087 (0.076)		−0.110 (0.074)
US inventor		0.185^{**} (0.079)		0.103 (0.086)		0.065 (0.084)
Other foreign inventor		-0.143^{***} (0.026)		-0.083^{***} (0.025)		-0.072^{***} (0.025)
Year FE	✓	✓	✓	✓	✓	✓
Observations	12384	12384	12384	12384	12384	12384
R^2	0.014	0.015	0.012	0.012	0.011	0.011

Observation = inventor–patent in Britain (UK patents, UK categories). The dependent variables are the centrality of the technology category associated with a patent, standardized to mean zero and standard deviation of one. For patents with multiple technology categories, centrality is averaged across categories. Foreign inventors are identified based on the reported addresses and an indicator for unspecified foreign origin (*communicated patent*). Robust standard errors in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

data, the majority of "other foreign inventors" are most likely from France. Interestingly, US-based inventors patenting in Britain are more central than the average British inventor.

In sum, it appears that British inventors were systematically working in more central technology categories than French inventors. This fact is derived from both British and French patents and innovation networks and is thus independent from the mapping of categories across countries. Furthermore, the result cannot be explained by the fact that inventors patenting in a foreign country might generally have patented in more central categories.

The results in this section provide a first piece of evidence showing that British inventors tended to work in technology categories that were located more centrally within the innovation network. From the theoretical results, we know that the optimal allocation of researchers, from a growth perspective, involves a larger allocation of researchers working in more central technology categories. However, these results alone don't tell us that the more central allocation of British inventions that we observe will necessarily translate into a higher growth rate. In order to take that next step, we need to use the theory in order to assess the growth implications of the different allocations of research effort that we observe in the two different economies.

2.7 Quantification of growth effects

In this section, we assess the quantitative importance of the different allocations of research effort observed in France and Britain. To do so, we start with one of the key results generated by the theory, which expresses the difference in growth rates between two allocations of research activity across different technology sectors (**b** vectors):

$$g(\tilde{\mathbf{b}}) - g(\mathbf{b}) = \lambda\, \mathbf{a}'(\ln\, \tilde{\mathbf{b}} - \ln\, \mathbf{b}) \tag{2.9}$$

This expression tells us that the difference in growth rates (in the BGP) depends on the interaction of the allocations of researchers across technology sectors (the **b** and $\tilde{\mathbf{b}}$ vectors) and the shape of the technology space, reflected in the **a** vector, as well as the λ parameter, which represents the size of each technology step in the model.

We have constructed a set of alternative innovation networks that can be used to obtain the **a** vector. We infer $\mathbf{b}^{\mathrm{FR}}$ and $\mathbf{b}^{\mathrm{UK}}$ from the number of patents filed by inventors from each country in each technology category. When calculating these, we use only the French patents filed by inventors who list a modal address in France, and for the British patents we drop all of those communicated from abroad or listing a foreign address.

Before moving on, it is interesting to observe how the allocations $\mathbf{b}^{\mathrm{FR}}$ and $\mathbf{b}^{\mathrm{UK}}$ differ. We do this, in Table 2.7, by comparing the allocation of patents for both countries but expressed in terms of the British technology categories. We can see that British inventors hold the highest relative share of patents ($\mathbf{b}^{\mathrm{UK}} - \mathbf{b}^{\mathrm{FR}}$) in several categories that feature importantly in historical accounts of the Industrial Revolution, including steam engines, metals, railroads, shipbuilding, and motive power. Relative to this set, the technology categories most associated with French inventors are typically not those we think of as crucial to the Industrial Revolution.

The final missing piece in Eq. 2.9 is the λ parameter. Recall from Eq. 2.2 that this parameter determines how much patents augment the stock of available technology. Below, we offer two approaches to dealing with this issue. First, we offer a less parametric approach that allows us to generate relative growth results without needing an estimate of λ. The downside of these results is that they are difficult to interpret. Second, we use a range of λ parameter estimates from existing studies to obtain more easily interpretable estimates of the difference in growth rates implied by the different allocations that we observe.

Table 2.7: Technologies most associated with inventors in each country

	Highest relative British allocations		Highest relative French allocations
1	Steam engines	1	Lamps
2	Shipbuilding	2	Wearing apparel
3	Metals	3	Stationary and bookbinding
4	Coaches and road conveyance	4	India-rubber and gutta-purcha
5	Railways and rolling stock	5	Sugar manufacturing
6	Fireplaces, stoves, furnaces	6	Paper and pasteboard
7	Motive power and propulsion	7	Gas manufacture and consumption
8	Brewing and distilling	8	Games, exercises and amusements
9	Cloth fulling and dressing	9	Heat, heating, evaporating
10	Harbors and lighthouses	10	Pipes, tubes and drain tiles

The table lists by country the top ten categories in which either British inventors hold the highest relative share of patents (left, highest $\mathbf{b}^{\text{UK}} - \mathbf{b}^{\text{FR}}$) or French inventors (right, lowest $\mathbf{b}^{\text{UK}} - \mathbf{b}^{\text{FR}}$). For example, steam engines accounts for 3.9% of British patents but only 2.2% of French patents, while Lamps accounts for 3.5% of French patents but only 1.9% of British patents. The results are expressed in terms of British technology categories. The pattern is very similar if one uses French technology categories.

Table 2.8: The effect of the innovation network on relative growth in Britain vs France

Network based on patents from:	Expressed in categories of:	British allocation, distance from optimum	French allocation, distance from optimum	Ratio of growth differences
Both countries	Britain	0.38	0.44	1.179
Both countries	France	0.28	0.30	1.080

For the less parametric approach, we begin by noting that the model provides a method for calculating the optimal allocation (from a growth perspective) of researchers across the different technology sectors, $\mathbf{b}^*$. Using this fact, we can express the differences in growth rates implied by the allocations observed in Britain and France relative to the optimal allocation:

$$\frac{g(\mathbf{b}^{\text{FR}}) - g(\mathbf{b}^*)}{g(\mathbf{b}^{\text{UK}}) - g(\mathbf{b}^*)} = \frac{\mathbf{a}'(\ln \mathbf{b}^{\text{FR}} - \ln \mathbf{b}^*)}{\mathbf{a}'(\ln \mathbf{b}^{\text{UK}} - \ln \mathbf{b}^*)} \tag{2.10}$$

At the cost of expressing the difference in growth rates relative to the (unknown) maximum rate of growth, the expression allows us to avoid taking a stand on the value of λ.

Table 2.8 presents estimates based on Eq. 2.10 showing that, within an innovation matrix based on patents from both countries, France was consistently further away from the maximum attainable technology growth rate than Britain. Column (1) shows that the British inventor allocation generates growth rates that are substantially below the optimum

Table 2.9: Differences in growth in Britain vs. France for different λ values

Network based on patents from:	Expressed in categories of:	Low estimate ($\lambda = 0.13$)	Medium estimate ($\lambda = 0.173$)	High estimate ($\lambda = 0.22$)
Both countries	Britain	0.0088	0.012	0.035
Both countries	France	0.0029	0.004	0.024
Average		0.0058	0.0077	0.0292

The table presents the differences in the growth rates between Britain and France, obtained from Eq. 2.9, for various values of λ. In the first column of results, we use a low estimate from existing studies, of $\lambda = 0.13$ from Acemoglu, Akcigit, Alp, Bloom, and Kerr (2018). In the second column of results, we use a medium estimate from existing work, 0.173 from Liu and Ma (2021). In the third column, we use a high estimate of 0.22 based on Aghion, Bergeaud, Boppart, Klenow, and Li (2019).

achievable growth rate. However, the French inventor allocation (column 2) generates growth rates that are even further from the optimum—and always more remote than the British. As a result, in each scenario the British allocation generates more rapid technology growth than the French allocation (column 3). Specifically, these results indicate that the French technology growth rate was between 8 and 17 percent further from the maximum achievable growth rate than the British allocation.

For the parametric approach, we consider a range of λ values obtained from existing studies and then study the implications of our results under each. Table 2.9 presents the growth difference between the British and French economies that are implied by the innovation network and different inventor allocations for low, medium, and high λ values found in previous studies.

These estimates indicate that differences in the allocation of researchers across sectors generate growth differences ranging from, on the low end. 0.5%, to 2.9% on the high end. Available estimates suggest that growth of industrial production in Britain was around 3 to 3.5% during the first half of the nineteenth century (Broadberry et al., 2015) and in the growth rate in france was around 1.7 to 2.5% in the same period (Crouzet, 1996; Asselain, 2007). This suggests growth rate differences ranging from 0.5 to 1.8 percentage points. Thus, our results indicate that the impact of differences in the allocation of researchers within the technology network was large enough to explain a meaningful fraction, and possibly the entirety, of the difference in growth rates estimated for Britain and France during this period.

2.8 Conclusions

Did it matter that in the early decades of the Industrial Revolution many British researchers worked in technology areas, such as steam engines or textile machinery, rather than technologies such as papermaking or chemicals? We argue that the answer to this question is that, yes, it did matter. Specifically, we show that the distribution of British inventors within the technology space differed in fundamental ways from the distribution of inventors in the most natural comparison country, France, and that this distribution had a meaningful impact on the difference in technology growth rates in the two countries. To make this argument, we bring together frontier theoretical tools, rich historical patent data, and a novel approach to measuring the structure of the innovation network in a historical setting.

Our results enrich our understanding of the factors that contributed to Britain's industrial dominance during the Industrial Revolution. They also contribute to a broader literature looking at the importance of innovation networks in economic growth, by providing direct evidence on the role that the structure of the innovation network played during an important period of economic history.

In addition to helping us better understand the nature Britain's advantages during the early decades of the Industrial Revolution, our findings may also shed light on why these advantages slipped away in the late-nineteenth and early-twentieth centuries. It seems likely that the structure of the innovation network was slowly evolving over the nineteenth century, with the rising importance of chemical and electrical technologies that characterized the the Second Industrial Revolution. This change in the technology space away from the mechanical technologies may help explain why Britain found it increasingly difficult to maintain its position as industrial leader. One interesting direction for future work is assessing the extent to which slow-moving changes in the underlying innovation network may have undermined Britain's advantages and contributed to the erosion of British leadership in the late nineteenth and early twentieth century.

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2.A Additional details on the British patent system

Figure 2.5 describes the number of patents filed in England and Wales from 1700 to 1849. The large increase in the number of patents starting in 1830 has been attributed to a set of court decisions that made it more likely that patents would be upheld in court, thereby making patenting more attractive (Bottomley, 2014a).

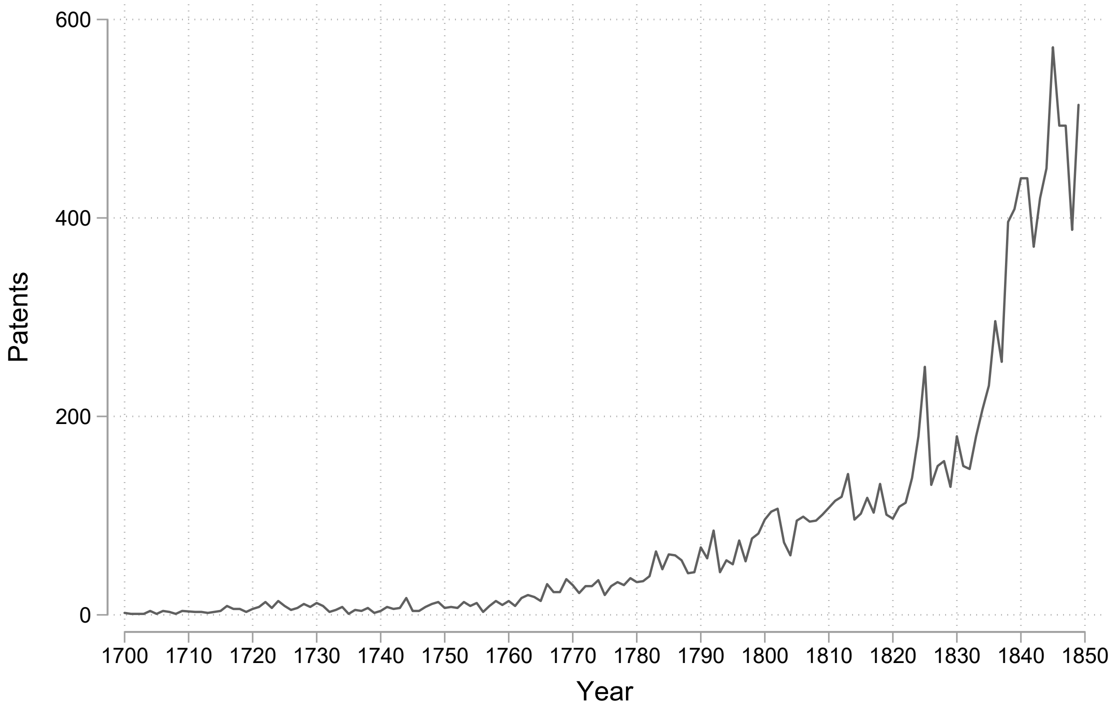

Figure 2.5: British patents over time

2.B Mapping French to British technology categories

This appendix provides some additional details regarding the construction of the mapping between the different British and French technology category classifications. As described in the main appendix, we construct three groups of patents where we can identify the same patent filed in both Britain and France:

1. Starting with French patents filed before 1844 and searching for corresponding patents in England, with matches constructed using a manual review based on inventor name, patent titles, and the patents being filed within a few years of one another. We identify 167 matched patents using this method.

2. Starting with English patents filed up to 1849 and searching for corresponding patents in France, with matches based on the same criteria as above. We identify 127 patents using this method.

3. Starting with French patents filed after 1844 and matched to English patents using the exact filing date of the English patent recorded by the French patent office. For these patents, as long as the title indicates that we have identified a correct match, we allow variation in the inventor name (common when patent agents appear as the inventor). We identify 855 matched French patents using this method, which correspond to 808 matched British patents, since some British patents correspond to more than one French patent.

Using these data, we construct a set of weights mapping French technology categories (i) to British categories (j) (and vice versa from British to French categories) where each weight is given by:

$$\theta_{ij} = Pat_{ij}/Pat_i \quad .$$

To provide a sense of what these category mappings look like, Table 2.10 presents, for the first twenty British technology categories, the most closely related French technology category, as well as the corresponding weight of the mapping between them. Table 2.11 presents similar information for the mapping for the first twenty French technology categories. While the mapping is clearly imperfect, we can see that it generally seems quite reasonable.

Focusing on Table 2.10, in a number of cases we observe a clear correspondence between the French and British technology categories. In some cases, such as “Aerial Conveyances” into “Aviation” or “Alkalis” into “Chemicals-General,” the British category fully maps into a French category. In a number of others, such as “Boots, Shoes, Clogs, Pattens, etc.” into “Shoemaking”, the weight is close to one. However, there are others–“Bearings, Wheels, Axles, And Driving-Bands” for example–where the mapping between the two categorizations is less clear. There are a small number of categories, such as “Blacking” (i.e., shoe polish) where it is not possible to construct a mapping. Any patents in those categories, which tend to be very small, will be dropped in any analysis where we map patents from one classification system to the other. Similar patterns are visible when focusing on the mapping from French into British categories in Table 2.11. Overall, we can conclude that our mapping approach is largely reasonable, though it is also clear that converting from one categorization to another will also introduce a meaningful amount of noise into our

Table 2.10: Mapping from British to French technology categories with weights

British category (first 20)	Closest French category	Mapping weight
Accidents, Prevention Of	Railroads	.26
Acids	Chemicals-General	.88
Adhesive Substances	Canned food	.5
Aerated Liquors, Mineral Waters, etc.	Drinks	.75
Aerial Conveyances	Aviation	1
Agricultural Produce	Milling	.82
Agriculture	Agricultural Machines	.61
Air and Gas Engines And Windmills	Misc Engines	.42
Alarms, Snares, And Vermin Traps	Construction fittings	1
Alkaline Lees, Wash Waters, And Bleaching	Chemicals-General	1
Alkalis	Chemicals-General	1
Assurance: Preventing Forgery And Fraud	Paper making	1
Baths And Bathing-Machines	Chemicals-Rubber etc.	1
Bearings, Wheels, Axles, And Driving-Bands	Railcars	.23
(tie)	Machine components	.23
(tie)	Misc Engines	.23
Bell-Hanging	Locks	1
Blacking		
Bleaching, Washing, And Scouring	Textile finishing	.57
Boilers And Pans	Steam engines	.74
Boots, Shoes, Clogs, Pattens, etc.	Shoemaking	.87
Boring, Drilling, Punching	Machine tools	.46

analysis.

Table 2.11: Mapping from French to British technology categories with weights

French category (first 20)	**Closest British category**	**Mapping weight**
Agricultural Machines	Agriculture.	.8
Fertilizer	Manure; Deodorizing Fecal Matters	.43
Rural Engineering	Agriculture.	.5
Breeding etc	Weaving, And Preparing For Weaving	.5
Milling	Agricultural Produce	.56
Baking	Cooking: Making Bread And Confectionery	.67
Sweets	Sugar Manufacture	.76
Canned food	Preserving & Curing Provisions, other Substances, Liquids	.53
Drinks	Brewing, Distilling, Rectifying, And Preparatory Processes	.4
Railroads	Railways And Railway Rolling-Stock	.64
Locomotives	Railways And Railway Rolling-Stock	.49
Railcars	Railways And Railway Rolling-Stock	.7
Spinning	Spinning And Preparing For Spinning	.8
Textile finishing	Printing	.36
Weaving	Weaving, And Preparing For Weaving	.57
Knitting	Spinning And Preparing For Spinning	.4
Lace etc	Weaving, And Preparing For Weaving	.71
Other textiles	Rope Manufacture	.75
Paper making	Paper And Pasteboard	.85
Carton	Calculating-Machines: Apparatus for Teaching	.25
(tie)	Games, Exercises, And Amusements	.25
(tie)	Lighting; Lamps And Luminaries; Matches	.25
(tie)	Paper And Pasteboard	.25

2.C British IO matrix construction

This appendix provides some additional details and discussion of the methods used to construct input-output links between technology categories. Note that these links are primarily used in our analysis of the impact of macroinventions, which uses only British data. Thus, our focus is on construct input-output controls for that context.

The main challenge in constructing these matrices is mapping technology categories to the industries available in the IO matrix. To do so, we first try to match the occupation found in the patent data to IO industries. This is done through a manual review of the roughly 7,000 occupation titles listed in British patents from 1700-1849. A subset of these occupations unambiguously match to industries present in the IO table. Note that this does not always mean that the patented invention is associated with that industry; our assumption is that on average individuals working in a particular industry are likely to be invention technologies associated with that industry.

To provide a sense of the types of occupations corresponding to different industries, Table 2.12 lists by IO industry the three most common "topics" contained in occupations that help us to establish unambiguous matches. Generally, we do not match generic occupations that refer to professions or class/status (e.g. merchant, manager, worker, officer) unless they are qualified by a topic that refers unambiguously to one industry. For example, we do not match "engineers" to the industry "Engineering" because the unqualified occupation title refers to a profession rather than an industry. However, we match coal mining (colliery) engineer to the coal mining industry because in this case, the qualifying topic is unambiguous.[21]

Once we have a mapping from occupations to industries, the mapping from technology categories to industries is straightforward given that occupations are associated with patents which are classified into technology categories.[22] We can use this mapping, together with the information included in the IO matrix, to construct measures of the upstream and downstream links between different technology categories.

The resulting probabilistic mapping from technology categories to industries appear quite reasonable. To illustrate this, Table 2.13 lists, for each IO industry, the most important technology category (highest weight). In cases where a technology category exists that is broadly similar to the IO industry, this technology category receives the highest weight:

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[21] Some professions are ambiguous even if qualified by a topic, for example "coal merchant" or "cloth merchant" because we do not know if this occupation worked in industry or in the excluded distribution services. One exception to the rule are composite occupations like "woollen manufacturer and merchant" because there the "manufacturer" clearly indicated involvement in production.

[22] Two minor technology categories are missing because we were unable to map their associated occupations to any IO industry. These are "Diving, engines for diving" and "Maps and Globes".

Table 2.12: Information used for matching input–output industries to occupations

	Most common occupation theme		
Input–output industry	ranked 1st	2nd	3rd
Agriculture, Forestry, etc	farmer	agriculturalist	planter
Coal Mining	coal	colliery	viewer
Other mining	quarry	quarryman	engineer
Coke ovens	coke	burner	breeze
Iron and Steel	iron	steel	founder
Non-ferrouse metals	brass	founder	tin
Engineering	machine	agricultural	engine
Metal Goods, NES	tool	lock	wire
Shipbuilding	ship	builder	shipwright
Railway Rolling stock	railway	builder	carriage
Cotton and silk	cotton	spinner	silk
Woolen and worsted	wool	spinner	worsted
Hosiery and lace	lace	hosier	hosiery
Other textiles	carpet	elastic	cloth
Jute, hemp, and linen	flax	spinner	rope
Textile finishing	dyer	finisher	printer
Clothing	hat	tailor	clothier
Boot and shoe	boot	shoe	gutta-percha
Leather and fur	leather	harness	currier
Food processing	miller	baker	sugar
Drink	brewer	water	distiller
Tobacco	cigar	tobacco	snuff
Chemicals	chemist	oil	chemical
Paper	paper	card	stainer
Printing and publishing	printer	stationer	publisher
Rubber	india-rubber	rubber	gutta-percha
Timber trades	sawyer	mill	saw
Furniture	cabinet	dressing	case
Other wood	block	bobbin	wood
Building materials	brick	tile	stone
Building, etc.	builder	architect	painter
Misc. Manufactures	instrument	glass	watch
Gas, electricity, water	gas	meter	apparatus

The topics are obtained from breaking splitting the occupation string in parts, e.g. “iron founder” into “iron” and “founder”. The table excludes generic themes such as manufacturing, manufacturer, maker, worker, master, manager, agent, proprietor. Note that we do not match the occupations to industries based on individual themes but based on the information contained in the full occupation string.

e.g. the *Agriculture* technology category to the *Agriculture, Forestry, etc* industry; the *Ship-Building, Rigging, And Working* technology category to the *Shipbuilding* industry. Furthermore, industries that one would expect to be more technologically diverse tend to place relatively low weight on the top technology category (e.g. Metal Goods, NES; Chemicals), while industries that one would expect to be more technologically specialized typically place a higher weight on the top technology category (e.g. *Boot and Shoe* to *Boots, Shoes, Clogs, Pattens, etc.*).

Table 2.14 lists, for the first 50 technology categories (in alphabetical order), the most important IO industry. Note that the difference in the weights between the two tables comes from a different normalization—here, weights are normalized to one by technology category. Again, this mapping conforms reasonably well to what we would expect. Highly specialized technologies are mapped with high precision into one industry (and the "correct" one), as in the cases of Bell-Hanging (to Non-ferrous metals), Blacking (to Boot and Shoe), Calculating Machines, and Combs (to Mixed Manufacture). This pattern holds consistently even when many specialized technologies should connect to the same industry (e.g. Chemicals industry, Acids, Alkaline Lees, Alkalis, and Chemical salts all receive high weights). Moreover, as one would expect, technology categories are mapped with low weights on many different industries when they are based on principles like "Prevention of Accidents," or composites like "Bearings, Wheels, Axles, And Driving-Bands," that are not particular to any one industry.

Table 2.13: Most important technology category by input–output industry

Input–output industry	Top technology category	Weight IO←TC
Agriculture, Forestry, etc	Agriculture.	0.495
Coal Mining	Water And Fluids	0.135
Coke ovens	Fireplaces, Stoves, Furnaces, Ovens, And Kilns.	0.5
Coke ovens	Heat, Heating, Evaporating, And Concentrating	0.5
Iron and Steel	Metals And Metallic Substances	0.31
Non-ferrouse metals	Lighting; Lamps And Luminaries; Matches	0.089
Engineering	Spinning And Preparing For Spinning	0.309
Metal Goods, NES	Locks And Other Fastenings.	0.101
Shipbuilding	Ship-Building, Rigging, And Working.	0.577
Railway Rolling stock	Railways And Railway Rolling-Stock	0.5
Cotton and silk	Spinning And Preparing For Spinning	0.494
Woolen and worsted	Spinning And Preparing For Spinning	0.487
Hosiery and lace	Weaving, And Preparing For Weaving.	0.775
Other textiles	Weaving, And Preparing For Weaving.	0.602
Jute, hemp, and linen	Spinning And Preparing For Spinning	0.429
Textile finishing	Printing.	0.244
Clothing	Wearing-Apparel	0.33
Boot and shoe	Boots, Shoes, Clogs, Pattens, &C.	0.567
Leather and fur	Tanning And Preserving: Treatment Of Skins; Curriery	0.434
Food processing	Agricultural Produce	0.161
Drink	Brewing, Distilling, Rectifying, And Preparatory Processes	0.476
Tobacco	Gas Manufacture And Consumption	0.4
Tobacco	Tobacco And Snuff	0.4
Chemicals	Chemical Salts, Compositions, Gases, And Processes	0.106
Paper	Paper And Pasteboard.	0.512
Printing and publishing	Printing.	0.453
Rubber	India-Rubber And Gutta-Percha	0.667
Timber trades	Lighting; Lamps And Luminaries; Matches	0.5
Furniture	Furniture and Cabinet-ware	0.398
Other wood	Ship-Building, Rigging, And Working.	0.379
Building materials	Building Materials.-Burning Lime	0.406
Building, etc.	Building And Relative Processes	0.149
Misc. Manufactures	Musical Instruments	0.197
Gas, electricity, water	Gas Manufacture And Consumption	0.419

The tables lists by input–output industry the most important technology, including the associated weight to map technology categories into industries.

Table 2.14: Most important input–output industry by technology category

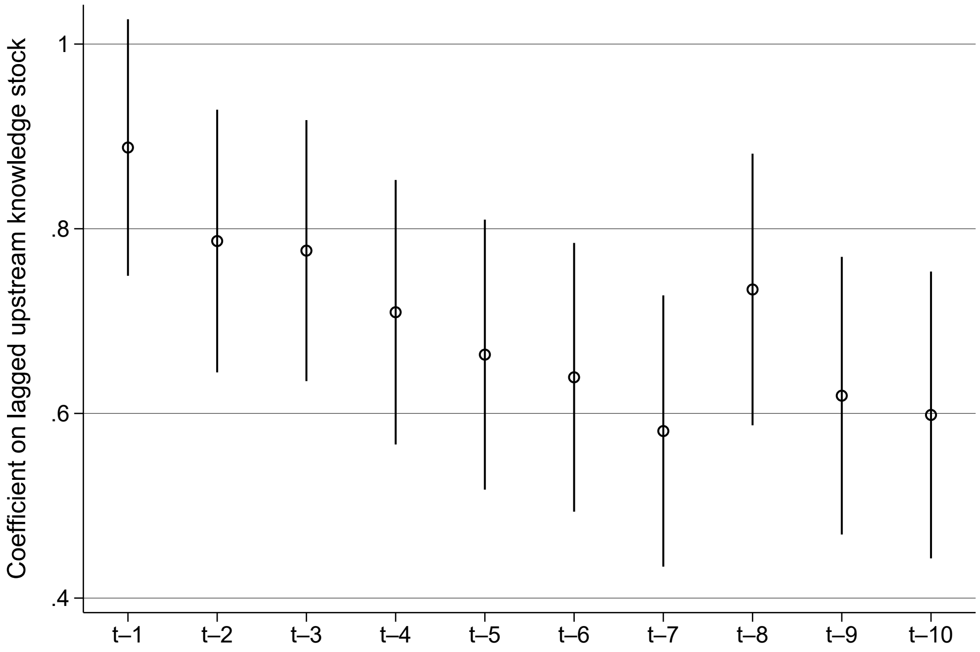
Technology category	Top input–output industry	Weight TC←IO
Accidents, Prevention Of	Non-ferrouse metals	0.155
Acids	Chemicals	0.753
Adhesive Substances	Chemicals	0.5
Aerated Liquors, Mineral Waters, etc	Chemicals	0.658
Aerial Conveyances	Furniture	1
Agricultural Produce	Food processing	0.299
Agriculture.	Agriculture, Forestry, etc	0.447
Air And Wind ;-Air And Gas Engines And Windmills	Misc. Manufactures	0.282
Alarms, Snares, And Vermin Traps	Misc. Manufactures	0.334
Alkaline Lees, Wash Waters, And Bleaching	Chemicals	0.676
Alkalis.	Chemicals	0.865
Assurance: Preventing Forgery And Fraud.	Printing and publishing	1
Baths And Bathing-Machines.	Misc. Manufactures	0.481
Bearings, Wheels, Axles, And Driving-Bands.	Metal Goods, NES	0.169
Bearings, Wheels, Axles, And Driving-Bands.	Cotton and silk	0.169
Bearings, Wheels, Axles, And Driving-Bands.	Boot and shoe	0.169
Bearings, Wheels, Axles, And Driving-Bands.	Rubber	0.169
Bearings, Wheels, Axles, And Driving-Bands.	Building, etc.	0.169
Bell-Hanging.	Non-ferrouse metals	1
Blacking	Boot and shoe	1
Bleaching, Washing, And Scouring	Textile finishing	0.458
Boilers And Pans	Chemicals	0.164
Boots, Shoes, Clogs, Pattens, etc	Boot and shoe	0.613
Boring, Drilling, Punching	Engineering	0.569
Bottles, Vessels, And Jars, Covers And Stoppers	Misc. Manufactures	0.43
Brewing, Distilling, Rectifying, And Preparatory Processes	Drink	0.545
Bridges, arches, viaducts, aquaducts	Building, etc.	0.522
Brushes.	Misc. Manufactures	0.808
Building And Relative Processes	Building, etc.	0.479
Building Materials.-Burning Lime	Building, etc.	0.364
Buttons, Buckles, Studs, And Other Dress-Fastenings.	Misc. Manufactures	0.469
Calculating-Machines; Apparatus for Teaching	Misc. Manufactures	1
Candle Manufacture;-Preparing Candle And Other Wicks.	Chemicals	0.91
Casks And Barrels	Drink	0.571
Casting.	Iron and Steel	0.5
Chains And Chain-Cables.	Iron and Steel	0.375
Chemical Salts, Compositions, Gases, And Processes	Chemicals	0.844
Clocks, Watches, Chronometers, And Other Timekeepers.	Misc. Manufactures	0.991
Cloth Fulling, Dressing, Cutting, And Finishing.	Textile finishing	0.319
Coaches And Other Road Conveyances	Iron and Steel	0.224
Coffee, Cocoa, Chocolate, And Tea.	Food processing	0.522
Combs For The Hair.	Misc. Manufactures	1
Condensing.	Chemicals	0.636
Cooking; Culinary Apparatus.	Non-ferrouse metals	0.484
Cooking; Making Decoctions And Infusions.	Non-ferrouse metals	0.667
Cooking;-Making Bread And Confectionery.	Food processing	0.83
Cork Cutting And Preparing.	Misc. Manufactures	0.419
Cutlery.	Metal Goods, NES	0.83
Cutting, Sawing, And Shaping	Engineering	0.185
Cylinders, Rollers, Pistons, And Stuffing-Boxes.	Non-ferrouse metals	0.368
Drawing And Photography	Printing and publishing	0.643
Dyeing And Colouring.	Textile finishing	0.431
Earthenware And Porcelain Manufacture.	Misc. Manufactures	0.62

The tables lists by technology category the most important input–output industry, including the weight that we use to map industries into categories. The sample comprises the first 50 technology categories in alphabetical order.

2.D Additional results for the impact of knowledge stocks on innovation

Here we present some additional results related to those shown in Figure 2.3 in the main text. In Figure 2.6 we present results using the same approach as in Figure 2.3 except that we also include a lag of the dependent variable in the regression. Our motivation for examining this alternative specification is that the inclusion of a lagged dependent variable may help pick up the effect of the number of researchers working in a technology area on patenting in that area (the $\ln r_{it}$ term in Eq. 2.3). In modern studies, this is dealt with through the inclusion of controls for R&D expenditures in particular technology areas. It is impossible to obtain such measures for the historical setting that we consider, but these values should be closely related to lagged patents. The results in Figure 2.6 show that the inclusion of the lagged dependent variable does not substantially affect our results.

Figure 2.6: The lagged effect of the knowledge stock on patenting rates



The figure presents estimated coefficients and 95% confidence intervals for PPML regressions based on Eq. 2.5 applied to all British patents and using the British innovation matrix. We include only patents by domestic inventors. Patents appearing in multiple (N) technology categories count as only a fraction (1/N) of a patent in each of category. Because there are many zeros in the data, we actually use $\ln(n_{it} + 1)$ in place of the $\ln(n_{it})$ terms shown in Eq. 2.5.

2.E Additional Macroinvention analysis results

This appendix provides some additional results related to our macroinvention analysis. Figure 2.7 presents event study results using the intersection list of macroinventions. These results are very similar to those reported for the other two macroinventino lists in the main text.

One potential concern in our main analysis is that, by using the log number of patents as the dependent variable, we are dropping some observations. In many cases this is sensible. For example, this causes us to omit observations for the Railroad technology category for many years because, prior to the invention of railroads, there were zero patents in this category. We also end up dropping observations for very small technology categories, such as Wigs, which often have zero patents even when aggregating up to five year periods.

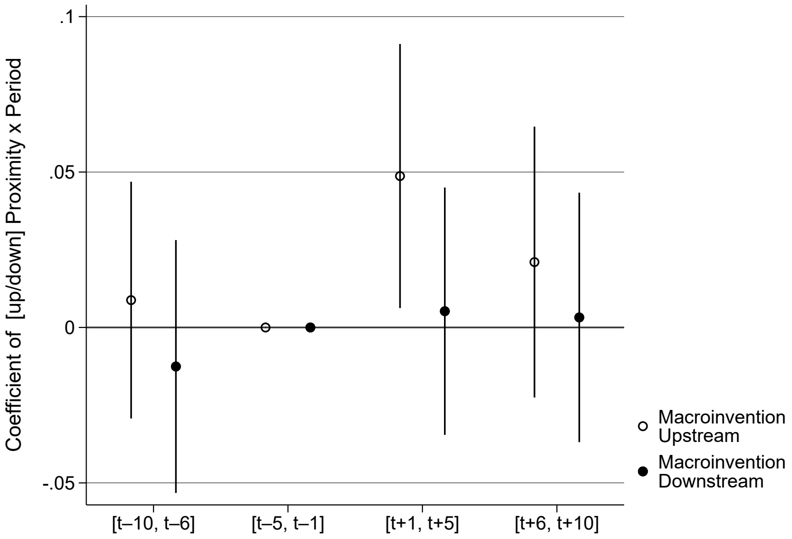
To ensure that omitting these categories by taking logs is not critical to our results, in Table 2.15 we present results from regressions where the outcome variable is the number of patents, rather than log patents. Other than that change, the format of the table follows that used in Table 2.4 in the main text. These results are similar to those presented in the main text, though less statistically significant in some specification. However, the overall similarity in the patterns shows that the omitted categories are unlikely to be key to our results. One notable difference here is that the eigenvalue centrality control is now more important.

2.F Validating our approach using modern data

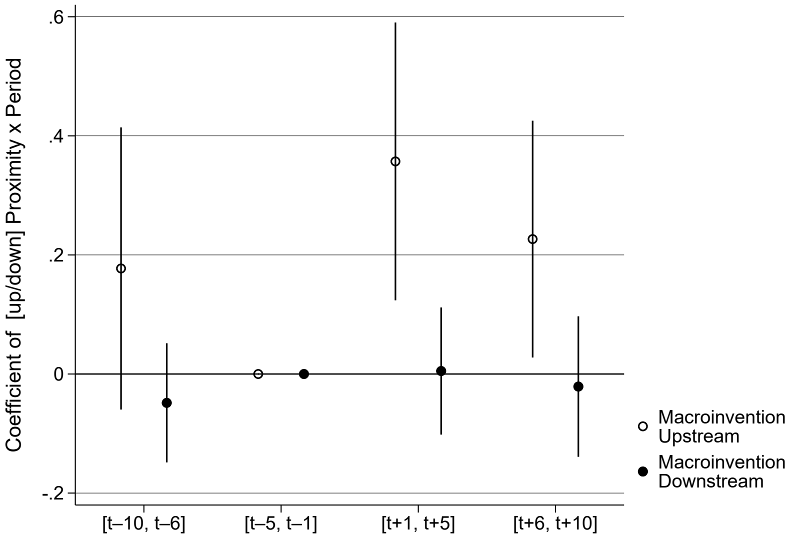
Because our approach to measuring the innovation matrix is novel, it is useful to provide some additional evidence showing that our approach provides an accurate measure of the underlying innovation network. To validate our approach, we turn to modern patent data, where we can observe both citations and individual identifiers for inventors that allow us to link their patents.

Our comparison focuses on the U.S. patent data provided in the 2015 version of PatStat. The PatStat database provides individual identifiers, International Patent Classification (IPC) technology categories for each granted patent, and bilateral patent citations. Using these inputs, we can construct and compare innovation matrices based on either citations or on the inventor-based approach that used in our main analysis. To keep the size of the networks manageable, we focus on the “three digit” IPC level (e.g., A41: Wearing Apparel) and classify each patent based on the first (primary) IPC code provided by the U.S. Patent and Trademark Office (PTO). The result is a 123 x 123 matrix, a similar level of detail to the

Figure 2.7: Macroinvention event study—different definitions



(a) Macroinvention: First patent in subcategory



(b) Macroinvention: Intersection

The figure presents estimated coefficients and 95% confidence intervals (robust standard errors) for PPML regressions of log patents on the interaction of proximity to a macroinvention ($Proximity_{ie}$) either upstream or downstream of a technology category and indicators for each five-year period before and after the event. The five-year period just before the macroinvention is the omitted reference category. The regression includes controls for upstream and downstream IO connections to the macroinvention technology category, as well as the eigenvalue centrality of each technology category, each interacted with time-period indicators.

Table 2.15: Macroinventions regression results in levels

	Dep var: Number of patents					
	Nuvolari et al		1^{st} in subcat.		Intersection	
	(1)	(2)	(3)	(4)	(5)	(6)
Proximity upstream × post	0.052^{**}	0.037^{*}	0.028^{*}	0.021	0.172^{**}	0.141^{*}
	(0.022)	(0.022)	(0.015)	(0.016)	(0.083)	(0.076)
Proximity downstream × post		0.005		0.014		0.036
		(0.022)		(0.014)		(0.041)
EV centrality × post		0.072^{***}		0.077^{***}		0.080^{***}
		(0.022)		(0.018)		(0.025)
Upstream I–O × post		−0.003		−0.001		0.017
		(0.009)		(0.014)		(0.018)
Downstream I–O × post		0.008		−0.001		−0.084
		(0.016)		(0.013)		(0.052)
Category × event FE	✓	✓	✓	✓	✓	✓
Period × event FE	✓	✓	✓	✓	✓	✓
Observations	19342	19086	36860	36368	3052	3016
Estim. FE coef.	5008	4944	9523	9400	787	778
Number of clusters	145	143	145	143	145	143
Pseudo R^2	0.656	0.656	0.638	0.638	0.642	0.643

Poisson pseudo maximum likelihood (PPML) regressions. Observation = category–event–period, with four periods per event, two before the event ($[t-10, t-6]$ and $[t-5, t-1]$) and two after the event ($[t+1, t+5]$ and $[t+6, t+10]$). Standard errors are clustered at the level of technology category. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

technology classifications used in our main analysis.

Our inventor-based innovation network is constructed using the approach shown in Eq. 2.4. Our citation-based network is generated using the approach used in Liu and Ma (2021) as well as other modern studies:

$$\omega_{ij} = Cites_{ij} / \sum_{l} Cites_{il}$$

where $Cites_{ij}$ is the number of patents in category i citing patents in category j.

We focus on citations between U.S. patents for this measure. Also, because we are interested in knowledge flows that contribute to the development of new technologies, we limit our analysis to only those citations provided by the patent applicant in the original

Table 2.16: Comparing the edges of French and British innovation networks

	Dep var: Citation-based edges	
	(1) incl zeros	(2) excl zeros
Inventor-based edges	1.078***	1.162***
	(0.084)	(0.061)
Constant	−0.000	−0.001**
	(0.000)	(0.000)
Observations	14884	7961
R^2	0.788	0.843

OLS. Observations are network edges connecting nodes (technology categories) i and j. Observations are weighted by the sum of patents in i and j (Stata analytical weights). Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

submission. This excludes other citations, such as those added by the patent examiner in the search phase or those added during opposition, which identify related technologies but may have been unknown to the inventor at the time of invention. After these cuts, we are left with a total of just over 30 million bilateral citations between U.S. patents.

After generating these two network measures, we compare the similarity of the resulting measures using the same methods that we apply to comparing the French and British innovation networks in Section 2.4.3. In Table 2.1 in the main text, we compare the centrality of nodes of the two networks, which we find to be very similar. Alternatively, in Table 2.16 below, we compare the edges of the two networks. This is a more demanding specification, but despite that we continue to find strong evidence that our method generates an innovation network that is very similar to the one obtained using citations. In particular, the estimated coefficients are close to one and the inventor-based network can explain a substantial fraction of the total variation in the citation-based network.

3 Access to Knowledge and Economic Growth: Evidence from Enlightenment Encyclopedias

This paper tests the hypothesis that access to enlightenment encyclopedias of useful technological knowledge accelerated economic growth during the Industrial Revolution. Prior research has documented a positive association between encyclopedia sales and measures of growth in France after 1750, yet this may solely reflect the effect of (upper-tail) human capital on growth and demand for books. This paper establishes the independent impact of the encyclopedias' *content* on growth. Using a novel city-level dataset on booksellers in 1781 in Europe, it isolates variation in the supply of encyclopedias due to the interaction of the local presence of booksellers and their geographic proximity to the location where encyclopedias were printed. Holding constant independent effects of booksellers and proximity, the interaction of booksellers with proximity strongly increased city-level encyclopedia sales. 2SLS regressions show that cities with better access to useful knowledge grew faster after 1750 but not before.

3.1 Introduction

Why modern economic growth (steady improvements in living standards fueled by sustained technological progress) began when and where it happened is one of the mysteries that hold the key to understanding today's global wealth and inequality (Landes, 1969; Rostow, 1975; Easterlin, 1981; Acemoglu, Johnson, and Robinson, 2005; Galor, 2011). When seen from a global perspective, one striking feature is that it first happened in a group of European countries within a similar period. Thus, any plausible explanation should explain both "growth take-offs" in general and the coincidence of geography and timing within Europe. One prominent hypothesis fulfilling these criteria maintains that access to useful knowledge (chiefly, what today is called science and technology) was critical for unchaining technological Prometheus, a feat which was accomplished by the "Industrial Enlightenment" that made useful knowledge widely accessible through journals, books, and encyclopedias (Mokyr, 2002, 2005).[1] While accepted as plausible (e. g. Crafts, 2021), the hypothesis nevertheless lacks support in the form of causal evidence that the Industrial Enlightenment contributed directly to the beginning of modern economic growth by reducing access cost to useful knowledge through printed compendia of knowledge.

Prior research has established that sales of enlightenment encyclopedias strongly correlate with city population growth and other proxies for industrialization in France (Squicciarini and Vogtländer, 2015). However, encyclopedia sales reflect a combination of supply and demand driven by the appetite for enlightenment literature of the "knowledge elite." Thus, the finding mixes the potential effect of access to useful knowledge with the effect of (upper tail) human capital on growth.[2] One would need to empirically disentangle the supply of encyclopedias from factors affecting demand to establish whether there was indeed an effect of the scientific–technological *content* of the encyclopedias on economic growth.

This paper draws on novel data on European-wide encyclopedia sales, booksellers, and publishers to isolate variation in the supply of encyclopedias that provided access to useful knowledge. On encyclopedia sales, I extend an existing dataset (Squicciarini and Vogtländer, 2015) on sales from publishers to booksellers for editions ca 1780 of two important encyclopedias—the *Encyclopédie* by Diderot and d'Alembert and the *Déscriptions des Arts et Métiers*—to include sales to locations outside France. On booksellers, I digitized the number of booksellers by city from a trade directory of booksellers in 1781, the *Almanach de la librairie* by Perrin, covering Europe from Portugal to Russia.[3] The data allow me to distinguish general access to books at a location (measured by booksellers) from access to particular books containing useful knowledge (measured by encyclopedia sales). Furthermore, I use the information on where the encyclopedia editions were published and printed.

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[1] The argument holds that reduced access costs to useful knowledge unchained technological progress by making the technology frontier available to producers; facilitating invention by recombination, analogy, and avoidance of reinventing the wheel; and facilitating improvements and adaptations through knowledge of why and how techniques worked.

[2] As demonstrated in the next chapter of this dissertation, the demand interpretation appears valid since up to one-third of the (city-level) variance in encyclopedia sales can be explained by factors that created upper-tail human capital.

[3] The Almanach was written in the French language and published in Paris. For some countries, booksellers are listed only for the capital and other cities of major economic and political importance. My core sample for which historians have assessed the *Almanach*'s coverage to be good comprises France, Germany, Italy, the Low countries, and Switzerland. In principle, I could also digitize the names of individual booksellers and link them to encyclopedia sales, but my primary analysis is at the city level.

The proximity of booksellers to the publisher influenced transport and transaction costs, thereby creating variation in the supply of encyclopedias to individual locations.

Following an extensive literature that uses city population growth as a proxy for economic development in the period before 1850, I first document a robust positive correlation at the city level between booksellers and city population growth after 1750 but not before. Motivated by abundant anecdotes on the competition for customers among booksellers and evidence that some booksellers operated proto libraries (*cabinet de littéraire*) (Darnton, 2018), I focus on bookseller density, the number of booksellers per thousand inhabitants, as a proxy for local access to books.[4] I find that a one standard deviation increase in bookseller density, corresponding to an increase from one bookseller per 8000 inhabitants to one bookseller per 3000 inhabitants, was associated with a 9.2 percentage point increase in city population growth during 1750–1850 (11% of the average and 15% of the median growth rate). The association is robust to controlling for factors that may have affected the listing in the booksellers' trade directory, including country fixed effects, and geographic fundamentals that may have affected transport cost, access to information, and city growth. Within the subsample of France, for which I have additional controls, the association also holds conditional on various determinants of upper tail human capital that likely affected the demand for useful knowledge.

Which books did booksellers sell—and did it matter for growth? I first document that bookseller density strongly predicts encyclopedia sales at the city level for both considered encyclopedias of useful knowledge. After that, I show that sales of both encyclopedias mediate the positive correlation at the city level between bookseller density and city growth from 1750 to 1850, suggesting that the particular type of books sold by booksellers mattered for growth—those which contained useful knowledge. As before, I find that the results are robust to the inclusion of controls, including controls for the local supply of upper tail human capital that likely affected demand.

Nevertheless, these demand controls do not solve the challenge of disentangling demand and supply since they will not be sufficiently highly correlated with upper tail human capital in the presence of directed migration. Moreover, there is a concern that some unobserved city characteristic like capital and wealth was both determining economic growth and creating a generalized demand for books and encyclopedias due to their consumption value and signal of social status.

To address this identification concern, I consider variation in the (wholesale) supply

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[4] Furthermore, there is much evidence that most booksellers marketed books locally. Empirically, it is not a major concern if some booksellers sold outside their location because, in this case, I would observe more book sales (per capita) but not more growth which would bias my estimates downward.

of encyclopedias to booksellers resulting from the geographic proximity of booksellers to the publisher and the print location. Proximity to the publisher and the print location mattered for at least two reasons. The first is that encyclopedias were seldomly published or reprinted due to the high fixed cost involved in printing complex works. The second is that there were substantial costs associated with transporting books due to general transport costs, which increase with distance, and the fragility of printed sheets of paper to wetness, dampness, and inappropriate handling.[5] The encyclopedia editions studied here were printed and shipped from Lyon in France and Neuchâtel in Switzerland. While Lyon was the second largest city in France with a large silk industry, neither city was a major hub for the European trade in goods and exchange of ideas like Paris, Amsterdam, or London.

To sidestep potential concerns that proximity to print locations in Lyon or Neuchâtel might correlate with other determinants of growth, I will use as an instrument the *interaction* of bookseller density and proximity to print location. This allows me to control for proximity to Lyon or Neuchâtel and hold constant any effect of proximity to these places that do not work through bookseller density. Likewise, by controlling for bookseller density, I hold constant a generalized demand for books and the factors that affect it. The first stage of encyclopedia sales on bookseller density and proximity is of separate interest, as it allows to establish whether booksellers had a causal impact on encyclopedia sales. I show that the interaction effect of booksellers and proximity is highly significant and large in magnitude. Cities with high bookseller density and close geographic proximity to the print location had substantially higher encyclopedia sales (absolute and per capita), in contrast to cities with high bookseller density but far away from the print location and cities that were proximate but thinly served by booksellers. The relative magnitudes suggest that the local presence of retail booksellers mattered less for encyclopedia sales than the booksellers' cost of procuring encyclopedias from the publishers.

In the 2SLS regression analysis, I show that encyclopedia sales positively and significantly impacted city growth in 1750–1850 after the encyclopedias were published. In contrast, I do not find an impact of encyclopedia sales on city growth in the period 1700–1750 before the encyclopedias were published, indicating the absence of pre-trends. The first stage is reasonably strong with a Kleinbergen–Paap F-statistic around 50, and the magnitude of the 2SLS point estimates is in the ballpark of the OLS estimates.

To validate the idea that proximity to the print location created regional variation in the

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[5] These difficulties in shipping were as true for the early period of the printed book—see in particular the literature cited and evidence provided in Dittmar (2011)—as it was for the later stages of the Ancien Régime. The real price of printing fell steeply in the first decades after Gutenberg's invention of movable type printing but afterward declined only mildly in the two centuries before 1789 (Van Zanden, 2009). The transport of books remained a bottleneck until the 19th century.

booksellers' cost of procuring encyclopedias from the publishers, I consider the proximity to alternative locations where editions of the same encyclopedias were published in a falsification exercise. If proximity mattered, I would expect to observe fewer sales closer to those alternative locations since booksellers there could acquire the product more cheaply from other publishers. Indeed, I find strong evidence that the interaction of bookseller density with proximity to alternative editions reduced sales of the Lyon and Neuchâtel editions. The inclusion of the alternative interaction variable increases the magnitude of the bookseller–proximity to Lyon or Neuchâtel interaction effect, suggesting that controlling for the availability of competing editions can purge some heterogeneity. Furthermore, I show that this pattern is not generic to proximity and interaction with other centers in the "fertile crescent of enlightenment publishing" (Darnton, 2021) like Amsterdam, where no alternative editions were published. Neither are the findings explained by the proximity or interaction of booksellers with proximity to Paris.

Related literature First, the paper extends the literature on the impact of the printed book on growth and societal change in pre-modern Europe (Van Zanden, 2009; Dittmar, 2011; Rubin, 2014; Dittmar and Seabold, 2022) by explicitly considering the publishing and distribution of books. Earlier work considered the impact of the printing press on city growth under the assumption that printing presses anywhere could, in principal, print the same books containing the same ideas, but since the printing technology spread slowly and since books were distributed locally due to transport costs, there was regional variation in where ideas became first accessible (Dittmar, 2011). This paper considers a period when printing presses were already ubiquitous across Europe but transport costs of books where still a binding constraint. Also, it considers encyclopedias of useful knowledge, which were particularly impactful books for disseminating ideas but only printed in few locations due to their complexity. Introducing novel data on booksellers to measure the European-wide retail network for distributing books, the paper then exploits the proximity of retail booksellers to the printer and publisher. This proximity created variation across European cities in the (wholesale) access to encyclopedias that translated into variation across cities where ideas become easier accessible.

Second, the paper contributes to a recent literature on technological progress during the Industrial Revolution. By establishing that two French encyclopedias were pivotal for growth by providing access to useful knowledge, it echoes results from alternative mechanisms providing access to useful knowledge like universities (Dittmar and Meisenzahl, 2020) or economic societies (Cinnirella, Hornung, and Koschnick, 2022). Whereas those mechanisms primarily explain why ideas diffused locally, this paper provides the first causal evidence why ideas diffused across Europe—the European (enlightenment) book trade network that delivered books from publishers to booksellers to readers. This mechanisms also provides a potential explanation for why the growth take-off in the European "core" was synchronized. As human capital is necessary for the adoption of technological knowledge (Nelson and Phelps, 1966), the relevance of encyclopedias for growth also complements research on the relevance of human capital, including (general) upper-tail human capital (Squicciarini and Vogtländer, 2015), mechanical competence (Mokyr, Sarid, and van der Beek, 2022), engineers (Hanlon, 2022), and science education (chapter 4 of this dissertation).

Third, the paper relates to a literature in innovation showing that access to knowledge affects the rate (and direction) of invention. Among others, (Biasi and Moser, 2021) show that a reduction in the access cost to science books can have a substantial positive impact on the production of scientific knowledge, and (Furman, Nagler, and Watzinger, 2021) show that the introduction of libraries which provided access to knowledge codified in patents had a positive impact on the rate of inventive activity. This paper considers a setting when public libraries and other institutionalized means of accessing information were either non-existent or yet in their infancy.[6]

3.2 Historical background

3.2.1 Publishing and book-selling during the Ancien Régime

Local booksellers were critical for readers' access to books by maintaining ties with publishers in an age where there was nothing like mail order catalogs. Partly, this was due to the high cost of information transmission: For example, publishers did print catalogs, but since paper was expensive, only small print runs of 100 or 200 pieces were sent out to their idiosyncratic network of booksellers. Also, there were hardly any supra-regional media with a broad reach like newspapers today through which publisher and wholesalers could have advertised their portfolio. Moreover, there were no financial institutions that would have supported retail customer finance. Books were expensive and typically sold by publishers and wholesalers to booksellers on credit (if not commission) in terms of bills of exchange—which only a tiny minority of wealthy private persons could write credibly. Finally, the product was typically sold unfinished: Booksellers received bales of sheets of printed paper, which they bound in leather locally before delivering or selling it to the

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[6] Given that I currently use only city population growth as outcome to summarize technological progress, this literature provides plausibility for my proposed argument. For future versions, it will be expedient to consider as outcome more direct measures of invention such as patents.

customer, the reader.[7]

However, the booksellers' access to the wholesale trade in books varied starkly across locations depending on where books were published and printed. The location of publishing and printing was influenced by economic and political factors, and on the cost associated with shipping them from the location of printing to the location of retail.

The key economic factor that restricted the number of publication places was the presence of substantial fixed costs for print runs. In general, the price of books and printing had changed little since the mid-seventeenth century (Van Zanden, 2009). Book editions usually came in size one thousand copies per printrun, whereas more complex endeavors like dictionaries and encyclopedias usually came at two thousand copies per printrun. Darnton (2021) provides many examples of publishers speculating on which books, new or reprints of old, might sell well and had not been recently published elsewhere or were already in the process of being published elsewhere.

The critical political factor that restricted publication and printing was local to France, where publishing required, in principle, a royal *privilège*. A *privilège* guaranteed a monopoly on printing the book, similar to modern copyrights. However, the market for *privilèges* was highly regulated, subject to censorship, and effectively monopolized by the Paris booksellers' guild. As a result, a "fertile crescent" of enlightenment publishing emerged around France, stretching from Amsterdam over the Rhineland down to Switzerland to Avignon Darnton (2021). Publishers in the "fertile crescent" not only printed original editions of works that could not get a *privilège* in France but also expanded into the market for pirated books, that is, reprints of books without regard to the French *privilège*.

Once a book was published by a particular publisher in a particular location, geographic proximity determined booksellers' wholesale access. Principally, distance worked by increasing transport costs and thus created variation in effective wholesale prices within France as across Europe. Out of the many examples given by Darnton (2018), he quotes a bookseller in Western France who was writing to a publisher–wholesaler in Switzerland that he was willing to order if they were to provide shipping free of cost and risk to Orléans. (The Swiss publisher–wholesaler refused, and no business was done.)

Besides transport costs, geographic proximity likely influenced other factors affecting local booksellers' wholesale access, including information, credit, and trust. The importance

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[7] The two principal reasons for this practice appear to be (a) the transport cost associated with leather, being relatively heavy but cheap compared to printed sheets of paper, and (b) the risk of damage to paper during transport from wetness, dampness, and inappropriate handling. For the second reason, print runs usually included a 10% allowance of additional printed sheets to replace potential transport damages (e. g. Darnton, 2018).

of information and credit has already been mentioned above.[8] Trust was important beyond the publishers' trust in the creditworthiness of booksellers. Given the general risk of transport damage, and the fact that returns were prohibitively expensive, there was scope for booksellers to claim damage compensation even if it was unjustified. Also, the bookseller's confidence in the quality of print and paper, correct transport, and timely delivery were all important influences for the bookseller's decision to place an order. These channels were likely affected by a history of successful transactions. As the likelihood of succesful past transactions also depended on transport costs, the channels thus reinforced the importance of proximity.

3.2.2 Encyclopedias of useful knowledge

Two encyclopedias were essential among the many works of industrial enlightenment that improved access to useful knowledge. One is the *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers* by Diderot and d'Alembert, published 1751–65 (plates published 1762–1772). Its goal was to "impose order on abundant but haphazard scholarship handicapped by a neglect of science and technology in favor of matters of history and religion" (Roche, 1998, 575). "The greatness of the *Encyclopédie* lay in the fundamentally important role assigned to its plates of drawings and models…These plates were not included solely for documentary purposes; it was hoped that they would contribute to further technical progress." (Roche, 1998, 575–6).

The second work is the *Déscriptions des Arts et Métiers*, edited by Réamur and Duhamel and published 1761–82 by the French Royal Academy of Sciences. In its style of depicting arts, trades, and technologies as they were practiced "on the shop floor," with copper engravings depicting on top of the workshop and below details of the tools, this work was hugely influential for the *Encyclopédie* (Watts, 1952; Hahn, 1981). Yet, its publication as an encyclopedia proper was probably precipitated by the publication of the *Encyclopédie*, who may be credited with forcing the *Déscriptions*' diffusion to the general public. The importance of this work can hardly be better summarized than by a quote from Benjamin Franklin, writing in 1788 to the governor of Massachusetts: "Has your Society among its Books the French Work sur les Arts et les Metiers? It is voluminous, well executed, and may be useful in our Country." (Carpenter, 2011, 20)

The two encyclopedias of useful knowledge had a European reach and were widely translated and imitated. The encyclopedias had readers across Europe thanks to France

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[8] Credit depended principally on reputation. For first-time customers, publishers would try to acquire this information through their business network, which may also have been shaped by distance.

being the lingua franca of the European elite in the eighteenth century. For example, in the quarto edition of the *Encyclopédie* (which this paper uses in the empirical analysis, see section 3.3), sales are documented as far as Lisbon, Dublin, Naples, and Moscow. The *Encyclopédie* received several reprints (see also section 3.5.3) and was translated in part or whole to other languages, including English as "Complete Dictionary of Arts and Sciences" (Croker, Williams, Clark, 1764–6, 3 vols folio, London). A revised and expanded edition, the *Encyclopédie Méthodique* (Panckoucke, 1782–1832, 203 vols in quarto, Paris), was subsequently translated to Italian (1785–91, Padova) and Spanish (1788–94, Madrid) (Donato and Lüsebrink, 2021). The *Déscriptions* were translated to German (1765–95), Dutch (from 1788), and Danish (from late 1790s) (Carpenter, 2011). These translations are only the tip of the iceberg because historians have not yet systematically documented references to and plagiarization of parts. It is also highly likely that the widely popular British *Encyclopedia Britannica* and German *Brockhaus Conversations-Lexikon* drew more than inspiration from the mentioned encyclopedias.

The *Encyclopédie* edition considered in this paper was published in 1777–9 by a consortium and printed mainly in Lyon. The consortium consisted of Panckoucke, one of the largest booksellers in Paris, Duplaîn of Lyon, and the Société typographique of Neuchâtel (STN). The edition came in 36 volumes as a quarto (cheaper than a full-size folio) at a total printrun of 8000 copies, which were mainly printed in Lyon.[9] The edition was entirely legal in France, as Panckoucke de facto owned the *privilège* (for the details, see Darnton (1973)).[10] Like other encyclopedias, the *Encyclopédie* was sold as a subscription, which means that it was delivered to the subscriber volume by volume as they were printed.

The *Déscriptions* edition considered here was published 1771–83 by the typographical society of Neuchâtel (STN) as quarto edition in 19 volumes. As the STN did not possess the *privilège* for publication, the edition was semi-illegal in France. The STN and editor Bertrand tried to market it as substantially revised and thus a quasi-new work. Since the work passed the censorship, it might thus be quasi-legally marketed with a tacit permission. In the legal gray zone, it was nevertheless at risk of confiscation if the *privilège* owner would initiate police action—something which Panckoucke did with a competing octavo (cheaper than quarto) edition of the *Encyclopédie* (Darnton, 1973). Adding to the uncertain legal status in France, a law of 1777 gave a general amnesty of pirated works but henceforth strictly prohibited any pirating. As a result, the STN lost subscribers over time and sold

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[9] The print run of the quarto edition was so large that printing shops in the area of Lyon printed nothing else for several months. Some volumes were outsourced to Geneve and Neuchâtel, Switzerland, but they were first shipped to Lyon and delivered to customers from Lyon.

[10] I do not have a good overview of whether other European states had import restrictions on books from France and where the *Encyclopédie* was banned due to sensitive articles on religion. By the time

only about half of their total printrun of 1000 copies.[11]

3.3 Data

The unit of analysis will be the city. I use a sample of European cities from Bairoch, Batou, and Chèvre (1988), which includes all cities in Europe that reached 5000 or more inhabitants by 1850.

Growth The primary outcome measure for economic growth will be city population growth. City population is widely used in the literature as a proxy for local economic development and technological progress in historical Europe, including De Long and Shleifer (1993); Acemoglu et al. (2005); Dittmar (2011); Bosker, Buringh, and van Zanden (2013); Cantoni (2015); Squicciarini and Vogtländer (2015). As some of the cited works show, the measure correlates with other proxies for development as height and also predicts economic activity and income in the earliest available survey and census data of the 19th century.

Booksellers The number of booksellers at the city level is based on the *Almanach de la librairie* by Antoine Perrin. The *Almanach* was the earliest repertory of booksellers in Europe.[12] It was originally published in three editions–The 1st as "Manuel de l'auteur" in 1777, the 2nd as "*Almanach de la librairie*" in 1778, and the 3rd "corrected and augmented" edition in 1781. Since the earlier editions had a few omissions, I focus on the numbers for 1781, which I digitized after the tabulations in Vercruysse and Collins (1984). The *Almanach* was published in the French language in Paris and thus primarily targeted the market for French language literature—which extended far beyond France in the 18th century (e.g. Darnton, 2021). While it provides names of booksellers from Portugal to Russia, it covers only the most important cities and capitals in countries far away. For countries closer to France, including Belgium, Germany, Italy, Netherlands, and Switzerland, historians assessed that it provides an accurate description (Vercruysse and Collins, 1984)—at least for the relative prevalence of booksellers within a country, which is what matters since I use country fixed effects. Table 3.9 provides an overview of the number of booksellers (and cities) by country.

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[11] In late 1783, the STN became insolvent and started restructuring and liquidation. While difficult to establish what caused it, a French law of 1783 massively raised import barriers for books, which effectively destroyed the STN's most important market in France (Darnton, 2021).

[12] For example, the first repertory for England, *The London and Country Printers Booksellers and Stationers* by John Pendred, was published in 1785 (Vercruysse and Collins, 1984).

Encyclopedias The number of encyclopedia sales at the city level comes from two principal sources. For the *Encyclopédie* by Diderot and d'Alembert, I digitized sales data—subscriptions by town and bookseller—for the quarto edition (1777–1779) as transcribed by Darnton (1979) after a secret list compiled by one of the publishers, Duplain. As the part on France has been previously digitized and used by Squicciarini and Vogtländer (2015), I only needed to digitize the data for other European cities. The sales of this edition are biased towards France because the quarto edition was legal in France and primarily marketed to the French market. For the *Déscriptions des Arts et Métiers*, I collected sales data on the by town and bookseller for the quarto edition of the STN (1771–1783) from Burrows and Curran (2014). Again, the data for France has been previously digitized and used by Squicciarini and Vogtländer (2015), so I verified it and extended it to other European cities. The sales of this edition are somewhat biased against France, as it was not fully legal in France.[13]

Distances I calculate all geodesic distances "as the crow flies." Optimally, I would have not only travel distances that take into account cheaper river and sea transport and more expensive mountain transport, but also tariffs that applied to the various jurisdictions.[14] Unfortunately, I do not have systematic data on these factors. As an approximation, it will be fine as long as the measurement error is standard.

Controls In the baseline regressions, I will control for a set of geography controls which I obtained for convenience from the literature (Johnson and Koyama, 2017). Furthermore, I will employ a set of country fixed effects.[15] For the subsample of cities in France, I also have an extended set of controls for upper-tail human capital comprising indicators for secondary schools, science education, universities, and scientific societies (see chapter 4 of this dissertation)

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[13] The STN did not possess the privilège and did not get the agreement of the privilège holder, Moutard of Paris, who printed the more luxury folio edition. In order to avoid confiscation as pirated work, the STN argued that its version was significantly extended by the editor Bertrand, who incorporated the latest material from other German, Swiss, and French sources. Nevertheless, it seemed to lose subscribers in France after the French state became tougher on counterfeit editions in 1777.

[14] For example, there were high tariffs for shipping goods through Alsace and Lorraine. Thus, the Swiss publisher STN did not use the route of shipping down the Rhine to Basel and then into France but instead the South–Western route through the mountain passes towards the Rhône and from there to the rest of France.

[15] The countries comprise Belgium, France, Germany, Italy, Netherlands, and Switzerland. Of course, the notion of the country is an anachronism for several of these. Except for France and perhaps Switzerland, these countries did not yet exist as legal entities. Needless to say, the borders were fuzzy in 1781. Furthermore, it might be more appropriate to include language fixed effects. However, it was probably the case that the elite was speaking and reading French everywhere in 18th-century enlightenment Europe (Darnton, 2021).

3.4 Booksellers, encyclopedias, and city growth

3.4.1 Empirical specification

Equation 3.1 represents the baseline regression to estimate the association of log population growth and log bookseller density before or after the publication of encyclopedias at the level of city i in country c, conditional on country fixed effects ϕ_c and a set of controls $\mathbf{X}$.

$$\ln \textit{growth pre/post 1750}_{i,c} = \beta_1 \ln \textit{bookseller density}_{i,c} + \phi_c + \mathbf{X}'\gamma + \varepsilon_i \tag{3.1}$$

As the first volume of *Encyclopédie* was published in 1751, I use the year 1750 to distinguish between pre-period (1700–1750) and post-period (1750–1850).

Ln bookseller density is the (natural) log number of booksellers per thousand inhabitants. I use bookseller density rather than the number of booksellers primarily to empirically distinguish the effect of market size—larger cities have larger markets for books and more total booksellers, see section 3.A.3—from the relevant measure, access to books. Access to books depends on the ratio of booksellers to potential customers, besides others, because of (i) the positive effects of competition on reducing prices, (ii) the practice of booksellers in operating reading rooms, and (iii) the importance of assessing the customer's creditworthiness in the case of subscriptions.[16] Figure 3.1 illustrates the distribution of bookseller density in the full sample (a majority of zeros) and the sample conditional on at least one bookseller (resembles a truncated normal).[17]

The baseline set of controls $\mathbf{X}$ includes geography variables that might correlate with economic growth and the accuracy of reporting booksellers (e. g. distance from Paris) or the access to books through trade networks (e. g. rivers or Roman roads). The extended set of controls, available only for the subsample of France, includes variables that measure the presence of upper-tail human capital, which created a demand for books and encyclopedias (Squicciarini and Vogtländer 2015, chapter 4) that may have supported more local booksellers in a given city. Moreover, upper-tail human capital arguably directly affected growth (Mokyr, 2010; Squicciarini and Vogtländer, 2015).

After implementing the baseline regression, I will estimate equation 3.2 to infer whether bookseller density can explain encyclopedia sales and equation 3.3 to infer whether ency-

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[16] The volumes were delivered over two years, and the customers usually pay after the final volume was delivered. The assessment of creditworthiness often depended on private information that the booksellers acquired over many years of business relationships with customers.

[17] I winsorize to the 99 percentile to ensure that spurious outliers do not drive results.

clopedia sales mediate the association of city population growth and booksellers.

$$\ln \textit{encyclopedia density}_{i,c} = \beta_2 \ln \textit{bookseller density}_{i,c} + \phi_c + X'\gamma + \varepsilon_i \tag{3.2}$$

$$\begin{aligned}\ln \textit{growth pre/post 1750}_{i,c} = \beta_3 \ln \textit{encyclopedia density}_{i,c} + \beta_4 \ln \textit{bookseller density}_{i,c} \\ + \phi_c + X'\gamma + \varepsilon_i \end{aligned} \tag{3.3}$$

Ln encyclopedia density is measured, analogously to bookseller density, as the number of encyclopedia sales per thousand inhabitants. This variable represents the access to useful knowledge created by enlightenment encyclopedias that were compiled and published. In robustness exercises, I use an indicator for the local presence of at least one encyclopedia as an extensive margin measure for access to useful knowledge. This corresponds to the idea that some booksellers may have provided access to a single copy in their reading room, enabling many more people to access it, quite like modern-day public libraries. I find that, yes, the extensive margin matters and is quantitatively meaningful. Unfortunately, there does not exist systematic data on whether booksellers operated reading rooms which would allow me to test this mechanism in more detail.

3.4.2 Results

Table 3.1 documents a significant, positive association between bookseller density and city growth from 1750 to 1850. The baseline coefficient of 0.55 is robust to the inclusion of a set of geography controls (column 2).[18] When evaluated at the mean, the standardized beta coefficient of 0.10 implies that a one standard deviation increase from one bookseller per 8000 inhabitants to one bookseller per 3000 inhabitants is associated with an additional population growth of 9.2 percentage points over the period 1750–1850, which corresponds to an increase of about 1200 inhabitants for a city of initial size 13000.[19] Including country fixed effects (column 3) slightly reduces the magnitude of the association, whereas conditioning on the sample of cities with at least one bookseller (column 4) roughly doubles the magnitude of the association. Both findings provide evidence against the concern that selective coverage by the Almanach, for example, of countries that were more important in the trade with France would explain the association.

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[18] All specifications are conditional on initial population, which is always negative and significant: Larger cities in 1750 grew on average less over 1750–1850. Table3.10 documents the coefficients on the geography controls: Besides the Paris indicator (always strongly positive) and elevation (cities at higher altitudes grew slightly less), none of the geography controls has a significant association once conditioning on country fixed effects.

[19] This is 11% of the average city growth of 82% and 15% of the median city growth of 60%.

The last two columns of table 3.1 probe the pre-trends associated with bookseller density. While bookseller density is positively associated with population growth in the period before 1750 (column 5), the association becomes insignificant and negative once one focuses on the intensive margin (column 6).[20] This suggests that cities with dynamic growth before 1700–1750 may have been more likely to attract at least one reputable bookseller (in the sense of being known to the author of the *Almanach*).

Did booksellers provide their customers access to encyclopedias of useful knowledge? Table 3.2 shows that bookseller density strongly predicts the sales density for two essential encyclopedias of the time. For the *Encyclopédie* by Diderot and d'Alembert, bookseller density explains (unconditionally) more than 30 percent of the variance in per capita sales (column 1). Even conditional on geography controls (column 2) and country fixed effects (column 3), a one percent increase in bookseller density is associated with a 1.5 percent increase in encyclopedia sales density. When evaluated at the mean, the standardized beta coefficient of 0.45 implies that a one standard deviation increase from one bookseller per 8000 inhabitants to one per 3000 inhabitants is associated with an additional 0.86 *Encyclopédie* sales per 1000 inhabitants. For a city of an average size of 13000, this would imply 11 additional *Encyclopédie* subscriptions— an increase of more than 150 percent against the baseline average subscription rate of 6.9. For the *Déscriptions des Arts et Metiers*, which did not have regular market access in the STN edition, bookseller density still explains about 12 percent of the variance in per capita sales. As before, the association is robust to geography controls, and country fixed effects. With a standardized beta coefficient of about 0.35, the economic magnitude is similar to that for the *Encyclopédie*.

Furthermore, the results are robust to focusing exclusively on cities in France and including an extensive set of controls for upper-tail human capital that plausibly created a demand for books (Appendix table 3.11). Some of the controls have highly significant coefficients, particularly the indicators for science education at the city's *collège* and the presence of a scientific society. As shown in another chapter of this thesis, the science education variable alone can explain about 30 percent of the variation in *Encyclopédie* per capita sales. Nevertheless, the coefficient on bookseller density decreases by merely 20 percent and remains highly significant, and the coefficient on *Déscriptions* per capita sales is barely affected. While not entirely ruling out upper-tail human capital and demand as an alternative explanation, the results are still highly supportive of the argument that

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[20] In additional analysis (not reported), I probe bookseller density and an indicator for at least one bookseller in joint regression. I estimate a highly significant and quantitatively sizeable positive coefficient on the bookseller indicator for the period before 1750 but an insignificant coefficient close to zero in the period after 1750.

booksellers provided the link between publishers and readers that proved critical for local access to encyclopedias of useful knowledge.

Table 3.3 shows that sales of encyclopedias of useful knowledge mediate the association between bookseller density and city growth. The sales densities of both *Encyclopédie* (columns 1) and *Déscriptions* (columns 2) are highly significant and positive predictors of city population growth 1750–1850. Including bookseller density next to encyclopedia density reduces the significance and magnitude of the encyclopedias' coefficients slightly (columns 3 and 4). Bookseller density, in contrast, becomes insignificant and its coefficient's magnitude shrinks between about 20% (*Déscriptions*) to about 80% (*Encyclopédie*). This result contrasts with the pre-period before the publication of the encyclopedias, where bookseller density remains positively associated with city population growth from 1700–1750, but the encyclopedias are not. (The coefficient of *Encyclopédie* is a precisely estimated zero, whereas that of the *Déscriptions* is positive but imprecisely estimated.)

Furthermore, I show in Appendix table 3.12 that the two encyclopedias are more or less independently associated with city growth. This result is evident when considering the extensive margin for whether cities got at least one encyclopedia (column 2). I also demonstrate that the same result of mediation after 1750 but not before 1750 is obtained when I use the first principal component of encyclopedia sales density (columns 3 and 5). This contrasts with an indicator for whether cities got at least one of the two encyclopedias, which is highly significant and quantitatively large after and before 1750 (columns 4 and 6). At least at the extensive margin, the parallel trends assumption appears to be violated since cities that grew more dynamically in the pre-period were more likely to get access to at least one encyclopedia. Thus, the challenge in the next section will be to establish a source of variation that affects the sale of encyclopedias while being orthogonal to city growth.

3.5 Identification

The main challenge is to empirically disentangle the growth effects from factors that cause demand for encyclopedias from the supply effects of access to the useful knowledge compiled in encyclopedias. In particular, there is concern that some unobserved city characteristic jointly influences economic growth and creates a generalized demand for books and encyclopedias. One such demand factor could be upper tail human capital, which arguably had direct impacts on growth but also created a readership for the encyclopedias (Squicciarini and Vogtländer, 2015). Another demand factor could be the capital and wealth of merchants and bourgeois who were ready to become entrepreneurs once the opportunities arrived but purchased books and encyclopedias less for their scientific–technological content rather than for their signal of social status.

One source of variation that may address these concerns stems from the effect on the propensity to sell books of geographical distance from the sales location to the print location—here, distance to Lyon for the quarto *Encyclopédie* edition[21] and distance to Neuchâtel for the quarto *Déscriptions* edition. Figure 3.2 documents a clear, negative association between total encyclopedia sales and distance to print location for both *Encyclopédie* and *Déscriptions.* Cities closest to the print location had the highest sales on average, and cities furthest away had no sales. For cities in between, average sales decreased more or less steadily with increasing distance. Figure 3.3 documents that this pattern of a negative association between encyclopedia sales and distance to print location also holds in terms of log encyclopedia sales per capita. Excluding cities with zero sales due to the log scale, there appears to be a log-linear negative relationship, with per capita sales dropping by one order of magnitude for every increase in distance of about 350km.

3.5.1 Empirical specification

The variation in encyclopedia sales due to the proximity to print location can help identify the causal impact of access to encyclopedias of useful knowledge on growth if it is orthogonal to the economic geography that determines the location of capital, entrepreneurs, and wealth. This assumption would be problematic if the print location was at the same time an economic hub, which naturally attracts and generates more capital, entrepreneurs, and wealth. To sidestep this concern, I will use the interaction of local bookseller density and proximity to print location and control directly for the (potentially endogenous) proximity to the print location.

In particular, I will estimate the following two-stage least squares regression,

$$\begin{aligned}\ln \textit{encyclopedia density}_{i,c} &= \delta_1 \ln \textit{bookseller density}_{i,c} + \delta_2 \ln \textit{proximity to [print loc.]} \\ &\quad + \delta_3 \ln \textit{bookseller density} \times \textit{proximity to [print loc.]}_{i,c} \\ &\quad + \phi_c + X'\gamma + \varepsilon_i \end{aligned} \tag{3.4}$$

$$\begin{aligned}\ln \textit{growth pre/post 1750}_{i,c} &= \beta_{IV} \ln \widehat{\textit{encyclopedia}}\,\textit{density}_{i,c} + \delta_4 \ln \textit{bookseller density}_{i,c} \\ &\quad + \delta_5 \ln \textit{proximity to [print loc.]} + \phi_c + X'\gamma + \varepsilon_i \end{aligned} \tag{3.5}$$

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[21] Some volumes were outsourced to print shops in Geneva and Neuchâtel but distributed from Lyon as if printed in Lyon. There was no difference in price between volumes printed in Lyon and Switzerland.

where *proximity to [print loc.]*$_i$ equals max(*distance Lyon*) − *distance to Lyon*$_i$ for the *Encyclopédie* or max(*distance to Neuchâtel*) − *distance to Neuchâtel*$_i$ for the *Déscriptions* and is measured in kilometers,[22] and β_{IV} is the effect of access to encyclopedias of useful knowledge on economic growth before or after 1750. The set of controls X will additionally include an indicator for the print location because these locations may be special. The identifying assumption in equation 3.5 is that conditional on bookseller density, proximity to print location, and additional controls, the interaction of bookseller density and proximity to print location is relevant for encyclopedia density and does not affect growth other than through encyclopedia density.

The first stage equation 3.4 has an independent interest, as it will allow answering the question of whether booksellers had an impact on access to useful knowledge. The coefficient of interest δ_3 informs whether bookseller density had a differential effect on encyclopedia sales density in cities that were geographically closer to the print location. The coefficient δ_1 will be positive if the differential effect comes on top of the positive baseline association of bookseller density and encyclopedia sales or negative if the differential effect explains away the baseline association. The interpretation of coefficient δ_2 will depend on the assumption one is willing to make about the orthogonality of print location (I do not need to take a stance). If it was orthogonal, δ_2 estimates the effect of proximity on encyclopedia sales independent of booksellers. If it was not orthogonal, δ_2 is contaminated by omitted variable bias and should be disregarded.

3.5.2 Results

Table 3.4 establishes that bookseller density had a differential effect on encyclopedia sales in cities closer to the print location. Columns (1) and (4) introduce proximity to Lyon or Neuchâtel without the interaction to examine the association of proximity to print location and book sales. The evidence is mixed; conditional on bookseller density and control variables, proximity to Lyon does not matter for *Encyclopédie* sales, but proximity to Neuchâtel does matter for *Déscriptions* sales. It also appears that proximity was mildly correlated with bookseller density since the coefficient on bookseller density shrinks by about ten percent. However, introducing the interaction terms in columns (2) and (4) shows that proximity and bookseller density strongly interacted. For *Encyclopédie* and Lyon, the interaction coefficient δ_3 is highly significant, R^2 increases by 10 percent, and its magnitude

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[22] This transformation is necessary to align the expected direction of the interaction effect: I expect cities with more booksellers (per capita) and with higher proximity (that is, shorter distance) to Lyon to have the highest encyclopedia sales (per capita).

is economically large with a standardized beta of 1.48. The coefficient δ_1 on booksellers turns strongly negative and significant, which shows that the unqualified association of booksellers with encyclopedia sales is explained by differentiating how costly it was for booksellers to procure it from the publishers. In contrast, the coefficient δ_2 on proximity to Lyon becomes negative and insignificant, which is reassuring because it suggests that proximity to Lyon was important for encyclopedia sales only because they were printed there. The result is hardly affected by the inclusion of country fixed effects (column 3). For *Déscriptions* and Neuchâtel, the results are very similar except that the coefficient δ_2 on proximity to Neuchâtel remains significantly positive in the specification without country fixed effects. Moreover, the results hold within the important subsample France even conditional on controls for upper-tail human capital (Table 3.13.[23] Thus, what mattered for encyclopedia sales was that booksellers in some cities had a lower cost of acquiring encyclopedias from the publisher than booksellers in other cities.

Table 3.5 establishes that access to encyclopedias of useful knowledge had a causal impact on city population growth after 1750. Column (1) reports the reduced form, documenting that places with higher bookseller density and were closer to Lyon had a significantly higher city population growth in 1750–1850. In addition, proximity to Lyon is also significantly positively associated with city population growth, whereas bookseller density is negatively but insignificantly associated. The 2SLS estimates of equation 3.5, column (2), show that this is explained by a causal effect of the sale of the *Encyclopédie*. The first stage is sufficiently strong with a Kleinbergen–Paap F-statistic of 59.2. The coefficient is larger than the OLS coefficient but not significantly different. Columns (3) and (4) document that there was no positive pre-trend related to proximity to Lyon nor the bookseller–proximity interaction: Cities that received more encyclopedia sales due to having more booksellers with good access to the publishers did not grow faster in the period before the encyclopedia was published.

Additional results document that the causal effect may work through both encyclopedias, the *Encyclopédie* and the *Déscriptions*, but that the bookseller–proximity to Neuchâtel interaction is too weak as an instrument. Table 3.14 uses the first principal component of encyclopedia sales density and interactions with both printing locations as instruments.

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[23] France was the most important market for the Quarto *Encyclopédie* edition. Table 3.13 documents that proximity to Lyon had a significant influence on encyclopedia sales (column 1), but this was only due to the interaction with bookseller density (column 2). Compared to the Europe sample, the effect size is the same (standardized beta 1.4) but with less precision (yet still significant at 1% level). The upper-tail human capital controls somewhat weaken the interaction effect, which remains statistically significant. The same holds for *Déscriptions* sales, with the exception that the interaction is less affected by the upper-tail human capital controls.

Columns (2) and (4) document that this combined measure of encyclopedia sales also significantly positively impacted city population growth in the period 1750–1850 but not earlier in 1700–1750. The first stage is barely strong enough, with F-stats of 9.9 and 9.6, which is primarily due to the weak predictive power of the proximity to Neuchâtel interaction. At least, the Hansen overidentification test cannot reject the null that both instruments are valid. The weak relevance of the booksellers–proximity to Neuchâtel interaction becomes apparent in table 3.15, which documents that, while coefficients have the correct (positive) signs, no reliable results can be obtained due to a weak first stage (F-statistics of 4.1 and 3.3). This result is consistent with the historical fact that the French state had erected significant trade barriers for the import of foreign books by requiring imports to be cleared at a *chambre syndical* like that of Lyon unless the publishers chose to ship them directly through smuggling routes (Darnton, 2018, 2021).[24] As a result, proximity to Neuchâtel becomes less relevant for transport cost, while proximity to Lyon may emerge as a factor that also picks up something of the in *Déscriptions* sales—consistent with the significant findings on the first principal component.

3.5.3 Falsification exercise

One assumption for using proximity to the location of printing and publication as an instrument for encyclopedia sales is that it had meaningful effects on sales rather than being spurious to some unobserved characteristic. This section proposes a falsification exercise based on proximities to the locations where alternative encyclopedia editions were printed and dispatched. If proximity to printing location determined encyclopedia sales, I should find that the editions considered thus far were less likely to be sold in locations with better access to alternative editions.

The *Encyclopédie* was originally published in Paris as a folio edition. As folios tended to be luxury editions, they did likely not satisfy market demand close to Paris for the cheaper Quarto edition considered in this paper. However, one of the publishers of the Quarto consortium (Panckoucke) was based in Paris and marketed it there, invalidating proximity to Paris as a proper falsification check. One set of alternative editions proper were the Lucca (1758–76) and Livorno (1770–9) folio reprints. Being in close geographical proximity (which is why I treat them as one), they served the Italian market in Tuscany and beyond (Shackleton, 1970). Another alternative edition was the *Encyclopédie d'Yverdon*, published

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[24] As emphasized by (Darnton, 2018), the STN never succeeded in opening the "Northeast passage" to Dijon, which would have significantly reduced transport costs for serving the Northern and Easter French markets.

1770–80 as a revised edition in quarto format and printed in Lausanne and Bern. This edition was marketed primarily to (Protestant) markets north of Switzerland through the sales networks of the *Typographische Gesellschaft Bern*, which is why I use Bern as the print location.

As the *Encyclopédie*, the *Déscriptions* was also published published in Paris as folio edition. The luxury folio edition in 86 volumes likely did not satisfy market demand around Paris compared to the cheaper 19-volume quarto (partly revised) edition published in Neuchâtel between 1771 and 1783. As before, however, proximity to Paris does not serve as a proper falsification exercise because the STN employed a sales agent in Paris for the primary task of selling it there. During 1771–83, there was only one other alternative edition, a German translation published 1762–95 in Prussia as "Schauplatz der Künste und Handwerke" (Carpenter, 2011).[25] This translation was a relevant competitor, as a bookseller in Prague, who ordered a copy of the Neuchâtel Descriptions, observed: "The great lords do not concern themselves with these sorts of works, while those who could make use of them either do not understand French or already have the German translation" (cited after Carpenter, 2011, 19). The place of publication did vary ("Berlin, Stettin, Leipzig, etc"), but it seems likely that much of it was sold through Leipzig, the most important center for German books and close to Prussia, where the "Schauplatz der Künste" enjoyed a privilege. The Dutch translation, which started in 1788 and was published in Dordrecht, may serve as an additional though indirect falsification test. There was a local market for this new edition, which the *Déscriptions* had left unsatisfied. The assumption would be that some persons in the Netherlands could read French but could not afford to order the edition from Switzerland due to the shipping costs.

Table 3.6 presents results of the falsification exercise on the *Encyclopédie*. The place of publication for the original folio edition was Paris. Proximity/distance to Paris, which is always included in the baseline geography controls, does not predict differences in *Encyclopédie* sales (column 1). Neither does the bookseller–proximity to Paris interaction—the strong effect of bookseller density and distance to print location Lyon remains (column 2). The null result is consistent with two counteracting effects, one decreasing sales due to the access to earlier folio editions printed in Paris, the other increasing sales due to the marketing efforts of one publisher who was based in Paris. The next alternative place of publication is Lucca (and Livorno). Cities closer to Lucca, where a folio edition was printed, had significantly fewer Quarto sales, ceteris paribus (column 3). This effect is solely due to the interaction effect of proximity to Lucca with bookseller density: Places with more

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[25] By 1775, volumes 1–12 (of 20) had been published.

booksellers but closer to Lucca had significantly fewer Quarto sales, precisely as expected. In contrast, the interaction effect of booksellers and proximity to Lyon becomes even more pronounced. The same pattern can be found in another alternative place of publication, Bern. The negative coefficients on proximity to Bern and the bookseller–proximity interaction are even larger than before: For a similar increase in proximity to Bern compared to Lucca, *Encyclopédie* sales decrease even more. The result indicates that the *Encyclopédie d'Yverdon*, which was also printed in quarto format and thus more affordable, was a closer substitute than the Lucca/Livorno folio reprints.

Repeating the exercise for the *Déscriptions* in table 3.7 confirms the conclusion that proximity to alternative editions affected encyclopedia sales. The place of publication for the original folio edition was Paris. The results in columns (1) and (2) indicate that booksellers' proximity to Paris significantly increased quarto sales, whereas booksellers' proximity to Neuchâtel was insignificant once conditioned on the proximity to Paris interaction. However, this does not provide a good falsification test because the STN which published the *Déscriptions* employed a sales agent in Paris.[26] If anything, it highlights that geographical distance could be overcome (to some degree) by directed efforts. As for alternative editions, access to the German translation measured by proximity to Leipzig has a negative (and significant) coefficient as expected: The closer cities are to Leipzig, in particular, if they had a higher bookseller density, the less likely they were to receive sales of the Neuchâtel edition. Notably, the coefficient on the bookseller–proximity to Neuchâtel interaction becomes significantly larger, which shows that the proximity to Leipzig interaction does remove some heterogeneity. The result is very similar to proximity to Dordrecht, the location of a (yet to come) alternative edition in Dutch. Admittedly, the evidence is more indirect and based on stronger assumptions, but it does conform to the established pattern of fewer sales in places close to alternative editions.

The falsification result is not generic to centers of enlightenment publishing or book trade. Darnton (2021) lists many centers in the "fertile crescent" of Enlightenment publishing from Amsterdam to Avignon. Here, I consider a set of centers to the North and East of France, which were heavily involved in enlightenment publishing but did not print editions of the *Encyclopédie*. As evidenced in table 3.16, proximity to each of these centers is negatively associated with encyclopedia sales, as is the interaction of booksellers with proximity to these places. Remarkably, however, the interaction coefficient of bookseller density

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[26] After their insolvency in 1783, the STN sold all their remaining copies to Moutard of Paris at a dumping price. On average, about 500 per volume were shipped in 1785 (see FBTEE database). Moutard held also held the *privilège* for the folio edition, which he still offered in first place in a 1783 catalog. In this catalog, there was neither mention of the forthcoming quarto nor a significant sale on the folio volumes. I have not yet found a trace of where his new quarto copies were marketed.

and distance to Lyon is hardly affected or mildly reduced.[27] The result contrasts with the previous findings for places where alternative editions were published, Lucca and Bern: In these cases, the inclusion of the interaction removed heterogeneity of the proximity to Lyon interaction and increased its explanatory power.

3.6 Conclusion

This paper provides novel evidence for the hypothesis that access to enlightenment encyclopedias of useful technological knowledge accelerated economic growth during the Industrial Revolution. First, it introduces a novel city-level dataset on booksellers in 1781 in Europe and extends existing data on encyclopedia sales ca 1780 in France to other European countries. Second, it documents a robust positive association at the city level between bookseller density and city growth after 1750; that bookseller density, in turn, strongly predicts encyclopedia sales; and that these sales mediate the positive association between bookseller density and city growth. Third, it exploits the proximity of booksellers to the location where the encyclopedias were printed, which affected transport and transaction costs. Conditioning independently on bookseller density and proximity to print location, it establishes that the interaction of booksellers with proximity had a strong positive impact on city-level encyclopedia sales. This variation positively affected city growth in 1750–1850 but not 1700–1750. In sum, this paper provides evidence that the combination of booksellers' local presence and ease of procuring encyclopedias from the publisher determined where readers got access to useful knowledge, which in turn affected economic growth during the Industrial Revolution and the growth "take-off."

Future work will fruitfully consider more detailed and direct outcome measures for technological change compared to the proxy employed in this paper, city population growth. In so doing, it will also be possible to test the particular mechanisms through which improved access to useful knowledge contributed to accelerating technological progress. Furthermore, it should be studied whether the impact on growth was heterogeneous with respect to the presence of upper-tail human capital. As the next chapter argues, the knowledge embodied in people was likely complementary to the knowledge codified in encyclopedias. Clearly, books cannot by themselves become agents of change.

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[27] I obtain very similar results for other centers like The Hague, Brussels, or Maastricht.

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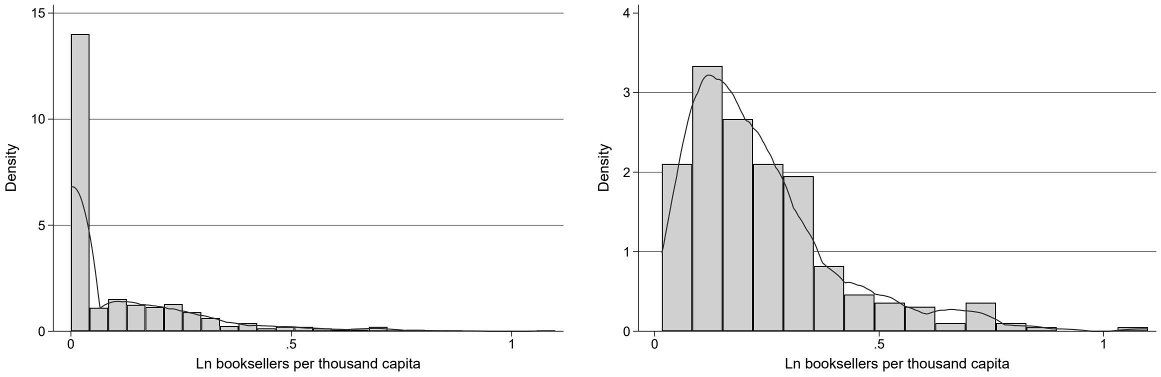
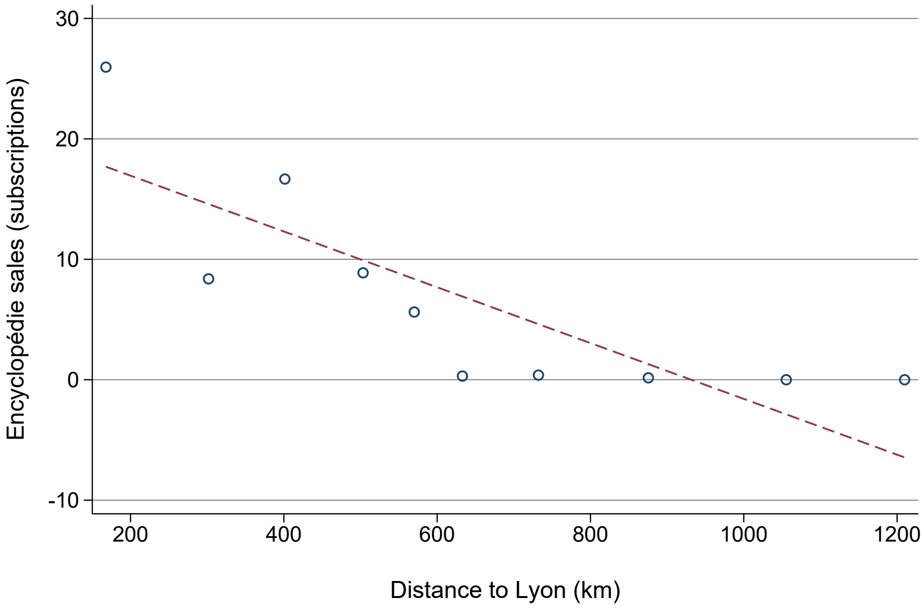
Figures



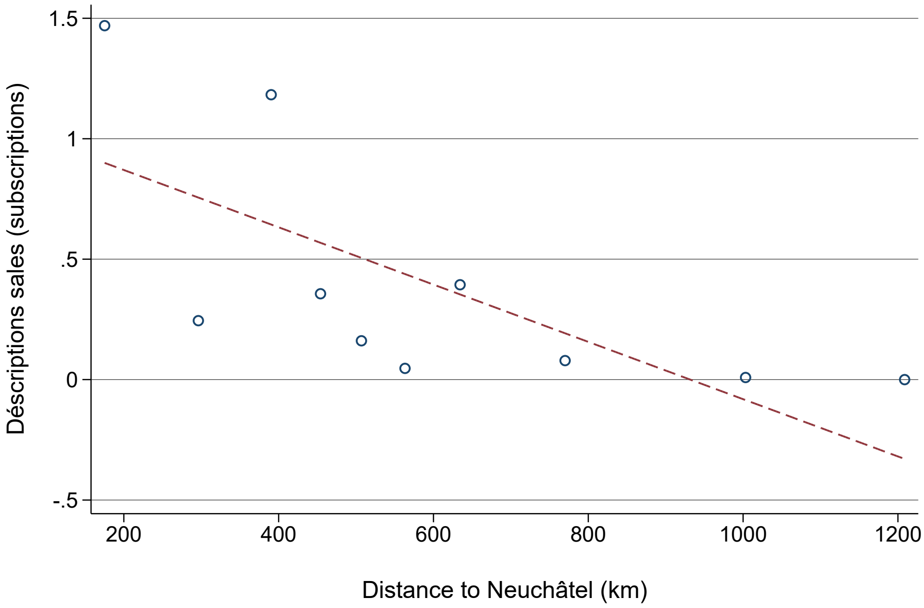
(a) Cities in Almanach core sample

(b) Conditional on booksellers > 0

Figure 3.1: Distribution of bookseller density

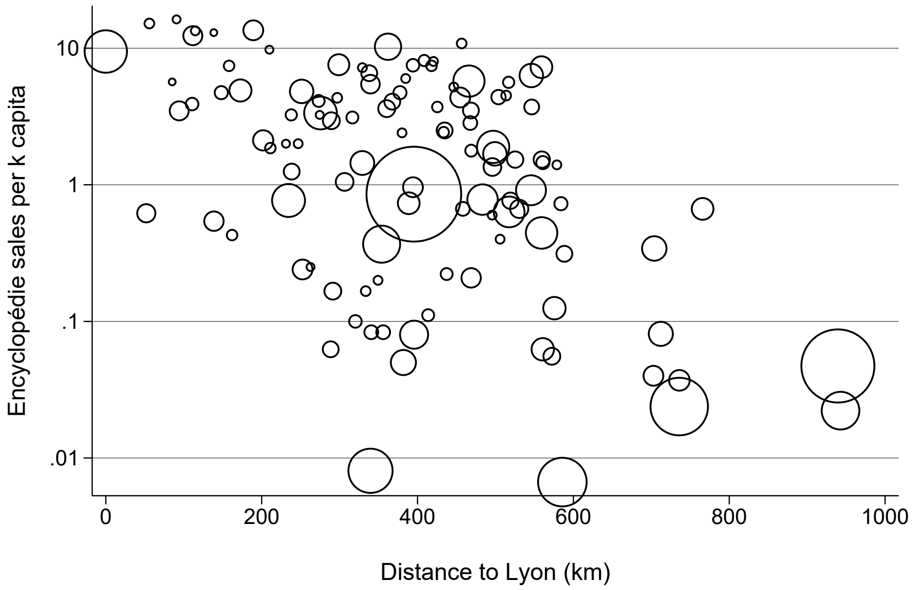


(a) *Encyclopédie*, printed in Lyon (quarto)

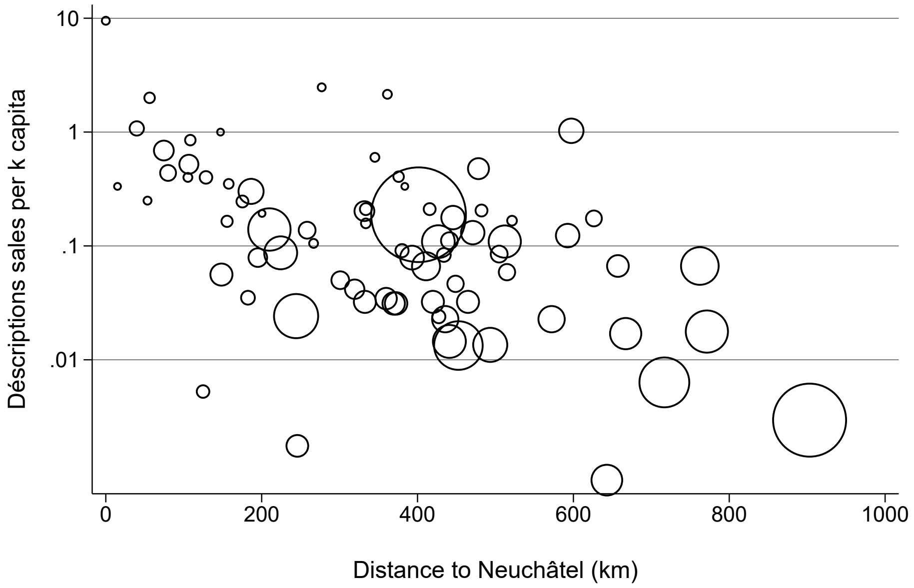


(b) *Déscriptions*, printed in Neuchâtel (quarto)

Figure 3.2: Binscatter sales vs distance to print location



(a) *Encyclopédie* (quarto), printed in Lyon



(b) *Déscriptions* (quarto), printed in Neuchâtel

Figure 3.3: Sales/subscriber density vs distance to print location

Tables

Table 3.1: A basic correlation: The higher bookseller density, larger city growth—after 1750

	Dep var: City population growth in [period]					
	1750–1850				1700–1750	
	(1)	(2)	(3)	(4) books.>0	(5)	(6) books.>0
Ln bookseller density	0.550***	0.572**	0.494*	0.923***	0.423**	−0.103
	(0.210)	(0.265)	(0.277)	(0.324)	(0.174)	(0.208)
Initial population	−0.338***	−0.339***	−0.284***	−0.155**	−0.207***	−0.172***
	(0.049)	(0.049)	(0.049)	(0.062)	(0.033)	(0.055)
Geography		✓	✓	✓	✓	✓
Country F.E.			✓		✓	
N (Obs = Bairoch cities)	665	665	665	287	554	243
R^2	0.09	0.17	0.24	0.13	0.21	0.19
Std. β bookseller density	0.09	0.10	0.08	0.20	0.13	−0.03

This table documents a significant positive association of bookseller density and city growth after 1750, the time when the publication of journals and encyclopedias of useful knowledge accelerated. In contrast, there is no positive association at the intensive margin before 1750.

OLS regressions. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Geography controls include an distance to Paris and an indicator for Paris; elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Columns (4) and (6) restrict sample to cities with at least one bookseller. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.2: Encyclopedias, or what books the booksellers sold

	Dep var: ln [encyclopedia] sales per capita					
	Encyclopédie			*Déscriptions*		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	1.916^{***}	1.581^{***}	1.509^{***}	0.263^{***}	0.280^{***}	0.237^{***}
	(0.210)	(0.219)	(0.221)	(0.069)	(0.088)	(0.076)
Ln population 1750		0.043^{*}	0.052^{**}		−0.005	−0.002
		(0.024)	(0.024)		(0.007)	(0.006)
Geography		✓	✓		✓	✓
Country F.E.			✓			✓
N (Obs = Bairoch cities)	684	684	684	684	684	684
R^2	0.32	0.40	0.42	0.12	0.17	0.30
Std. β booksellers	0.566	0.467	0.446	0.350	0.373	0.316

OLS regressions. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Geography controls include an distance to Paris and an indicator for Paris; elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.3: Encyclopedias meditate association between booksellers and city growth

	Dep var: City population growth in [period]					
	1750–1850				1700–1750	
	(1)	(2)	(3)	(4)	(5)	(6)
Ln *Encyclopédie* density	0.304*** (0.074)		0.290*** (0.081)		0.057 (0.059)	
Ln *Déscriptions* density		1.005*** (0.362)		0.885** (0.369)		0.188 (0.305)
Ln bookseller density			0.121 (0.296)	0.379 (0.285)	0.333* (0.201)	0.374** (0.189)
Initial population	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓	✓	✓
N (Obs = Bairoch cities)	665	665	665	665	554	554
R^2	0.25	0.24	0.25	0.25	0.21	0.21
Std. β [encyclopedia]	0.177	0.130	0.168	0.114	0.058	0.039
Std. β booksellers			0.021	0.065		0.111

OLS regressions. Encyclopedia density is measured as the number of encyclopedias sold per thousand inhabitants. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Initial population is log city population in 1750 (columns 1 through 4) or in 1700 (columns 5 and 6). Geography controls include an distance to Paris and an indicator for Paris; elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.4: Why not all booksellers sold the Encyclopedias: Proximity to print location

	Dep var: ln [encyclopedia] sales per capita					
	Encyclopédie			*Déscriptions*		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	1.453***	−3.017***	−2.919***	0.219***	−0.534***	−0.540***
	(0.210)	(0.520)	(0.503)	(0.073)	(0.196)	(0.180)
Proximity to Lyon	0.032	−0.025	−0.010			
	(0.044)	(0.033)	(0.035)			
Books. dens. × prox. Lyon		0.537***	0.521***			
		(0.072)	(0.071)			
Proximity to Neuchâtel				0.030***	0.019**	0.000
				(0.010)	(0.008)	(0.009)
Books. dens. × prox. Neuchâtel					0.083***	0.082***
					(0.027)	(0.025)
Print location	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Country F.E.			✓			✓
N (Obs = Bairoch cities)	684	684	684	684	684	684
R^2	0.44	0.52	0.53	0.31	0.34	0.40
Std. β booksellers	0.43	−0.89	−0.86	0.29	−0.71	−0.72
Std. β [proximity]	0.20	−0.15	−0.06	0.81	0.52	0.01
Std. β [interaction]		1.41	1.37		1.03	1.01

OLS regressions. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Proximity to Lyon is the maximal minus the city's distance to Lyon. Proximity to Neuchâtel analogously. Print location are indicators for Lyon, Geneva, and Neuchâtel (columns 1 through 3) or an indicator for Neuchâtel (columns 4 through 6). Geography controls include an distance to Paris and an indicator for Paris; elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.5: Instrumental variable results for *Encyclopédie*

	Dep var: City population growth in [period]			
	1750–1850		1700–1750	
	(1) r. f.	(2) 2SLS	(3) r. f.	(4) 2SLS
Ln bookseller density	−1.365	−0.045	0.688	0.489*
	(0.971)	(0.388)	(0.717)	(0.296)
Proximity to Lyon	0.193***	0.200***	−0.058	−0.062
	(0.061)	(0.059)	(0.040)	(0.040)
Books. dens. × prox. Lyon	0.233**		−0.035	
	(0.117)		(0.080)	
Ln *Encyclopédie* density		0.422*		−0.064
		(0.217)		(0.145)
Initial population	✓	✓	✓	✓
Print location	✓	✓	✓	✓
Geography	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓
N (Obs = Bairoch cities)	663	663	554	554
R^2	0.26	0.26	0.21	0.21
1st stage F (Kleinbergen–Paap)		59.52		47.59

OLS reduced form regressions (columns 1 and 3) and 2SLS regressions implemented by “ivreg2” STATA command (column 3 and 4). Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Proximity to Lyon is the maximal minus the city’s distance to Lyon. Encyclopedia density is measured as the number of encyclopedias sold per thousand inhabitants. Initial population is log city population in 1750 (columns 1 and 2) or in 1700 (columns 3 and 4). Print location are indicators for Lyon, Geneva, and Neuchâtel. Geography controls include an distance to Paris and an indicator for Paris; elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.6: Falsification exercise—proximity to other editions of the *Encyclopédie*

	Dep var: ln *Encyclopédie* sales per capita					
	X = Paris		Bern		Lucca	
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	1.395^{***}	-3.324^{***}	1.434^{***}	-0.593	1.420^{***}	-2.940^{***}
	(0.212)	(0.844)	(0.212)	(0.669)	(0.212)	(0.489)
Proximity to Lyon	0.047	-0.002	0.151^{**}	0.032	0.098^{*}	0.030
	(0.046)	(0.035)	(0.067)	(0.050)	(0.051)	(0.037)
Books. dens. × prox. Lyon		0.490^{***}		0.918^{***}		0.750^{***}
		(0.103)		(0.103)		(0.089)
Proximity to [X]	-0.020	-0.039	-0.124^{**}	-0.005	-0.088^{***}	-0.012
	(0.042)	(0.036)	(0.051)	(0.042)	(0.021)	(0.019)
Books. dens. × prox. [X]		0.051		-0.651^{***}		-0.362^{***}
		(0.102)		(0.128)		(0.083)
Print location	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓	✓	✓
N (Obs = Bairoch cities)	684	684	684	684	684	684
R^2	0.45	0.53	0.46	0.58	0.46	0.56

OLS regressions. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Proximity to Lyon is the maximal minus the city's distance to Lyon. Proximity to other locations [X] analogously. Print location are indicators for Lyon, Geneva, Neuchâtel, and other location [X]. Geography controls include an distance to Paris and an indicator for Paris (unless already included); elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.7: Falsification exercise—proximity to other editions of the *Déscriptions*

	Dep var: ln *Déscriptions* sales per capita					
	X = Paris		Leipzig		Dordrecht	
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	1.440^{***}	-2.695^{***}	1.498^{***}	2.789^{***}	1.443^{***}	2.406^{*}
	(0.217)	(1.010)	(0.218)	(1.053)	(0.216)	(1.341)
Proximity to Neuchâtel	−0.007	−0.011	0.020	0.007	0.018	−0.041
	(0.040)	(0.036)	(0.042)	(0.034)	(0.044)	(0.039)
Books. dens. × prox. Neuchâtel		0.147		0.327^{***}		0.305^{***}
		(0.134)		(0.095)		(0.105)
Proximity to [X]	0.029	−0.016	-0.066^{**}	−0.022	−0.069	−0.036
	(0.047)	(0.045)	(0.029)	(0.025)	(0.043)	(0.042)
Books. dens. × prox. [X]		0.216^{**}		-0.434^{***}		-0.269^{***}
		(0.094)		(0.058)		(0.078)
Print location	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓	✓	✓
N (Obs = Bairoch cities)	684	684	684	684	684	684
R^2	0.42	0.45	0.43	0.53	0.43	0.47

OLS regressions. Bookseller density is the number of booksellers in 1781 per thousand inhabitants. Proximity to Neuchâtel is the maximal minus the city's distance to Neuchâtel. Proximity to other locations [X] analogously. Print location are indicators for Neuchâtel, and other location [X]. Geography controls include an distance to Paris and an indicator for Paris (unless already included); elevation; distance to Atlantic, to Mediterranean, and to North-sea or Baltic; distance to Rivers and Roman Roads; and potato and cereal suitability within 25km. Country F.E. for Belgium, France, Germany, Italy, Netherlands, and Switzerland. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

3.A Data Appendix

3.A.1 Summary statistics

Table 3.8: Summary statistics

	Obs	Mean	S.D.	Min	Max
pop1750_k	685	12.89	30.39	1.00	570.00
Ln population 1750	685	8.93	0.85	6.91	13.25
growth_1850_1750	666	0.82	0.92	−0.80	5.40
booksellers_pc	685	0.12	0.22	0.00	2.00
Ln bookseller density	685	0.10	0.16	0.00	0.80
subscriptions_pc	685	0.53	1.92	0.00	16.25
Ln *Encyclopédie* density	685	0.18	0.53	0.00	2.78
descriptions_pc	685	0.04	0.40	0.00	9.50
Ln *Déscriptions* density	685	0.02	0.12	0.00	1.25

3.A.2 Sample: Almanach and Bairoch

My baseline sample is cities in (what are today) Belgium, France, Germany, Italy, Netherlands, and Switzerland. For these countries, the *Almanach de la librairie* covers extensively, and probably accurately, booksellers (Vercruysse and Collins, 1984). For several other countries, the *Almanach* covers booksellers only in the capitals and similar major cities. These countries include (what were in 1989) Austria, Czechoslovakia, Denmark, Hungary, Ireland, Malta, Poland, Portugal, Spain, Sweden, Russia, and United Kingdom. They are not included in my analysis.

Table 3.9 lists by country the countries' urban population; the number of cities in Bairoch; the number of booksellers listed in the Almanach; the number of Bairoch cities with at least one bookseller; and the number of non-Bairoch cities with at least one bookseller.

3.A.3 Why bookseller density

In the empirical analysis, I use bookseller density (and encyclopedia density)—the number of booksellers per thousand inhabitants in 1750—rather than the plain number of booksellers. The main motivation is that bookseller density helps to distinguish city size from access to books. As documented in Figure 3.4, this seems expedient because of the strong positive correlation of the (log) number of booksellers and the number of inhabitants in 1750 (log).

Table 3.9: Overview on countries covered by *Almanach de la librairie*

Country	Population	B.sellers	B.sellers p.c.	Towns (Bairoch)	Towns w b.seller in Bairoch	Towns w b.seller not Bairoch
Panel A: Main sample—good coverage						
Belgium	518	59	0.11	72	10	1
France	2896	1055	0.36	341	201	54
Germany	1512	263	0.17	245	80	10
Italy	3154	131	0.04	406	46	0
Netherlands	633	109	0.17	60	31	3
Switzerland	122	61	0.5	19	8	4
Panel B: Partial coverage						
Austria	271	13	0.05	17	2	1
Czechoslovakia	179	5	0.03	36	2	0
Denmark	108	7	0.06	10	1	0
Ireland	255	3	0.01	22	1	0
Luxemburg	0	1		1	0	1
Malta	27	1	0.04	1	1	0
Poland	305	14	0.05	55	6	0
Portugal	442	23	0.05	53	3	0
Russia	1061	11	0.01	218	5	0
Spain	1623	27	0.02	265	5	0
Sweden	138	13	0.09	20	2	0
Ungarn	271	2	0.01	47	1	0
United Kingdom	1363	89	0.07	165	7	0
Panel C: No coverage						
Albania	28	0	0	13	0	0
Bulgaria	143	0	0	22	0	0
Finland	13	0	0	8	0	0
Greece	67	0	0	24	0	0
Norway	50	0	0	10	0	0
Romania	194	0	0	34	0	0
Yugoslavia	145	0	0	40	0	0

Country as of 1988 (a legacy of the Bairoch et al. (1988) dataset). *Population* is urban population in thousand from Bairoch et al. (1988). *B.sellers* is the number of booksellers in 1781 listed in the “Almanach de la librairie.” *B.sellers p.c.* is the number of booksellers in 1781 per thousand inhabitants. *Towns (Bairoch)* is the number of cities in Bairoch et al. (1988), where cities are defined as reaching 5000 inhabitants by 1850. *Towns w b.seller in Bairoch* is the number of towns with at least one bookseller in 1781 that are also cities as defined by Bairoch et al. (1988). *Towns w b.seller not Bairoch* is the number of towns with at least one bookseller in 1781 that did not reach 5000 inhabitants by 1850.

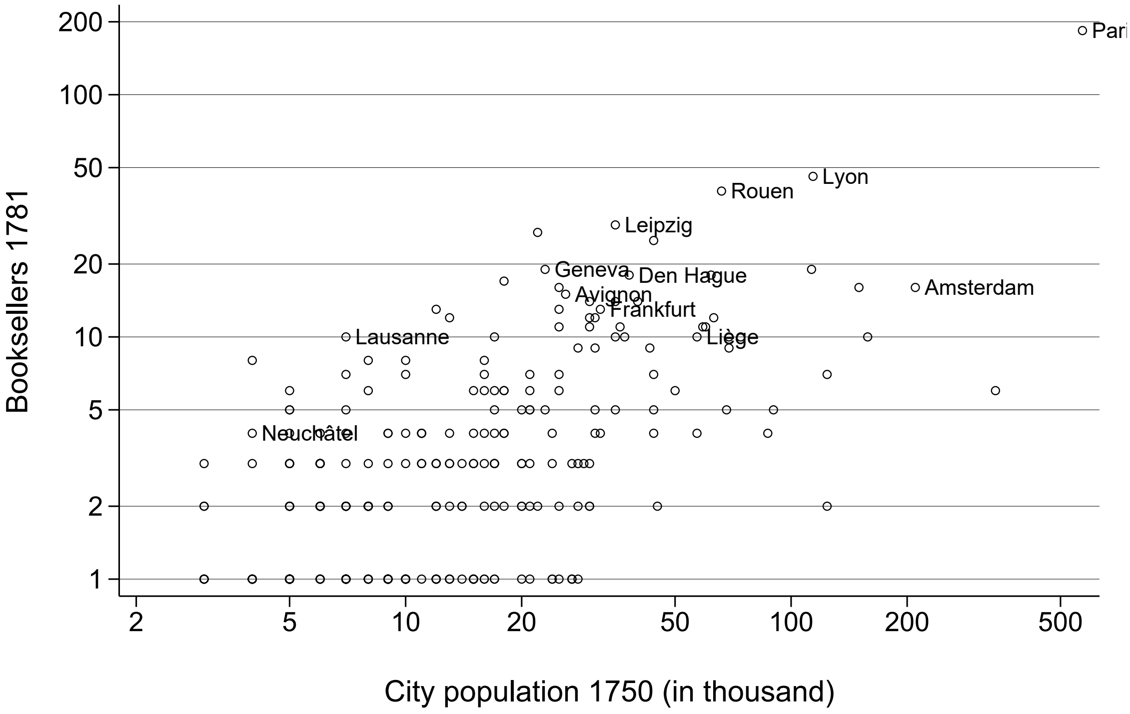


Figure 3.4: Caption

Note: Labels highlight important European cities in the French enlightenment book trade (publishing, printing, and distribution; see Darnton (2021) for more detail).

The bivariate correlation 0.69 in logs—in levels, it is even larger at 0.79. The correlation is only slightly smaller when conditioning on cities with at least one bookseller (as done in the figure because of the log scale).

Normalizing the number of booksellers by the number of inhabitants more or less removes the correlation. The bivariate correlation of bookseller density and number of inhabitants in 1750 is 0.08 (in logs, it is 0.25). Figure 3.5 illustrates why this is the case: On the one hand, cities with the largest bookseller density tend to be small towns; on the other hand, larger cities ore more likely to have at least one bookseller.

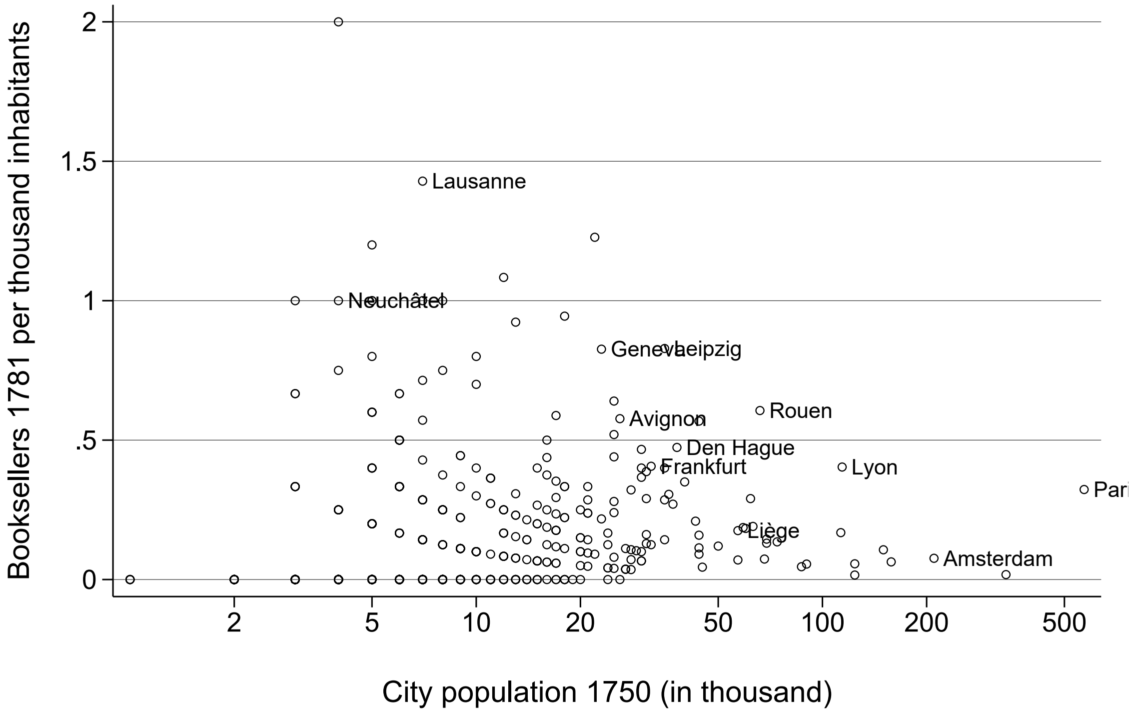


Figure 3.5: Caption

Note: Labels highlight important European cities in the French enlightenment book trade (publishing, printing, and distribution; see Darnton (2021) for more detail).

3.B Additional results

Table 3.10: Association of bookseller density and growth: Coefficients of geography controls

	Dep var: City population growth in [period]					
	1750–1850				1700–1750	
	(1)	(2)	(3)	(4) books.>0	(5)	(6) books.>0
Ln bookseller density	0.550^{***}	0.572^{**}	0.494^{*}	0.923^{***}	0.423^{**}	−0.103
	(0.210)	(0.265)	(0.277)	(0.324)	(0.174)	(0.208)
Paris		1.669^{***}	1.383^{***}	1.039^{***}	0.941^{***}	0.697^{***}
		(0.240)	(0.247)	(0.282)	(0.178)	(0.252)
Distance to Paris		0.081^{*}	0.083	0.088^{*}	0.042	−0.004
		(0.046)	(0.058)	(0.051)	(0.039)	(0.049)
Ln elevation		−0.000	-0.001^{***}	−0.000	-0.000^{**}	0.000
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Ln dist. Atlantic		0.019	0.009	0.033	−0.006	−0.005
		(0.032)	(0.042)	(0.035)	(0.030)	(0.027)
Ln dist. Mediterranean		-0.084^{*}	−0.015	−0.056	−0.043	−0.021
		(0.044)	(0.048)	(0.063)	(0.030)	(0.045)
Ln dist. Northsea/Baltic		−0.106	-0.166^{*}	-0.224^{**}	−0.080	0.053
		(0.078)	(0.100)	(0.099)	(0.073)	(0.109)
Ln dist. rivers		0.079	0.042	0.032	0.047	−0.029
		(0.064)	(0.070)	(0.126)	(0.039)	(0.076)
Ln dist. Roman roads		−0.101	-0.146^{*}	0.100	−0.061	0.103
		(0.068)	(0.078)	(0.092)	(0.044)	(0.072)
Potato suitability		−0.060	−0.072	−0.056	0.057	−0.004
		(0.077)	(0.085)	(0.104)	(0.054)	(0.084)
Cereal suitability		0.023	0.065	−0.006	-0.086^{*}	−0.026
		(0.071)	(0.075)	(0.099)	(0.051)	(0.095)
Initial population	✓	✓	✓	✓	✓	✓
Country F.E.			✓		✓	
N (Obs = Bairoch cities)	665	665	665	287	554	243
R^2	0.09	0.17	0.24	0.13	0.21	0.19

NOTES. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.11: Within France: Encyclopedias, or what books the booksellers sold

	Dep var: ln [encyclopedia] sales per capita					
	Encyclopédie			*Déscriptions*		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	2.491^{***}	2.407^{***}	1.909^{***}	0.192^{***}	0.181^{*}	0.166^{*}
	(0.283)	(0.315)	(0.339)	(0.072)	(0.108)	(0.087)
Humanistic *collège*			0.142			0.010
			(0.125)			(0.035)
Philosophy *collège*			0.083			−0.025
			(0.133)			(0.035)
Science education at *collège*			0.389^{**}			−0.017
			(0.167)			(0.028)
University in 1750			0.245			0.099
			(0.183)			(0.078)
Scientific society			0.527^{***}			0.111^{*}
			(0.184)			(0.067)
Ln population 1750		0.230^{***}	−0.026		0.007	−0.026
		(0.072)	(0.082)		(0.017)	(0.031)
Geography		✓	✓		✓	✓
N (Obs = Bairoch cities)	193	193	193	193	193	193
R^2	0.31	0.41	0.49	0.06	0.11	0.19
Std. β booksellers	0.56	0.54	0.43	0.25	0.23	0.21

NOTES. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.12: Encyclopedias jointly meditate association between booksellers and city growth

	Dep var: City population growth in [period]							
	1750–1850				1700–1750			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ln *Encyclopédie* density	0.265^{***} (0.087)				0.049 (0.058)			
Ln *Déscriptions* density	0.519 (0.367)				0.130 (0.306)			
Encyclopédie > 0		0.287^{**} (0.133)				0.294^{***} (0.082)		
Déscriptions > 0		0.317^{**} (0.135)				0.336^{***} (0.091)		
Encyclopedias (1st P.C.)			0.137^{***} (0.037)				0.029 (0.032)	
Any encyclopedia				0.533^{***} (0.120)				0.463^{***} (0.086)
Ln bookseller density	0.044 (0.294)	0.196 (0.286)	0.091 (0.291)	0.131 (0.276)	0.311 (0.210)	0.022 (0.192)	0.313 (0.209)	0.040 (0.190)
Initial population	✓	✓	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓	✓	✓	✓	✓
N (Obs = Bairoch cities)	665	665	665	665	554	554	554	554
R^2	0.25	0.26	0.25	0.26	0.21	0.28	0.21	0.28
Std. β Encyclopedias (1st P.C.)			0.18				0.06	
Std. β Encyclopedia dummy				0.23				0.37

NOTES. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.13: Within France: Transport cost from print location

	Dep var: ln [encyclopedia] sales per capita					
	Encyclopédie			*Déscriptions*		
	(1)	(2)	(3)	(4)	(5)	(6)
Ln bookseller density	2.410^{***}	-3.711^{*}	-1.964	0.163	-0.610^{**}	-0.510^{**}
	(0.305)	(1.942)	(1.890)	(0.105)	(0.305)	(0.227)
Proximity to Lyon	0.186^{**}	0.070	0.077			
	(0.083)	(0.064)	(0.065)			
Books. dens. × prox. Lyon		0.648^{***}	0.418^{**}			
		(0.206)	(0.195)			
Proximity to Neuchâtel				0.038^{*}	0.016	0.014
				(0.020)	(0.019)	(0.019)
Books. dens. × prox. Neuchâtel					0.084^{**}	0.072^{**}
					(0.041)	(0.030)
Print location	✓	✓	✓			
Geography	✓	✓	✓	✓	✓	✓
Upper-tail human capital			✓			✓
N (Obs = Bairoch cities)	193	193	193	193	193	193
R^2	0.43	0.46	0.51	0.13	0.15	0.22
Std. β booksellers	0.54	−0.84	−0.44	0.21	−0.78	−0.65
Std. β [proximity]	0.33	0.12	0.14	0.41	0.17	0.15
Std. β [interaction]		1.39	0.90		1.03	0.88

NOTES. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.14: Instrumental variable results—for principal component

	Dep var: City population growth in [period]			
	1750–1850		1700–1750	
	(1) r. f.	(2) 2SLS	(3) r. f.	(4) 2SLS
Ln bookseller density	−0.440 (1.511)	−0.140 (0.404)	0.125 (0.830)	0.495* (0.299)
Proximity to Lyon	0.136 (0.135)	0.136 (0.128)	−0.132* (0.076)	−0.139* (0.076)
Books. dens. × prox. Lyon	0.407** (0.182)		−0.120 (0.131)	
Proximity to Neuchâtel	0.082 (0.164)	0.059 (0.138)	0.071 (0.084)	0.093 (0.080)
Books. dens. × prox. Neuchâtel	−0.268 (0.282)		0.138 (0.153)	
Encyclopedias (1st P.C.)		0.207** (0.090)		−0.034 (0.056)
Ln *Encyclopédie* density				
Initial population	✓	✓	✓	✓
Print location	✓	✓	✓	✓
Geography	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓
N (Obs = Bairoch cities)	663	663	554	554
R^2	0.26	0.26	0.22	0.21
1st stage *F* (Kleinbergen–Paap)		11.94		11.05
Hansen $\mathcal{J}$ (p-value)		0.66		0.45

Note. 2SLS regressions implemented in STATA using ivreg2 command. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.15: Instrumental variable results—separately for *Déscriptions*

	Dep var: City population growth in [period]			
	1750–1850		1700–1750	
	(1) r. f.	(2) 2SLS	(3) r. f.	(4) 2SLS
Ln bookseller density	−1.219 (1.149)	0.267 (0.397)	−0.612 (0.743)	−0.199 (0.284)
Proximity to Neuchâtel	−0.002 (0.020)	0.097 (0.060)	0.033 (0.039)	−0.012 (0.051)
Books. dens. × prox. Neuchâtel	0.208 (0.128)		0.064 (0.078)	
Ln *Déscriptions* density		1.873 (1.723)		0.579 (0.813)
Initial population	✓	✓	✓	✓
Print location	✓	✓	✓	
Geography	✓	✓	✓	✓
Country F.E.	✓	✓		✓
N (Obs = Bairoch cities)	662	662	553	553
R^2	0.25	0.25	0.05	0.10
1st stage *F* (Kleinbergen–Paap)		11.62		9.49

Note. 2SLS regressions implemented in STATA using ivreg2 command. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.16: Falsification exercise—proximity to other centers of Enlightenment publishing and book trade

	Dep var: ln *Encyclopédie* sales per capita							
	X= Amsterdam		Liège		Bouillon		Neuwied	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ln bookseller density	1.406^{***}	−1.109	1.417^{***}	−0.627	1.426^{***}	−1.259	1.430^{***}	−0.048
	(0.211)	(1.291)	(0.211)	(1.181)	(0.213)	(1.060)	(0.211)	(0.827)
Proximity to Lyon	0.071	0.007	0.072	0.003	0.071	−0.002	0.083	0.017
	(0.051)	(0.038)	(0.050)	(0.038)	(0.051)	(0.039)	(0.051)	(0.037)
Books. dens. × prox. Lyon		0.484^{***}		0.509^{***}		0.555^{***}		0.497^{***}
		(0.072)		(0.066)		(0.070)		(0.064)
Proximity to [X]	-0.079^{*}	−0.058	-0.078^{**}	−0.048	−0.078	−0.050	-0.082^{**}	−0.038
	(0.042)	(0.040)	(0.039)	(0.038)	(0.051)	(0.052)	(0.033)	(0.031)
Books. dens. × prox. [X]		−0.107		-0.166^{**}		−0.148		-0.208^{***}
		(0.073)		(0.083)		(0.093)		(0.052)
Print location	✓	✓	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓	✓	✓
Country F.E.	✓	✓	✓	✓	✓	✓	✓	✓
N (Obs = Bairoch cities)	684	684	684	684	684	684	684	684
R^2	0.46	0.54	0.46	0.54	0.46	0.54	0.46	0.56

Print location controls are for Lyon, Neuchâtel, Geneva, and the location of the additional book trade place.
Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4 Knowledge, Education, and Economic Growth: Evidence from the Enlightenment in France

with Uwe Sunde

We investigate the hypothesis that economic development crucially depends on the interaction between two distinct notions of productive knowledge: human capital—knowledge embodied in people and at least partly acquired in schools—and the availability of codified knowledge. The analysis is based on a unique historical setting that allows us to disentangle both directions of the interaction and using newly digitized data on the establishment and curriculum of the universe of public secondary schools (colleges) in France from 1500 to 1789. The analysis documents the historical origins of colleges, including the role of the church and religious competition in the post-reformation period. Scientific education in colleges is associated with greater demand for codified productive knowledge as measured by subscriptions to the Encyclopedia. In reverse, the availability of codified knowledge in the form of Encyclopedia subscriptions is associated with higher enrolment in post-Revolution schools with scientific education. The results also show that education was instrumental for the adoption of codified knowledge, and affected long-run development through increased innovation and patenting activity.

4.1 Introduction

Human capital is generally considered as the main determinant of economic growth and development and mounting evidence suggests that human capital is key for understanding aggregate and regional disparities in development (Gennaioli, Nicola, La Porta, Lopez-de-

Silanes, and Shleifer, 2013; Hanushek, Ruhose, and Woessmann, 2017). Yet, the evidence regarding the growth effects of school attainment is mixed, pointing to a crucial role for education quality (Hanushek and Kimko, 2000; Hanushek and Woessmann, 2012; Hanushek, 2013). Moreover, the evidence for the relevance of human capital in the average population during the early phases of development is weak (see, e.g., Allen, 2003), which shifted the focus to the role of the industrial enlightenment for the accumulation and dissemination of productive knowledge among knowledge elites (Mokyr, 2002, 2005, 2009; Squicciarini and Vogtländer, 2015). The reasons for the discrepancy in the evidence for the role of human capital acquired in schools for development at different stages of development are not fully clear. There is little evidence regarding the role of school-based human capital for growth during the early stages of development and the relevance of the particular education curriculum, e.g., in terms of math and science skills, remains largely unknown.

This paper advances and tests the hypothesis that economic development crucially depends on the interaction between two distinct notions of productive knowledge: human capital – knowledge embodied in people that is, at least partly, acquired in schools and non-transferable across individuals – and codified knowledge – knowledge that is stored in books and other storage devices and therefore transferable. This hypothesis lies at the heart of the endogenous growth paradigm, according to which the availability and sustained expansion of codified productive knowledge represents the basis of modern growth (Romer, 1990) and where human capital is the key prerequisite for this expansion: human capital enables the adoption of codified frontier knowledge (Nelson and Phelps, 1966) as well as the expansion of the stock of codified productive knowledge (Lucas, 1988; Romer, 1990). This two-way interaction between embodied and codified knowledge provides a powerful explanation for the failure of development when one of the two components is absent. At the same time, it poses serious problems for an empirical decomposition of their distinct roles.

To make progress on testing the empirical relevance of the hypothesis of an interaction between embodied and codified knowledge, we exploit a unique setting that exhibits variation in both dimensions of productive knowledge and thereby allows us to disentangle the elements of the interaction. In particular, in the context of 18th century France, the Europe-wide process of enlightenment culminated in a singular and unprecedented event of dissemination of codified productive knowledge – the publication of the *Encyclopédie* ("Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers") edited by Denis Diderot and Jean Baptiste le Rond d'Alembert. This book was the encyclopedia of the Age of Enlightenment *par excellence* and contained essentially all available scientific knowledge of the time. Its publication constituted the critical turning point in the universal availability of codified productive knowledge, which before was mostly dispersed and tacit. Ultimately, this enabled the industrial enlightenment (Mokyr, 2002, 2009). As consequence of the publication of the *Encyclopédie*, the focus of science shifted towards a more systematic approach to accumulating technical knowledge, in particular improved measurement experimentation, and disseminating this knowledge in terms of publications in journals and handbooks. Importantly, with the *Encyclopédie*, codified knowledge became available throughout France at the same point in time. Several open questions remain regarding the reasons for the heterogeneity in the demand for the newly available codified productive knowledge and, in particular, the role of schools and their curriculum. Similarly, beyond a reduced-form effect, the implications for subsequent development are largely unknown.

We address these questions by combining heterogeneity in sales of the *Encyclopédie* after its initial publication with a newly digitized data set that comprises the universe of secondary schools, *collèges*, in France between 1500 and 1789. As result of historic developments in France, the organization of education in all secondary schools was comparable. This allows us to identify which schools offered which curricula and, in particular, which schools offered education in modern scientific methods. The crucial innovation is a newly collected data set on the curriculum and the composition of the faculty, in particular the number of teachers and chairs in different fields, in each school. In particular, this provides unique information on whether the curriculum of a particular school contained education in philosophy (which comprised basic scientific education including the most recent scientific advances of the time, particularly in physics) or not (and instead focused on Latin, rhetorics or theology). The combination of these school data with Encyclopedia subscriptions and with newly digitized city-level data on the existence of Huguenot communities during the seventeenth and eighteenth century. We also collected new data on whether the existing schools were run by religious orders such as Jesuits. According to historical accounts, Jesuits were particularly important for creating an environment that was conducive to scientific inquiry and public debate in a world of fierce religious competition that often resulted in censorship or even the use of inquisition. The reason is that the Jesuit ideology was to win over Protestants by establishing the priority of Catholicism through excellence in science. We complement these data with existing city-level data sets, including data on birth and death places of famous individuals.

The empirical strategy to disentangle the interaction between embodied and codified knowledge exploits a combination of cross-sectional and intertemporal variation. Cross sectional variation in human capital at the time of the publication of the *Encyclopédie* comes from the regional variation in the existence of public secondary schools in France in 1750. This also includes the curriculum in these secondary schools, particularly in terms of a dedicated scientific education. The intertemporal variation comes from the sudden and universal availability of codified knowledge through the publication of the *Encyclopédie* during the second half of the 18th century.

Our analysis proceeds in four steps. First, we investigate the historical determinants of the existence of schools and scientific curricula and the respective heterogeneity across France, paying particular attention to the role of protestantism and the religious competition between protestants and Jesuits in the aftermath of the Protestant reformation. Second, we consider the role of secondary schools for the adoption of codified productive knowledge, in terms of subscriptions of the *Encyclopédie* after it became available. We conjecture that the availability of an appropriate basis of human capital, and particularly scientific literacy – the ability to understand the characteristics of science and the significance of scientific results, to apply scientific knowledge, identify issues and describe scientific phenomena, to draw conclusions and make decisions based on evidence, and to reflect on and engage with scientific ideas and subjects – played a crucial role for the adoption of the knowledge codified in the *Encyclopédie*. Third, we investigate whether, inversely, the local availability of the *Encyclopédie* led to an increased demand for scientific education. To test this conjecture, we exploit education reforms during the French Revolution that led to the establishment of central schools with a modular curriculum and free course enrolment. Fourth, we investigate the implications for subsequent development and innovation.

The analysis documents several pieces of new evidence. The investigation of the determinants of secondary schools, in particular schools with a scientific curriculum, reveals an important role of historical factors. Cities with a bishop's see, which were more advanced in medieval times, were more likely to establish *collèges* to teach Latin to clergy. In addition, humanistic education was a necessary condition to enter the liberal professions as well as the state bureaucracy, which constituted an additional motif for the establishment of schools. These school foundations exhibited considerable historical persistence. Later, these schools spread the ideas and methods of scientific englightenment, and of the teaching of scientific thinking, irrespective of when and by whom the colleges had been established in the first place. We also find evidence for religious competition in the context of the Protestant Reformation and the Catholic (particularly Jesuit) Counter-Reformation that fostered the establishment of secondary schools offering scientific education. In particular, this religious competition influenced the presence of a scientific curriculum by fostering a distinct education in philosophy and physics.

Regarding the hypothesis that secondary school education increased the demand for codified knowledge, the empirical results document that cities with a secondary school that provided a full curriculum of humanistic and, in particular, scientific education – a full college – exhibited more subscriptions to the *Encyclopédie*. To identify the role of the content of the education, we investigate the link between the availability of schools with a scientific curriculum. Consistent with the hypothesis, the results also document that it was the exposure to scientific reasoning and natural sciences instead of merely attending school and receiving general education that affected the demand for the *Encyclopédie*. The key role was played by education in philosophy, in particular when this education was dedicated to physics and logic, rather than metaphysical theological education or humanistic education, suggesting that curricular differences were crucial for the receptiveness to the ideas and empirical methods of the enlightenment.

We also find evidence for the reverse direction of the interaction between embodied and codified productive knowledge. To this end, we exploit the substantial spatial heterogeneity in the availability of the *Encyclopédie* and document that a greater availability in terms of more subscriptions in a city during the 1770s was associated with greater demand for scientific education in central schools around the turn of the century as measured in a survey of enrolment rates. This suggests that a greater availability of codified knowledge indeed led to an increased subsequent demand for school-based scientific education.

Finally, regarding the implications for economic development, the data allow us to dig deeper into the mechanisms of industrial enlightenment and the interplay between embodied human capital and codified productive knowledge. In particular, the results show that the interplay between schools and the adoption of codified knowledge affected long-run development. The education content also mattered in this context, with a greater prevalence scientific literacy exhibiting stronger effects. The results also show an effect on patenting activity during the early 19th century and on the prevalence of births of famous scientists, thus providing direct evidence for the role of scientific human capital acquired in schools for the creation of new useful knowledge.

Contribution to the Literature. The results of this paper contribute to the literature in various ways. Our findings help reconciling the contradictory evidence regarding the role of human capital for historical and contemporaneous development. The lack of evidence for the relevance of (average) human capital has led economic historians to associate the timing and geographic determinants of the industrial revolution to economic mechanisms that focus on incentives (Allen, 2009; Broadberry, Stephen, and Gupta, 2009), to demographic forces (Clark, 2007; van Zanden, 2008), and to cultural changes (Mokyr, 2002, 2009, 2016), without emphasis on school-based human capital. More recently, the focus has shifted from human capital to the role of knowledge elites (Squicciarini and Vogtländer, 2015), taking subscriptions to the *Encyclopédie* as proxy for the presence such elites. Our hypothesis states that schools, particularly schools offering a scientific curriculum, provided the epistemic knowledge base that enabled the comprehension and adoption of the new scientific and technological developments of the industrial enlightenment, and that thereby influenced the demand for codified productive knowledge in general. In this view, subscriptions to the *Encyclopédie* reflect the demand for codified productive knowledge. Our evidence documents that this demand correlates with the availability of embodied scientific knowledge – human capital – as proxied by the presence of secondary schools with the corresponding curriculum. In this context, the evidence shown here is consistent with the view that human capital, in particular scientific literacy, constitutes an enabling factor in the adoption of codified productive knowledge, thereby shedding new light on the role of schools for the creation of knowledge elites.

The evidence in this paper is also informative in the context of the literature on long-run development, which has emphasized the importance of bi-directional feedback between technology and education for the transition from stagnation to growth (Galor, 2005, 2011, 2012). Our results provide new evidence for such a bi-directional feedback during the early phases of the economic transition, by documenting the interaction between human capital acquired in public schools and the demand for codified technical knowledge. The coincidence between a modern, scientifically oriented secondary education sector and the publication of codified knowledge might also have contributed to France's exceptionally early demographic transition (Landry, 1934; Weir, 1994). Our findings also shed new light on determinants of the timing and the geographic patterns of the industrial revolution. While the industrial revolution was essentially a (Western) European phenomenon, it was primarily the result of a change in the creation and dissemination of useful knowledge that was enabled by the spread of enlightenment, thus explaining the temporal aspect. Moreover, our evidence points at substantial heterogeneity in the spatial adoption of the ideas of enlightenment which was related to historically determined differences in the receptiveness of the population to these ideas and had to do with variation in access to scientific education.

Our findings complement results by Becker, O., Hornung, and Woessmann (2011) regarding the role of basic education for industrialization by emphasizing the consequences of differences in the education content related to higher education for subsequent development. In this respect, our analysis also contributes to recent work by Cantoni and Yuchtman (2014) who emphasized the causal role of legal education in medieval universities for the expansion of economic activity, mostly through the establishment of markets. We do find evidence that the provision of a humanistic education, which was propeadeutic to the study of law, is related to the spread of Enlightenment. However, our evidence documents that scientific education was particularly important for the adoption and development of useful technical knowledge.

From an economic growth perspective, our findings provide systematic evidence for the interaction between codified knowledge and human capital, i.e., knowledge embodied in the population, that lies at the heart of endogenous growth theory (Lucas, 1988; Romer, 1990). The results also contribute to the literature on the role of human capital, and particularly the type of education and knowledge, for the adoption of new technologies along the lines of Nelson and Phelps (1966); Foster and Rosenzweig (1995) as well as for the invention of new technologies as stipulated by the endogenous growth literature (e. g. Jones, 2005). In particular, we contribute to the debate about education as a determinant of absorptive capacity to assimilate and apply new knowledge and technology (see, e.g., Aghion, Philippe, and Jaravel, 2015).

Our findings also complement a recent literature that studies the determinants of innovation and invention. In particular, Toivanen, Otto, and Väänänen (2016) study the effects of a higher supply of engineering education at technical universities on local inventions. Akcigit, Grigsby, and Nicholas (2017) document in nineteenth century US data that individuals with college degree were four times as likely to become an inventor compared to individuals with high-school diploma. Aghion, Akcigit, Hyytinen, and Toivanen (2018) find that individuals with an STEM Master's degree are twice as likely to be an inventor than individuals at the top of the IQ distribution. Our results complement this literature by providing novel evidence for the role of the education curriculum for the adoption of frontier knowledge during the 18th century, as well for the implications for growth and innovation, using novel data on patenting in the early 1800s.

Our evidence also contributes to the literature emphasizing the effect of cultural and technological factors for education attainment (Becker and Wößmann, 2009; Dittmar, 2011) by documenting the role of schools and curricula and disentangling it from cultural and technological factors. In this respect, our evidence sheds new light on the findings by Hornung (2014) and Valencia Caicedo (2019) that have documented the long-lasting effects of Protestant (Huguenot) and Jesuit influence, respectively, and directly addresses the conjecture that the Huguenots constituted the French enlightened knowledge elite that has been proposed in previous work (e.g. Squicciarini and Vogtländer, 2015). Our findings show that the availability of scientific education has been fostered by Jesuits and continued to have effects even after the abolition of the Jesuit order. Moreover, this influence is shown to be distinct from that of Protestantism reflected by the presence of Huguenot communities.

More generally our findings contribute to the literature on the origins of knowledge-based development. In documenting the distinct roles played by religious denomination and religious orders for education curricula, for the Industrial Enlightenment, and ultimately economic development, our findings add to recent evidence that points to the role of the Protestant reformation for establishing public good institutions that provided education Dittmar and Meisenzahl (2020) as well as for changing the content of education (Cantoni, Davide, Dittmar, and Yuchtman, 2018), which both affected pre-industrial development. The role of embodied knowledge is also shared with recent work by Jensen, Sandholt, Lampe, Sharp, and Skovsgaard (2018), who do not focus on the role of schools and curricula but instead on experience-based knowledge.

The remainder of the paper is structured as follows. Section 4.2 discusses the historical background. Data and empirical strategy are described in Section 4.3. Section 4.4 investigates the determinants of schools and scientific education. Section 4.5 presents the results for role of local human capital for the demand for codified knowledge. Section **??** explores the demand for human capital, and Section 4.7 sheds light on the implications for economic development. Section 4.8 concludes

4.2 Historical Background

19th Century France, with the combination of the education system and the Enlightenment, provides a unique historical setting that allows us to study the interaction between embodied knowledge and codified knowledge. From about 1500 until 1792, secondary education in France was almost exclusively provided by so-called colleges (*collèges*). The colleges were public schools and offered education that followed a curriculum in the “style of Paris”. The three most distinctive features of the “style of Paris”, which was practiced by colleges in Paris and adopted across the nation, was the use of the class system, the absence of tuition fees for local or poor students, and a standardized curriculum.

In this section, we describe the historical background of pre-revolution secondary schools in France, the colleges (*collèges*), and the changes of the education content provided in colleges in response to the Englightenment.

4.2.1 History of French secondary schools ca 1500–1792

Origins of Colleges The large majority of colleges had been established by the end of the seventeenth century, thus before the spread of the Enlightenment. In most large towns, schools were established during the sixteenth century. The establishment of colleges across France from the early sixteenth century on occurred in context of a general spread of Humanistic thought in Europe. The colleges principally offered education in Latin based on the classical Roman authors, which had been rediscovered and disseminated during the fifteenth century. In some places, the Latin education was complemented by the study of Greek and texts from its classical antiquity. Around the same time, Humanism and humanistic schools spread not only in France but across Europe. **?**, for example, document the parallel establishment of schools during the sixteenth century in Germany. Until the middle of the seventeenth century, schools had been founded also in middle-sized and even smaller towns. After 1700, only few towns opened a new school, and even less closed an existing school. Figure 4.2 shows the pattern of college foundations over time.[1] This implies that the distribution of colleges across towns had essentially been completed long before 1750.

Compared to the rest of Europe, French colleges were peculiar in combining a humanistic education with philosophy education which was traditionally—and continued to be elsewhere—tought at universities. The full college (*collège de plein exercise*) which offered humanistic education *and* philosophy had its origin in residential colleges in Paris. These were study houses attached to the university where poor scholars were lodged and fed at the expense of a benefactor. In the middle of the fifteenth century, a number of residential colleges started to offer a philosophy course in competition with lecturers at the faculty of arts. When establishing schools in the sixteenth century, the humanist reformers took this colleges as role model (Brockliss, 1987, p. 20). In this tradition, schools outside Paris generally adopted the organization, mode of instruction, and curriculum from the Paris colleges (the "style of Paris"). Many humanistic reformers had attended the Paris colleges, which explains why they would became the prototype for schools nationwide.[2]

Curriculum The curriculum moved in progressive order from the basics of Latin grammar in lowest class (6th) up to composition (2nd) and rhetorics (1st). In the higher Latin classes, the students read classical works by authors like Cicero or Sallustius in the original. At the end of school, students were fluent in written and spoken Latin (Brockliss, 1987, p. 112).[3] Many colleges offered courses in philosophy to attend after the completion of the Latin curriculum (and some even theology after philosophy). Colleges that offered only Latin grammar up to rhetorics (1st) were called "humanistic colleges." Colleges that offered a philosophy curriculum in addition were called "full colleges" (*collèges de plein exercise*).

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[1] During the eighteenth century, some small towns did open small Latin schools, but these seldom had more than two teachers and did not offer more than Latin grammar education (see figure 4.6).

[2] For example, Erasmus, Calvin, and Ignatius of Loyola, the founder of the Jesuit order, all attended the same college in Paris during the early sixteenth century. There were other potential prototypes—the medieval *college de boursiers* or the episcopal choir school—but it was exactly those medieval education institutions which the humanist reformers wanted to replace.

[3] Some colleges offered also Greek as part of the humanistic curriculum.

Figure 4.1 illustrates the full curriculum.

The philosophy curriculum covered two years (theology, if it was offered, three). Traditionally, the subject of philosophy was taught as four separate sciences: Logic, ethics, physics, and metaphysics. The separation was initially reflected in an evenly divided teaching time between the four subjects. Following the traditional structure, students would study the subjects logic and ethics during the first year, where logic was viewed as the science of right reasoning, ethics the science of human behavior. During the second year, students would then proceed to study physics—which originally meant natural philosophy and described the science of the natural body—and metaphysics, the science of being per se. This sequence of the philosophy curriculum also reflected the division into what were believe to be *practical* sciences, logic and ethics, and *speculative* sciences, physics and metaphysics. Broadly speaking, ethics was propaedeutic to law, metaphysics to theology, and physics to medicine, while logic was essential for every science.

Philosophy education became institutionalized at colleges through the establishment of chairs before the Age of Enlightenment. In the earlier sixteenth century, philosophy was often given by the principal and not yet fully institutionalized. Thus, for some full colleges in Figure 4.2 that were founded in the sixteenth century it is unclear whether they offered philosophy from the beginning. The definite institutionalization of philosophy teaching coincides with the foundations of chairs dedicated to philosophy from 1570 onward. Figure 4.3 shows the pattern of chair foundations over time, including the foundation dates of a second philosophy chair at a college. The large majority of chairs for philosophy had been established by 1680, around the time when the Enlightenment began, and considerably before the publication of the first volume of the *Encyclopédie* in 1751.[4]

As consequence of the new developments, the traditional structure and content of education changed during the seventeenth century. Physics (natural philosophy) became the dominant part of the course and would increasingly be taught last and take up most if not all of the second year (). By the end of the seventeenth century, physics took up the whole of the second year (Brockliss, 2006, 1987, pp. 185–188). Also within the subject of physics, the content evolved with the scientific advances of the seventeenth and eighteenth century, reflecting an increasing interest in the newest scientific findings in society.

Professors for philosophy were usually also expected to give some instruction in the independent science of mathematics when teaching physics. With the increasing importance of physics, an introduction in mathematics became an essential part of the philosophy course (Brockliss, 1987, pp. 186). Some colleges founded independent chairs in mathematics even

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[4] A precise dating of the Enlightenment is difficult. The foundations of Royal Society in London 1660 and Academy of Sciences in Paris 1666 certainly represent important turning points.

before (see figure **??**). Instead of a mathematical philosophy, however, these professors were primarily teaching applied mathematical subjects like hydrography, navigation, fortification, or ballistics.[5]

Organization The colleges were public schools, funded by municipality and private or religious endowments. Colleges with sufficient funding employed one teacher per class. Colleges with less funding either employed one teacher per two Latin classes, or dropped the 6th and sometimes even 5th class. Schools with very limited funding offered only the lower Latin grammar classes. In many smaller colleges, the principal also taught the rhetorics class.

Schools were supervised by a municipal school board, which would contract with a principal or religious congregation to run the daily school operations. During the hiring process, the candidates were often subject a public examination by the municipal school board. The preferred qualification of a principal was a Master's degree from the university of Paris. The principal would live in the school building, which was generally provided for by the municipality and spacious enough that it could house the principal's family as well as accommodate boarding students from the countryside. Often times, the principal was given a local monopoly for accommodating boarding students in the school house. The boarding fees provided an additional source of income for the principal. This arrangement implied incentives for the principal to offer good education, as the school's reputation influenced how many parents from the countryside and surrounding small towns would send their sons to the college (Huppert, 1984).

Under the political pressures of the Wars of Religion, many colleges were taken over by Catholic teaching congregations such as the Jesuits, Oratorians, and Doctrinaries between 1570 and 1630. While by 1600 the majority of schools was still secular, by 1650 most colleges were run by some kind of religious organization (see figure 4.7, panel b). This development was supported by efforts of the state to gain control over education. As the state itself did not have the resources to organize education, it was easier to control centralized religious orders than independent municipal teachers and school boards. In general, however, the state did not force take-overs on municipalities.[6] To the contrary, most municipalities and orders voluntarily entered contracts that required the orders to provide education as it was before, with a curriculum in the style of Paris. Municipal boards would continue to oversee the schools. As a result, the take-overs did not result in a shift in instruction

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[5] This applied education can be seen as a precursors to the royal military academies of the later eighteenth century, which again were precursors of the French elite engineering schools like the *École polytechnique*.

[6] One notable exception was the town La Rochelle, a Huguenot stronghold which was laid siege on 1627–28 by Cardinal Richelieu. After the capture of the town, Jesuits took over the *collège*.

towards religious content but instead in an increase in educational stability and, at times, even teaching quality. Many of the famous philosophers of the Enlightenment attended colleges run by religious orders, including René Descartes, Voltaire, or Denis Diderot.

Attendance The colleges were primarily attended because Latin and philosophy were propaedeutic for obtaining a university degree in theology, law, or medicine: Latin because it was the language used in philosophy as well as university education; philosophy because a degree in philosophy was a requirement for obtaining a degree in theology or medicine. [7] Such advanced eduction could eventually provide entry into the French state administration. Thus, the attendance of the schools offered the promise to climb up the social ladder.

Typically, college education was free of tuition for all sons of citizens, and only students from outside would have to pay tuition. Even in towns where education could not be offered free because of the lack of financial resources, exemptions from tuition for poor students were common.[8]

The free access to education is reflected in the broad social background of students, including all strata of urban society, from nobles over bourgeois to artisans, only excluding the very poorest as, for example, day workers. Nationwide estimates suggest that about one in fifty French children attended the colleges, whereas the number could in cities be as high as one in ten or one in five (Roche, 1998, p. 430). Appendix 4.C) provides for a number of exemplary colleges detailed data on the social composition of students by occupation of the father, as well as the rural–urban composition. It appears that just between two-thirds and three-quarters of the students came from the political, social, and economic elite, while the rest were sons of artisans, small shopkeepers, or peasants. While the higher classes were clearly over-represented compared to their share in total population, the lower classes were not generally excluded. Often times, however, it was the requirement to run the shop or learn the trade of the father which prevented good students from completing their college education.

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[7] While philosophy was taught at colleges, only universities had the power to bestow a degree. Few universities had lecturers in philosophy, but all possessed a faculty board that examined philosophy students who wished to obtain a degree.(Brockliss, 1987, p. 14)

[8] For example, the town Soissons ran a college since about 1530, a first chair in philosophy in 1636 and a second in 1682. Because of the lack of funds, non-boarding students had to pay tuition (boarders would pay tuition anyways). Tuition fees were 6 livre per year until 1740, 12 livre 1780 and 13 until the revolution. For poor students, however, there were always exemptions: One fifth of all students did not have to pay any tuition, even though “from the rare archives on the collège, there emerge two principal impressions: The stability of staff and the permanent poverty of the establishment.”(Compère and Julia, 1988, pp. 608–611).

4.2.2 Determinants of Colleges and Scientific Education

Determinants of college foundations The subsection discusses the determinants of variation across towns in college existance and college type. The following subsection will discuss the determinants of content and curriculum *given the existence of colleges.*

The main limitation on college foundations was not a lack of interest in humanistic education but the requirement of funds. The colleges were public, endowed schools and received income from gifts, usually of land and buildings, made in the recent of distant past. To set up a college, a not unsubstantial amount of ressources were needed to build or buy the school building as well as to endow the lectureships for principal, professors, and teachers. Town councils often supported the foundation and maintenance through grants, but they would not, for example, pay the teacher's wages by levying taxes on its citizens. Instead, the lectureships were endowed with funds from various sources, including individual bequests, local administrative districts (*baillages*), provincial appellate courts (*parlements*) and estates, bishoprics, and at few colleges from the king (Brockliss 1987, p. 20; **?**, p.8; Roche 1998, p. 430).

Among the many sources of funding, the most systematic was the bishopric. As feudal lord, the bishopric possessed steady income from porperty and the tithe. Part of this income funded "positions for clerics" called *benefice*), which entailed a yearly salary from certain pieces of property. The Edict of Orleans (1561) stipulated that the annual income of the first vacant benefice was dedicated to permanently fund a teacher position at a public college in the bishopric (Huppert, 1984, pp. 94-5). Further, the bishopric had a direct interest in establishing a college locally. Both Latin and philosophy education were the scholarly foundations of the study of theology and thus required for the training of priests. [9]

Towns with a bishop's see were also for historical reasons centers of learning and may have had persistently higher demand for Latin education. Throughout the Middle Ages, the church had a monopoly in the provision of Latin education. Apart from monasteries, episcopal towns were the primary locations of scholarship and Latin education. Cathedrals (the bishop's churches) often had a school attached to them, where clerics would offer Latin teaching (Brockliss 1987, p. 19; also Huppert 1984).[10]

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[9] As consequence of the French state's lack of state capacity, the regulation of the Edict of Orleans was implemented slowly, sometimes only decades later. Such delay was normally not caused because of the bishopric's lack of interest in education, but by its refusal to hand over income to the municpaility. When the Edict was implemented, it provided an impetus for the foundation of the college if it had not already been founded.

[10] Teaching quality in such cathedral schools was heterogeneous and sometimes bad. Huppert (1984) argues the low education quality was a motif why citizens to eventually re-organized education and provided education facilities at the municipal level.

The variation across towns in colleges due to the presence of a bishop's see reflects historical persistance in development. Figure 4.8 shows that most bishop's sees were established during the late Roman Empire. Some towns were early adopters of Christianity, before it became state religion in 380. Others constituted it's citizenry through the church when the West Roman Empire desintegrated in the fifth century. The spatial distribution of French bishoprics persisted by and large throughout Middle Ages and Early Modern period.

While towns which got a bishop had likely a more prosperous economy during Roman times than those which did not, they were not necessarily so at the begin of the Early Modern period. Michaels and Rauch (2017) document that, in France, town locations and town network have been highly stable since antiquity. Because the geographic characteristics conducive to economic development changed between the first and second millenium, many erstwhile Roman towns became trapped in suboptimal locations. As a result, Michaels and Rauch (2017) find that such towns experienced less city growth between 1200 and 1800.

Besides bishops, the second important determinant of colleges was the increase in religious competition during the sixteenth century between Catholics and Protestants. The spread across France of Protestantism resulted in college foundations supported by Protestant communities. Whereas at the begin of the sixteenth century colleges were founded as secular institutions, the begin of Protestant school foundations around 1560 reflects an increasing willingness to fund public education (see figure 4.7). As argued by Becker and Wößmann (2009), the teachings of Martin Luther—and later Calvin, who was a more important influence in France—provided a religious impetous for education.

At the same time, the Catholic (Counter-)Reformation—in particular, the Jesuit order—provided the impulse for Catholics to support school foundations. The Jesuit order was organized around teaching. All Jesuits had to teach at a Jesuit college at least once in their career. The order's teaching regulations, the *Ratio Studiorum* of 1599, reflected and standardized teaching *in the style of Paris*. Essentially, the Jesuits provided the analogous religious impetous for education as the Protestants: "By adding also a religious imperative to the [educational mission] of the humanists, the [Jesuit] Society was able to chivvy municipal notables into unprecedented acts of educational charity. The Jesuit's sales technique was impeccable. They persuaded municipal élites that they needed the product, then offered it to them cheaply and reliably packaged." (Brockliss, 1987, p. 21). Jesuit colleges began to spread in France at the same time as Protestant colleges (figure 4.7). From about 1650 to 1760, there were about 100 Jesuit colleges in France, of which about 80 were full colleges.[11]

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[11] The Jesuits were banned from France in 1762 for political reasons that were unrelated to schools and education.

Determinants of science education This subsection explains how religious competition influenced not only the foundation of colleges per se but also the curriculum and the establishment of philosophy and science education at colleges. What was taught in philosophy and how, and how it changed from the seventeenth to the eigteenth century, will be explained in the following section 4.2.3.

The importance of the church for education and the timing of the foundation of colleges and chairs for philosophy also raises the question about the role of religious competition after the protestant reformation, which largely coincided with the "education revolution" during the 16th century. The advent of Protestantism in France resulted in increased religious competition, political tensions, and civil war between Catholics and Protestants. At the time of Reformation, much of present-day France was under control of one king and one state. Wereas the king and majority of people stayed Catholic, part of the nobility, together with some southern region's local majority of people, converted to Protestantism. The period between 1560 and 1630 saw some of the bloodiest episodes of French history and a succession of wars collectively termed "Wars of Religion."

One of the ways Protestants deviated was their attitude towards learning and science. Cantoni et al. (2018) show for Germany that Protestant towns spent more on public education, trained more university students in law and less in theology, and generally attracted more highly educated individuals. In France, Protestantism did not take hold of the universities. Nevertheless, many highly educated individuals and holders of university degrees converted to Protestantism. Reportedly, there was for some time a shortage of well-trained Catholic principals and teachers, and Catholic towns had to hire Protestants for their college (Huppert, 1984).

The Jesuits played a particularly important role in the Catholic response to Protestantism in France. Founded in the context of the counter-reformation, the Jesuits' expressed goal was to demonstrate the superiority of Catholicism over Protestantism in all dimensions, including, in particular, in science and mathematic, in order to drive the Huguenots out of the market for education and to win back sceptical Protestants through excellence in teaching and science.

The French state, while indifferent or even hostile to science education, supported the Jesuits due to the lack of state capacity to establish a public education system, with the consequence that Jesuits took over many secular and Protestant colleges. In 1750, there were about 100 Jesuit colleges, of which around 80 were full colleges (see Figure 4.7). These colleges were predominantly founded during the 16th and 17th century (see Figure 4.9). Eventually, Jesuits were banned from France in 1762 for political reasons that were unrelated to the schools.

The shift in focus of scientific education from older Aristotelian view towards a mechanical understanding of the world following ideas of Descartes originated at the university of Paris and its colleges. The widespread adoption of Descartes was made possible by a conflict over religious doctrine within the Catholic church, which got conflated with a political conflict between the king and his noble opposition, which stalled the Catholic opposition against Descartes (see below). The empirical analysis is conducted on a sample that excludes Paris to prevent any concerns or complications. Although the evolving scientific curriculum and the replacement of Aristotelian thinking by that of Descartes in the 1690ies at the Paris colleges was not initiated by the Jesuits, their contribution was to spread and establish scientific education across the country on the model of the Paris colleges: "[T]he Jesuits did not create the colège de plein exercise, [but] they indisputably turned it into an educational commonplace." (Brockliss, 1987, p. 21). They did so, if necessary, in opposition to an ultra-orthodox Catholic opposition.[12] In particular, the Jesuits played an important role for the establishment of philosophy education at colleges. Especially until about 1650, many philosophy chairs were founded at Jesuit colleges (see Figure 4.9)

The success of the Jesuits was based on two aspects: the quality of their education and their far-reaching influence throughout France. The quality of Jesuit education was based on their system of educating their teachers. For instance, Brockliss notes that "no one (apart from the partisans of the University of Paris) ever suggested that Jesuit teaching was poor, even though their professors were young and often not greatly in advance of their pupils." (Brockliss, 1987, p. 50). Notably, some the most eminent figures of the enlightenment, including Descartes, Voltaire, Diderot, were educated in a Jesuit college. Moreover, the Jesuits established a network of schools and teachers. As a teaching order, they required each Jesuit to teach at a Jesuit college at least at some point during their career as monk. They employed young teachers "fresh from university" (or sometimes even college) and made it mandatory for teachers to rotate across the country, which contributed to the rapid and universal integration of new scientific concepts into the philosophy curriculum. The Jesuits thereby played a central role for the adoption of standardized and highly uniform curricula in the education of philosophy, physics, and science and ensured that the new scientific findings and scientific curriculum was not concentrated in Paris and some occasional provincial college. In fact, Jesuits quickly became the largest Catholic teaching order in Europe and France and were particularly successful in channeling funds into education.[13] The quality of Jesuit education is documented by its long-lasting influence

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[12] For instance, the Jesuits did not refrain from teaching Copernican astronomy as a useful mathematical approximation in spite of its prohibition by the catholic church.

[13] "By adding also a religious imperative to the [educational mission] of the humanists, the [Jesuit] Society

on human capital and cultural values in many parts of the world (see, e.g., Valencia Caicedo, 2018; Valencia Caicedo and Voth, 2018).

4.2.3 Scientific Education: Content and mode of instruction

Natural philosophy, the precursor of modern science, was taught in Europe since the late Middle Ages in university faculty of arts within the subject of philosophy. Leading up to the enlightenment, the content of education in philosophy and in particular physics changed fundamentally. The possibly most important change was the replacement of traditional, scholastic scientific authority with the principles of scientific analysis and focus on mechanics of Descartes. From Descartes, it was not far to Newton and other empiricists, whose arrival (or adoption) mark the onset of modern science. The spread of empiricism represents not only a methodological change, but also a change in epistemology to the belief that theory of whatever kind can and should be tested by empirical evidence.

The change from scholasticism to science Initially, the physical works of Aristotle determined the structure of the physics course as well as its content. The Christian interpretation of Aristotle's principles was provided by the work of the Scholastics of the Middle Ages, in particular by Thomas Aquinas. Aquinas may have been rejected on particular questions, but his synthesis of Aristotle and the Bible was never questioned in its fundamentals (Brockliss, 1987, pp. 337–8). During the seventeenth century, the contentual focus changed from Aristotle's and Aquinas' works towards the novel findings of the Scientific Revolution, which were primarily empirical in nature. It did not, however, mean that Aristotle and Aquinas were abandoned as scientific authority in light of novel, contradicting facts. As Brockliss (1987, pp. 340–1) explains,

> "After 1640 … there can be no doubt at all about the [philosophy] professors' interest in the new science, not only in the novel astronomical developments but in the other areas of physics where new information and theories were now being presented for the first time: dynamics, pneumatics, physiology, optics, and so on. … [B]y the late seventeenth century, the large majority of the discoveries, if not the theories, had been accepted and integrated into the course." However, "the ideas and discoveries of contemporary science were only accepted on Aristotelian terms. Even a new discovery would be rejected or reinterpreted if it apparently contradicted fundamental Aristotelian principles."

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was able to chivvy municipal notables into unprecedented acts of educational charity. The Jesuit's sales technique was impeccable. They persuaded municipal élites that they needed the product, then offered it to them cheaply and reliably packaged." (Brockliss, 1987, p. 21). See also the discussion in Section 4.2.

This led scientist and philosophy professors to reject, for example, the literal existence of sunspots. It was not that they denied the observation of sunspots through the telescope. Rather, they refused to believe they were actually located on the sun, which would have implied that the planetary heavens are subject to change and not incorruptible as stated by Aristotle. To save his principles, they instead believed—or pretended—that sunspots were solar satellites (Brockliss, 1987, pp. 342).

Only after 1690, the attempt to reconcile the principles of Aristotle and Aquinas with the new science was increasingly abandoned by the philosophy professors. Instead, (theoretical) physics became based on principles of René Descartes. When the new physical philosophy took roots after 1690, the rejection of Aristotle and its replacement by Descartes was rapid and universal (Brockliss, 1987, pp. 350). Until 1690, all Paris colleges still taught physics based on Aristotle. Yet, by 1700, most had begun to teach physics based on Descartes (Brockliss, 2006). By the 1720ies there was hardly a college in the whole country that had not accepted the doctrine.[14] However, Descartes' physics was never accepted completely and was always the subject of constant critical appraisal and critical revisions (Brockliss, 1987, pp. 350–4).

The triumph of Descartes over Aristotle signaled the triumph of purely rational science that would use deductive or inductive analysis to create new knowledge. The mechanical principles of Descartes were in their scientific approach were also much closer to the empirical approach to science as promoted by Bacon and Newton, which was central to the industrial enlightenment (Mokyr, 2016). It replaced the earlier scientific methods of starting out with a-priori assumptions that were to be proven right at all cost. The triumph of Descartes and transition to English-inspired empiricism was reflected in a novel epistemology of science that became taught in the colleges. "In eighteenth-century France the liberal professional élite was instructed in an epistemology of natural science which was justified in terms of its simplicity and social utility and which increasingly stressed the conditionality of all conclusions and their need to be continually tested on the anvil of carefully regulated empirical inquiry" (Brockliss, 1987, p. 452).

Parallel to rejection of Aristotle and Aquinas as foremost scientific authorities, science became separated from religion. In the seventeenth century, physics was ultimately dependent on theology. Subject to the arbitration of what was considered divinely revealed truth—the writings in the Bible—, physics was restricted by the belief that the Bible should always be taken as literally true. It was on this reason that, for example, Copernicus findings were rejected because they offended passages in Job 38, Joshua 10, Ecclesiastes 1, and Psalm

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[14] The first Jesuit theses at Louis-Le-Grand to defend a mechanist physics (i. e. a physics based on Descartes' principles) date from 1708. (Brockliss, 1987, p. 351)

104 (Brockliss, 1987, p. 374). The followers of Descartes and Newton of the eighteenth century escaped from the dictate of the Bible by asserting that a literal interpretation need only be followed in matters directly referring to faith and discipline (Brockliss, 1987, p. 376).

Drivers of the change The rapid and thorough replacement of Aristotle with the natural philosophy of Descartes is remarkable as it happened against the will of the establishment. Descartes' mechanistic world view had been suppressed by the political and social establishment since its origin and was contested until about 1715 when the establishment finally lost the fight (Brockliss, 1987, pp. 353). According to Brockliss (2006), this scientific coup d'état was made possibly by an intricate conflict between several factions split along religious and political lines.

The bone of contention was a particular form of Catholic moral theological doctrine, "Jansenism", which was deemed heretic by the church because of its closeness to Calvinism. The ideas had existed in the underground for about 50 years and already gained acceptance with parts of the nobility and clergy. When the king identified political opponents within this group and then with this group in general, he tried to crush the opposition by attacking their religious doctrine with help of the pope. Once the pope had declared the Jansenist teachings heretic, however, the *parlement* of Paris and other proponents of "Gallicanism," the doctrine that the king of France is sovereign in all matters including matters of the church in France, in which the pope should accordingly not interfere, sided with the Jansenists. Thus, the king's strategy backfired and only strengthened the political opposition. Within this complex factionalization of political interest, powerful clerics and nobles on to the Jansenist side or leaning towards it, as for example the archbishop of Paris, de Noailles (1695–1726), sympathized with the proponents of Descartes, who were also oppressed by the king but otherwise not related to the conflict. In this situation could a new, very wealthy, and thus prestigious Paris college, the *collège Mazarin*, appoint open proponents of Descartes as philosophy professors without being immediately attacked. The philosophy professors indeed started to teach Descartes' principles directly and even published their course in print. Stalled in the conflict about Jansenism, the faculty of theology at the University of Paris—supervisory authority of the Paris colleges and guardian of traditional scholastic philosophy—did not immediately take disciplinary sanctions against the professors. By the time of the first disciplinary sanctions—further delayed by the archbishop de Noailles—other colleges, who were in competition for prestige and scholars with the *collège Mazarin*, had appointed proponents of Descartes as philosophy professors as well. Descartes quickly became the new authority in philosophy teaching at almost all Paris colleges, and, subsequently, in the whole of France.

The universal adoption of the scientific approach was closely related to the Jesuits. Although the Jesuits were not the *origin* of the evolving scientific curriculum or the reason for why Aristotelian thinking was replaced by that of Descartes in the 1690ies at the Paris colleges, the contribution of the Jesuits was to spread it across the country. After Descartes made inroads into philosophy teaching at the Paris colleges, the Jesuit network of schools and teachers, their habit to rotate teachers, and their habit to employ young teachers "fresh from university" (or sometimes even college) all contributed to the rapid and universal integration of Descartes into the philosophy curriculum. The Jesuits thereby ensured that the new scientific findings and scientific curriculum was not concentrated in Paris and some occasional provincial college, but that they were spread out evenly across the country.

Changes in the mode of instruction The shift towards empirical science is also reflected by a change in the method of teaching physics. When in the second half of the seventeenth century experimental work of contemporary natural philosophers was discussed in the classroom, no visual aids to understanding except printed diagrams were employed. This changed at the turn of the century when Paris professors started to give their students some practical instruction. In the period from 1720 to 1750, colleges in the largest towns purchased their own *cabinet de physique*, with which the professors of philosophy could perform the experiments themselves. The experimental demonstrations were typically given outside class hours and were to the general public. It was not until the eve of the French Revolution, however, that the cabinets became commonplace at colleges everywhere and experimental physics a customary college course (Brockliss, 1987, pp. 189–90).

Teaching was generally done in Latin and ex cathedra, employing a scholastic method of argumentation, where the parts of the course were divided into a number of logically connected sections that were in turn divided into questions, each of which would be resolved by a series of arguments and counter-arguments (Brockliss, 1987, pp. 188–9). Traditionally, the way of teaching relied on dictates. With the introduction of mathematics, that part of the philosophy course became almost immediately textbook oriented. Only from about 1765 onwards, however, when the Enlightenment was already spreading, the whole philosophy course became textbook based (Brockliss, 1987, pp. 190–1). Also with the introduction of mathematics, French entered the philosophy course, as printed textbooks were always in the vernacular. Still, Latin remained the main language of instruction in the physics course until the 1780ies (Brockliss, 1987, pp. 191–2).[15]

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[15] The first professor who taught the whole philosophy course in French was Jean-Antoine Nollet, who held since 1753 the first Chair for experimental physics in the country at the Parisian *Collège de Navarre*.

4.2.4 Science education and the Enlightenment Encyclopedia

Historically, productive knowledge was usually embodied knowledge that was passed on tacitly within narrow groups, and not disseminated widely in society (la Croix, David, Doepke, and Mokyr, 2017). With the enlightenment, both the creation and dissemination of useful knowledge changed dramatically. The spread of the scientific method, combining the methods of deductive and inductive analysis by Descartes (Raftopoulos, 2003) with the empiricism propagated by English enlightenment in the tradition of Bacon and Newton (Mokyr, 2016) led to an increasingly epistemic basis for technical know-how and thus facilitated the development of new technologies. At the same time, the dissemination of useful knowledge changed dramatically, as reflected by the establishment of scientific journals and the publication of the Encyclopedia by Diderot and d'Alembert (Mokyr, 2005). Together, this led to an acceleration of the development, the availability, and the dissemination of knowledge. Our evidence sheds light on the interplay between persistent regional heterogeneity in access to scientific education and the newly available codified knowledge contained in the *Encyclopédie*.

Through the full colleges, the French liberal professional elite, who typically received their education in these colleges, was exposed to the scientific advances as well as the associated scientific mindset. Presumably, it was this education in science that created an audience that was receptive to the ideas of enlightenment and had a demand for the new knowledge becoming available in the context of enlightenment.

The changes in philosophy curriculum away from a metaphysical scholastic science towards an empirical science concerned with the real world prepared the way for the Industrial Enlightenment. In particular, it prepared the way for the most paradigmatie Enlightenment publication, the Encyclopedia by Diderot and d'Alembert. As Roche (1998, p. 575) explains, "[t]he *Encyclopédie* would have been inconceivable without …the confluence of Cartesian analysis with English thought; …through Locke and Newton, analysis became experimental, …[i]t no longer defined essences or innate ideas but described reality."

The Encyclopedia was conceived as a work of popularization and diffusion of knowledge. Its goal was to "impose order on abundant but haphazard scholarship handicapped by a neglect of science and technology in favor of matters of history and religion. The *Encyclopédie* drew on the work of mechanicians, geometers, experimental scientists, technicians, artists, and engineers rather than of the dogmatic theologians of the Middle Ages or the humanists of the Renaissance and their followers of the baroque period, caught between ancient thought and modern traditions." (Roche, 1998, p. 575)

The spread of technical knowledge embodied in the Encyclopedia contributed to technological progress by facilitating the access to knowledge which was previously the secret of different trades and arts. “The nature of the technological knowledge proposed by the *Encyclopédie* was strikingly different from that of traditional technical know-how…Traditional know-how was instinctive, a form of manual dexterity,…more mechanical and physical than intellectual[,] exclusive,…acquired through initiation, (p. 576)…[and] its techniques…likely to be secrets…This contrasts sharply with the rational, theoretical, scientific, and universal knowledge advocated by Diderot and d’Alembert. ‘The greatness of the *Encyclopédie* lay in the fundamentally important role assigned to its plates of drawings and models, which paid homage to…rational knowledge of technical operations.’ These plates were not included solely for documentary purposes; it was hoped that they would contribute to further technical progress. Rational knowledge—rational because it relied on calculation, measurement, and objective analysis—was thus made available to the general public without restriction or secrecy” (Roche, 1998, pp. 575–6)

4.2.5 Demand for education: Central schools

In the course of the French Revolution, all colleges were closed by law in 1792. By 1795, every *département* was required by law to open a central school and offer nine subjects. Of those, ancient languages, grammar, literature, history, and law comprised a curriculum that resembled a humanistic education, whereas drawing (including technical drawing), mathematics, physics/chemistry and natural history comprised the part of the curriculum devoted to technical or scientific issues. As a result, most *départements* opened a central school, but not all central schools offered all subjects.

The central schools had several unique features. In particular, the curriculum was modular: there was no mandatory sequence of instruction. Instead, students were free to enroll in any subject they wanted and could attend up to 3 courses at a time. In 1799, the Ministry of the interior conducted a survey on student enrollment, which we use as primary data source for enrolment patterns and the demand for scientific education (?).

4.3 Data

4.3.1 Secondary Education Institutions in France

The analysis is based on a novel city-level data set of the universe of French secondary education institutions from 1500 to 1792. Further, we collected novel data on the spatial distribution of religious activity, including bishoprics and Protestant churches. Table 4.35

provides an overview.

For all French towns, we know whether a college existed in 1750, and if so, which type of college. The types are full college (philosophy, humanistic, and Latin grammar education), humanistic college (humanistic and Latin grammar education), small college or Latin school (only Latin grammar education). In the main analysis, we construct dummies for the three types of education offered. For example, the dummy “Latin education” will equal one for all full, humanistic, and small colleges. Except for some large cities as Bordeaux, Lyon, and Paris, most towns had only one college.

For all of France except the East, we know exactly how many philosophy chairs and thus professors there were at a college. We will either sum across all colleges the number of philosophy professors, or construct dummies for whether there was one professor, or two, or two but separately dedicated to logic and physics.[16] [17]

For the same sample, we also know the total number of teachers and professors at colleges in a given town. The number provides a good proxy for the total amount of ressources spent on education as teachers and college professors were hired on a national market, either directly or by contracting with nation-wide operating religious teaching congregations. Further, we know the year of first college establishment in a town, which measures how long history of education towns had, as well as whether, before that, there existed an older Latin school not operating in the “style of Paris.”

Further, we collected detailed information on the teaching “institutions”—secular teachers, priests, teaching congregations as Jesuits and Oratorians, other religious orders, or Protestants (secular or religious). In our analysis, we are particularly interested in the role of the Jesuits, who, as teaching congregations, carried the religious competition with Protestantism to the class room. We further know whether a course of philosophy was offered at the college, or separately in a seminary for future priests.

Finally, we obtained for the central schools in 1798-99 student enrollment data by subject. We use the ratio of students enrolled in scientific and technical subjects (design, mathematics, physics-chemistry, natural history) over all students (science plus ancient languages, general grammar, belles lettres, law) as measure for the demand for scientific and technical education.

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[16] If there were more than two philosophy professors in a town, we categorize by whether at least one of those was dedicated to physics.

[17] We have not collected the exact number of philosophy professors for Paris, because Paris had more than 10 colleges with philosophy professors and thus approximately 10 times more professors than an average town. If we were to include Paris for regressions with the number of philosophy professors, we would have to treat it separately as outlier anyways. Historically, Paris is an outlier because it hosted the most prestigious colleges which drew their students from all across the country, different to the provincial colleges which catered primarily to the town and region.

4.3.2 Data on Religious Institutions and Communities

We obtained data on all bishop's sees in France and their date of establishment. The presence of a bishop's see in a town means the presence of a cathedral, which in the Middle Ages often had Latin schools attached.[18] Primarily, though, the bishop's see dummy is a proxy for the availability of financial ressources for the college as described in section ??.

We also digitized data on the local presence of Huguenots from 16th and 19th century. The Huguenot dummy by century equals one if at least for some time a Huguenot church existed, or for some time a Huguenot priest resided permanantly there, or Huguenots were granted special rights by law. For the period 1685 to 1790, the churches were clandestine, as the Protestant religion was not allowed to be exercised publicly.

4.3.3 Data from Other Sources

We combine these data with existing data from other sources, building on the city-level dataset constructed by Squicciarini and Vogtländer (2015) on the basis of Bairoch, Batou, and Chevre (1988).

Encyclopedia subscriptions We measure the demand for codified knowledge at the time of Enlightenment by city-level per capita sales of the quarto edition (1777–79) of the *Encyclopedia* by Diderot and d'Alembert. The data has first been compiled by Darnton (1979) and was digitized by Squicciarini and Vogtländer (2015). For this edition, city level sales—subscriptions—are fully known. From a total of 8,011 subscriptions, 7,081 were sold in 118 French cities. It has been estimated that in total about 11,500 copies were sold to France. Thus, the sales data for the quarto edition cover the majority of copies circulating in France Darnton (1979, p.37).

The quarto edition was widely available to the interested public. It was marketed across France through travelling agents of the publishing house. Most sales were made to booksellers, who often had collected orders and payments beforehand. Its cheap price compared to the originial folio edition allowed middle class readers a purchase.[19] Further, many booksellers had reading rooms (*cabinets littéraires*) where, for a modest yearly access fee, people could read the *Encyclopedia* without buying it Darnton (1979, pp.287–99).

The demand for codified knowledge during Enlightenment, measured by per capita sales

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[18] If so, this will be recorded as "earlier school" as described above. We do not, however, have information whether the earlier school was directly or indirectly attached to the cathedral, or otherwise supported by the bishop.

[19] Information on occupations of subscribers for the town of Becançon, presented in section 4.C.3, confirms the accessibility to middle class readers.

rates of the *Encyclopédie*, was heterogeneous across France, not spatially clustered, and does not reflect variation other than a demand for codified knowledge. Figure **??** presents the heterogenous sales rates and confirms that the variation does not capture regional differences or spatially autocorrelated noise. Data from the same publishing house on total booksales 1769–94 allows to control for differences in city-level sales unrelated to a demand for codified knowledge. We use per capita total booksales as control variable for potential differences across towns of the publishing houses' market penetration and of general book demand.

City-level characteristics To construct per capita Encyclopedia sales as measure of demand for codified knowledge, we use population data from Bairoch et al. (1988) for the year 1750. Population is known for a sample of 189 French towns in the borders of 1789.[20] Excluding the département Seine (Paris and Meudon) and the East, we do have detailed school information on teachers and philosophy professors for 154 towns for which population in 1750 is known. Figure **??** shows the towns of the Bairoch et al. (1988) sample and the region East with restricted information.

Using biographic data on famous people from De la Croix and Licandro (2015), we construct two city-level outcome or control variables. First, we count the number of famous scientist born 1600–1750. We use it as plausibility test for whether colleges with philosophy and physics chairs actually offered a scientific education. Second, we count the number of famous businessmen born 1600–1750. We use it as proxy for unobserved city-level characteristics related to economic activity and availability of capital.

Further control variables are taken from the dataset of Squicciarini and Vogtländer (2015). As baseline, we control for the geographic characteristics (atlantic or mediterranean port, navigable river, non French speaking region) and knowledge institutions (printing press and number of printed books by 1500,—and from our novel sources—Latin school by 1500, university in 1750). As additional control variables, we use the departement-level density of nobles, literacy rate in 1786, and pre-industrial economic activity.

Data on historical growth Our analysis also investigates the implications of differences in human capital and codified knowledge for historical development. As no city-level panel data exists which would cover both the period before and after Enlightenment, we rely on three different proxies of economic development.

The first measure uses a panel of city population growth from Bairoch et al. (1988). This approach follows Squicciarini and Vogtländer (2015). These data have the advantage of

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[20] This excludes Corsica (cities Bastia and Ajaccio), which was incorporated into the French state only in 1789, and the region of Savoy (cities Chambery and Annecy), which came to France in 1860.

availability in cities going back to 1500. This allows testing whether the establishment of schools and chairs for philosophy influenced economic growth *before* codified knowledge became widely accessible with the *Encyclopédie*. The data are available in panel form by century until 1750 and in 50 year periods until 1850. The disadvantage of this measure is that it is a coarse proxy of economic development that relies on the assumption of a Malthusian environment. As consequence, the measure may be biased downwards by the early onset of the demographic transition in France (**?**).

As second measure of economic development, we use four different cross-sectional estimates of GDP per capita in 1860 from the literature. Constructed at department level, the data allow to test whether places with higher population growth actually experienced differential income per capita growth: If they did, such places should be richer in 1860. Section **??** provides more details on the sources of the GDP data.

The third measure for economic development focuses on innovation and productivity. In this respect, we use a ten-year city-level panel on patents of invention 1791–1855 compiled by **?** who show that the patents do correlate on arrondissement level (a unit of administration smaller than department) with total factor productity from an industrial census 1840. It is therefore reasonable to assume that patenting rates reflect rates of technological progress, which in turn are associated with income growth.

4.4 The Determinants of Education

We begin the analysis by investigating the determinants of college foundations, of the adoption of philosophy in the education curriculum, and of the content of scientific education, as reflected by the creation of a chair in physics as opposed to theology, at the colleges.

4.4.1 Empirical strategy

The empirical strategy is based on regressions of the existence of a (full or humanistic) college in 1750 in a given city (or, in later analysis, of the number of chairs devoted to philosophy, physics or theology) on a large set of historically predetermined variables. This approach reflects that education in natural philosophy was delegated to *collèges* already during the “education revolution” in the sixteenth century, which is when most colleges were founded, as discussed in Section 4.2. Cultural values and religious beliefs in the local context presumably played an important role for the establishment of colleges and a scientific education curriculum. Consequently, we hypothesize that access to secondary education, in particular education with scientific curriculum, was shaped by historical and institutional factors. Among those, the presence of an bishop's see is likely to be the most important determinant for the foundation of a school. An bishop's see comprised a cathedral and a cathedral chapter of canons, and most bishop's sees dated back to the late stages of the Roman Empire (see Figure 4.8), thus substantially preceding the foundation of schools. With the exception of occasional relocations around 1300, the spatial distribution of French bishoprics has been stable since the the early Middle Ages.[21]

Three factors support the hypothesis that the establishment of colleges was closely linked to bishop's sees. First, cathedral towns were historical centers of learning. Throughout the Middle Ages, the church had a monopoly in the provision of education in Latin, by then the *lingua franca* of learned Europe, and apart from monasteries, episcopal towns were the primary locations of scholarship and Latin education. Cathedrals often had a choir school attached to them, where canons would offer Latin teaching(Brockliss, 1987, p. 19); see also Huppert (1984).[22] Second, Latin and philosophy were prerequisites for the education of clerics and theology students at university. This implied that bishops had an incentives to provide this education locally. Third, the resources required for establishing colleges were more readily available in cathedral towns. The Edict of Orleans (1561) stipulated the annual income of the first vacant benefice in the cathedral chapter to be dedicated to permanently fund a teacher position at a public college in the bishopric (Huppert, 1984, pp. 94-5).[23]

In the empirical analysis, we also explore the role of other town characteristics for the establishment of colleges. In particular, we account for the existence of a Latin school or of a university in 1500, which reflects historical heterogeneity in the demand for (or tradition of) Latin or of higher education. The control variables also include city size (in terms of log population) in 1550 and the existence of a printing press in a city in 1500, reflecting potential heterogeneity in economic development. The controls also include a binary indicator of the existence of a Huguenot (protestant) community during the 16th century to account for historical factors related to the protestant reformation. Additional controls include geographic characteristics (ports on the Atlantic coast, ports on the Mediterranean coast, location on a navigable river, location in a non-French speaking department, and distance to

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[21] (Michaels and Rauch, 2017) document that the French town locations and town network have been highly stable since antiquity.

[22] Teaching quality was heterogeneous and sometimes bad. Huppert (1984) argues bad education quality was an important motif for citizens to eventually (re-)organize education and provide education facilities at the municipal level.

[23] Bishops and cathedral chapters possessed steady income from property and the tithe. Part of this income funded "positions for clerics," which entailed a yearly salary from a certain piece (or pieces) of property. Such a position was called *benefice*. As consequence of the lack of French state state capacity, th regulation of the Edict of Orleans was implemented slowly, sometimes only decades later. Yet, when it was implemented, it provided an impetus for the foundation of colleges if they had not already been founded.

Paris). Importantly, This set of controls reflects cross-sectional heterogeneity across cities that is historically pre-determined and accounts for systematic variation in the demand for higher education and corresponds to the baseline and early knowledge controls in the analysis by Squicciarini and Vogtländer (2015).

4.4.2 Determinants of *Collèges*

Table 4.1 presents the estimation results, ordered by decreasing explanatory power of the respective determinants. Colleges, in particular full colleges, are more likely in towns with a bishop's see. Also the existence of a Latin school or a university by 1500 makes college foundations more likely, although the effects differ with respect of the type of college. Whereas Latin schools are associated more with humanistic colleges, universities are associated with full colleges.

The early adoption of the printing press (by 1500) may reflect a generally higher demand for knowledge and human capital in printing towns as well as a higher demand for knowledge and human capital as result of the printing press. The printing press played an important for the dissemination of skills that were valuable in commerce (Dittmar, 2011). The findings do not reveal significant evidence that towns that were early adopters of the printing press were also more likely to have a college and to have an earlier college foundation, however.

The presence of a Huguenot community is positively associated with the foundation and earlier foundation of colleges, although the association is not significant when controlling for other factors. In particular, in the course of the sixteenth century, almost every larger town in France hosted at some point a Huguenot community (cf. ?). During the French Wars of Religion (1562–1598), Huguenot communities voluntarily left or were expelled from some towns and consolidated in others. To capture towns where Huguenot communities were important and potentially influenced development, we thus measure the presence of a Huguenot community by the existence of a Huguenot church during the seventeenth century or the special rights granted to Huguenots in particular cities in the Edict of Nantes. The finding that Protestantism was related to a greater demand for institutionalized, public education is in line with Becker and Wößmann (2009) and Dittmar and Meisenzahl (2020).

Finally, larger towns in terms of population in 1550 exhibit both a greater likelihood of a college foundation as well as an earlier date of the foundation. With population (density) as proxy for economic activity and wealth in a Malthusian context, this effect likely reflects that greater affluence as result of trade, production, or commerce, which made the foundation of colleges more likely.

4.4.3 Determinants of the Scientific Curriculum

The results of regressions with the same specification as before are shown in Table 4.2. In fact, colleges in towns with a bishop's see also had a significantly higher number of philosophy chairs. This finding particularly applies to theology chairs, however, whereas the presence of a bishop's see has no significant effect on the presence of physics chairs. The estimates also provide some evidence that colleges in larger towns exhibited more philosophy chairs, and here particularly physics chairs, although this effect is quantitatively small and only marginally significant. The estimates reveal no significant influence of other factors such as the existence of a Latin school, a university, or a printing press by 1500, or the presence of a Huguenot community during the 16th century, on the curriculum. Taken together, these results are consistent with earlier findings of long-term persistence related to bishop's sees and cathedrals by (Guiso, Sapienza, and Zingales, 2016). Towns that had a higher level of development in the past would become bishop's sees and were more likely to become medieval centers of learning and were also more likely to install or reform existing human capital promoting institutions during the sixteenth century.

The importance of the church for education and the timing of the foundation of colleges and chairs for philosophy also raises the question about the role of religious competition after the protestant reformation, which largely coincided with the "education revolution" during the 16th century. In particular, the local competition betwgeen Jesuits and Huguenots gives rise to the hypothesis that Jesuits put a particular focus on scientific education in the presence of a Huguenot community.

Table 4.3 shows the results for the role of the competition between Jesuits and Huguenots for the foundation of philosophy chairs, and in particular for chairs denominated to physics or theology. The empirical specification represents an extended version of the previous model, accounting for the existence of a Jesuit college, a the presence of a Huguenot community during the 16th century, as well as an interaction term to capture the competition element. The results indeed show that Jesuits and Huguenots were associated with a greater number of philosophy chairs in colleges, reflecting their focus on education. The only determinant that exhibits a consistently significant association with whether there was a physics chair at a college is the administration by Jesuits. Neither bishops nor Huguenot communities play a systematic role. Most importantly, however, the specification with interaction terms show that it was the presence of both, Jesuits and Huguenots, that led to a higher number of philosophy chairs, and in particular to the foundation of physics chairs. There is no effect on chairs in theology. This supports the view that the competition between forces of reformation and counter-reformation was particularly fierce in the field of science.

4.5 Education and the Demand for Codified Knowledge

After having established that the foundation of colleges and the adoption of a particular curriculum within the philosophy education of a college were determined by historical factors, in this section we turn to testing the hypothesis of complementarity between embodied knowledge and codified knowledge and consider the role of human capital for the demand for codified knowledge. In the next section, we then turn to the role of codified knowledge in shaping the demand for human capital.

4.5.1 Empirical Strategy

Here, we investigate the hypothesis that scientific education in schools was a critical determinant of the demand for codified knowledge during the enlightenment. To do so, we exploit city-level variation in the existence of colleges, as well as city-level variation in the (degree of) scientific curriculum. In the analysis, we use subscription density to the *Encyclopédie* as measure for the demand for codified useful knowledge and regress subscriptions to the *Encyclopédie* on the availability of embodied knowledge, proxied by the existence of colleges as well as by the existence and number of chairs for philosophy at the colleges.

Conceptually, this empirical strategy is based on the combination of cross-sectional heterogeneity in the prevalence of human capital at the time of the publication of the encyclopedia. Since the foundation of colleges and chairs began during the sixteenth century and was essentially completed by the eighteenth century, long before the *Encyclopédie* was published (see Figures 4.2 and 4.7), reverse causality or simultaneity is generally no concern for the regressions and the distribution of human capital can be viewed as predetermined. The publication of the *Encyclopédie* constitutes an exogenous event that made codified knowledge available everywhere at the same point in time. Once codified knowledge becomes universally available, the hypothesis is that demand is greater in places with a greater availability of human capital. In addition, one would expect that education content mattered and that the demand for codified knowledge would be particularly high in towns with greater scientific literacy and education, not necessarily with any education.

A potential concern with this approach is the omission of factors that are correlated with subscriptions to the *Encyclopédie* and with the prevalence of scientific education in schools. In our setting, endogeneity could arise from three potential sources: First, through factors related to the establishment of schools; second, through factors related to the establishment of philosophy education given the establishment of a school; third, through factors related to the degree of science education within philosophy. None of these factors are likely to affect our empirical analysis. In particular, as revealed by the previous analysis, the colleges were established in the first place not for the purpose scientific education, but instead for the purpose of a humanistic education, primarily in Latin grammar and rhetorics based on the Roman classical writers. Thus, in many places philosophy was established with a school even though it was not the original objective of establishing a school. Resources were often the key limiting factor for the establishment of both schools and philosophy. To account for this, we consider subscriptions per capita and control for city size as a proxy for resource affluence in a pre-modern Malthusian economy in all specifications. Additionally, we control for the number of nobles, the extent of pre-industrial economic activity, and also literacy levels in the *département*. In addition, we account for the existence of an episcopal see and cathedral chapter in a town. Moreover, we also control for school size by the total number of teachers (relative to city size), which is a direct measure for the amount of resources available for education. Finally, we control for the year in which education was offered for the first time in the style of Paris, for most towns corresponding to the year of establishment of the school, which proxies for a wide range of unobserved city level factors related to the historical demand for education. All results are robust when controlling for these variables. Finally, regarding the determinants of the content of the philosophy curriculum, the combination of historical developments outside the schools and their dissemination within existing teaching institutions support the idea that the particular scientific content which was taught within physics, and which provided the human capital that generated the demand for codified knowledge in the Enlightenment, did not depend on unobserved city level factors.

4.5.2 Education, Curriculum, and *Encyclopédie* Subscriptions

Table 4.4 presents the results from regressions of subscriptions to the Encyclopedia on the existence of a college. The results in Column (1) reveal that the existence of a full college in a city is associated with significantly higher per capita subscriptions to the Encyclopedia compared to cities without a full college. In fact, the existence of a full college explains 16% of the variation in subscriptions across cities, and an additional college increases subscriptions per capita by more than 70 percent. As suggested by the results in Column (2), this finding remains qualitatively unaffected and quantitatively comparable when adding a rich set of controls, including population in 1750 as proxy for development, the existence of a university in 1750, the availability of a printing press in 1500, the number of books printed by 1500, and geography in terms of ports, location on a navigable river, or language.[24] The result also continues to hold when excluding cities in Eastern France for which more detailed school data is not available, see Column (3).

As next step, we investigate the role of education content. Table 4.5 presents the results for specifications that distinguish between colleges that offer philosophy education, humanistic education, or plain Latin grammar education. Full colleges generally offered philosophy additionally to the humanistic and introductory Latin curriculum, and humanistic colleges the humanistic curriculum additionally to introductory Latin classes. The specifications are as before without controls (Column (1)), with the full set of baseline controls (Column (2)), and with controls but excluding cities in Eastern France (Column (3)). The results show that, compared to a town with no college, the existence of a college with humanistic education exhibits almost 50 percent more subscriptions. The availability of education in philosophy is associated with even more subscriptions, although the effect is only marginally significant once controls are added (and not significant when considering only the core sample excluding eastern France). In contrast, compared to a town with no college, towns with colleges that offer only Latin grammar education but no extended curriculum exhibit almost 20 percent fewer subscriptions. This could be an indication for brain drain due to selective out-migration. Introductory Latin grammar classes were offered at smaller Latin schools with one or two teachers as preparation for the higher humanistic curriculum at a college. Such schools existed in many smaller towns that could not afford a full college. Moreover, attending classes at a college was costly for students from other towns because of lodging and tuition (many colleges exempted only local students from tuition). Local Latin schools lowered the access cost to higher secondary education, as students could get the basic education in Latin at home before moving to a college town to finish their humanistic education—and, if successful, obtain further philosophical education (Brockliss, 1987, p. 24–26). However, talented students leaving the town for other towns with better education prospects did not necessarily return after completing their education.[25]

One possibility to explain the finding of no significant effect of the existence of a philosophy curriculum could be that small colleges primarily offered an education in logic and metaphysics, instead of a thorough syllabus in natural philosophy and physics. To explore this issue, Table 4.6 accounts for the number of philosophy chairs with the idea

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[24] This set of controls corresponds to the baseline and early knowledge controls used by Squicciarini and Vogtländer (2015).

[25] This interpretation is in line with findings from a recent case study of a French town from 1730 to 1895 that the opening of a school greatly enhanced spatial and social mobility (Wacziarg, Romain, and Blanc, 2019).

that the existence of two philosophy chairs allowed for specialization, with the second chair being devoted to physics, and hence a modern scientific curriculum. The results indeed show that a higher number of philosophy chairs is associated with significantly more subscriptions. Adding one chair increases the subscriptions by roughly 50 percent. At the same time, the results for a humanistic curriculum or Latin grammar education are effectively unchanged. Adding controls for the number of teachers at the college, or for the year of college foundation does not affect the results.

The argument for the role of specialization among philosophy professors implies a particularly important role for the second chair, as the first chair was typically devoted to the basic education in logic and natural philosophy. Table 4.7 presents results for more flexible specifications that account for the different role of philosophy chairs. The results reveal that encyclopedia subscriptions were not affected significantly by the presence of one philosophy chair. However, the existence of a second chair was associated with a significant increase in subscriptions. The existence of distinct chairs for physics and logic has the largest positive effect on subscriptions. Again, controlling for other curricular or resource variables leaves these results unaffected.

Three results emerge from these results: First, cities in which colleges offered the humanistic curriculum exhibited substantially higher subscriptions per capita compared to towns without humanistic education. Second, cities in which colleges offered additionally philosophy education exhibited even higher numbers of subscriptions, although the additional effect is only marginally significant. Third, the intensity and content of philosophy education are key for the demand for codified knowledge.

4.5.3 Robustness: Alternative Explanations and Potential Confounds

The Content of Education. The analysis implicitly assumes that the existence of colleges with particular curricula or chairs appropriately reflects the content of the education conveyed in these institutions. To explore whether the prevalence of a philosophy curriculum or the existence of a chair in physics is indeed consistent with this assumption, we investigated outcomes in terms of the success of alumni of these schools. In particular, we test whether school variables and information about education content predicts whether individuals were born in a town in the period 1650–1750 that eventually turned out to become famous scientists as these individuals are likely to have attended the local college. The hypothesis is that philosophy education, in particular physics education, provided students with the necessary knowledge that enabled them to access and expand the frontier of codified knowledge. The results are shown in Table 4.14. They provide evidence that towns with philosophy education, in particular with more than one chair in philosophy and with distinct chairs for physics and logic, are associated with significantly more births of famous scientists who presumably received their basic education in their town of birth. This suggests that education facilities helped in developing the talents of gifted individuals. Consistent with the previous results, the number of famous scientists is larger the larger the number of chairs in philosophy, and in particular if the school has chairs in physics and logic, while no effect is found for humanistic education or technical chairs, respectively.

The Role of Protestantism. A potential confounder for the effects found so far could be the role of protestantism and the existence of a history of protestant communities. The protestant reformation played an important role for the change in attitudes towards education and science (Becker and Wößmann, 2009). In fact, existing research suggests that the Huguenots, the predominantly Calvinist protestants in France, represented a "knowledge elite" (Hornung, 2014; Squicciarini and Vogtländer, 2015). This could affect the demand for codified knowledge in various ways. The presence of Huguenot communities might have influenced the foundation of schools, and through this the demand for codified knowledge induced by appropriate embodied knowledge. This would be consistent with the hypothesis under consideration and with the results on the determinants of the curriculum shown in Table 4.1, which suggest that the presence of Huguenot communities affected scientific education in the context of religious competition with the Jesuits.

The other possibility is that the presence of Huguenot communities had a direct effect on the demand for codified knowledge, confounding the findings regarding the presence of schools. To account for this, we replicated the estimation in an extended specification that controls for the presence of Huguenot community. Table 4.15 in the Appendix shows that the presence of a Huguenot community during the 18th Century was indeed associated with significantly more subscriptions to the encyclopedia. However, the influence of huguenots seems to be largely orthogonal to that of scientific education, as suggested by the essentially unchanged estimation results for the latter.

Wealth. Another potential confounder is the role of wealth for the acquisition of the encyclopedia. To account for systematic differences in wealth as result of a well-to-do class of business owners, we control for the number of famous people in business occupations born 1700–1799. While the presence of such famous business people is indeed associated with a larger number of encyclopedia subscriptions, the results regarding the presence of schools in general, and a scientific curriculum in particular, are unaffected (see Table 4.16 in the Appendix).

Before the French Revolution, the wealth distribution was highly unequal, with much wealth concentrated in the hands of the nobility. Following Squicciarini and Vogtländer (2015), we therefore use the size of the nobility relative to population in the département of the city as an alternative proxy. The presence or density of nobility is indeed a good predictor for Encyclopedia subscriptions, but the results for the role of human capital as proxied by schools are unaffected by the inclusion of this control variable (see Table 4.17 in the Appendix).

General Demand for Books. Another concern is that the relationship between philosophy education and subscriptions might be driven by a generally larger demand for books instead of a greater demand for books that contain useful knowledge. Alternatively, factors related to the distribution of the Encyclopedia, as for example a varying penetration of the French book market by the Swiss publishing house Société Typographique de Neuchâtel (STN) that published the quarto edition of Encyclopedia might confound the results. To account for systematic heterogeneity due to variation in the general demand for books or due to unequal access to encyclopedia, we also estimated extended specifications with controls for total book sales in the period 1767–94 of the Société Typographique de Neuchâtel (*STN book sales per capita*). While demand for or access to books correlates with encyclopedia subscriptions, the main results remain robust (see Table 4.18 in the Appendix). This means that neither factors related to the distribution of the Encyclopedia nor a generally larger demand for books drive our results.

Another determinant of the demand for codified knowledge is overall literacy. Controlling for literacy among men in 1786 only reveals a weak influence on encyclopedia subscriptions, while leaving the main findings intact (see Table 4.19).

We also find that the presence of a full college is a good predictor for whether a city later hosted a scientific society. As illustrated in Table 4.20, most cities with a scientific society had a college with chairs for philosophy. The establishment of chairs for philosophy predates the foundation of a scientific society in many cities by more than 100 years.

Catholic Religious Institutions. Finally, the historical determinants of schools, in particular the role of the existence of a bishop's see and the competition between Jesuits and Protestants for the foundation of a college and its curriculum, raises the question about the role of institutional factors for the demand for codified knowledge as proxied by encyclopedia subscriptions. The respective estimation results reveal no significant effects of bishop's see or of the joint presence of Huguenots and Jesuits on encyclopedia subscriptions, however, while the main results are unaffected (see Appendix Tables 4.21 and 4.22).

4.6 Codified Knowledge and the Demand for Education

Taken together, the results presented in the previous section provide systematic evidence in favor of the hypothesis that human capital, and in particular scientific education, was a prerequisite for the demand for codified knowledge, once it became widely available and affordable. This establishes evidence for the first aspect of the hypothesis that economic development crucially depends on the interaction between embodied knowledge and the availability of codified knowledge, i.e., for the crucial role of human capital in enabling the application of codified knowledge.

In this section we test the second aspect, the demand for human capital created by the availability of codified knowledge.

4.6.1 Empirical Strategy

The empirical strategy makes use of a peculiar aspect related to the French Revolution, namely the closure of all colleges and the establishment of the central schools in 1795. Central schools offered nine subjects, of which ancient languages, grammar, literature, history, and law comprised a curriculum that resembled a humanistic education, whereas drawing (including technical drawing), mathematics, physics/chemistry and natural history comprised a scientific curriculum.

Students were free to enroll in any subject they wanted and could attend up to 3 courses at a time, and the sequence of instruction was not mandatory so that students were free to enrol to a curriculum of their liking. Using the survey on student enrolment conducted by the Ministry of the interior in 1799 allows us to measure the effect of encyclopedia subscriptions as a measure of the local availability of codified knowledge after 1780 on the demand for scientific education. According to the hypothesis of an interaction between codified knowledge and embodied knowledge, this gives rise to the prediction that the demand for human capital, in particular scientific education, should have been larger in towns with a greater local availability of codified knowledge. In practice, we use newly collected data on enrollment in technical or scientific school subjects in *central schools* 20 years later, during the 1790s, as measure the demand for scientific education, and regress it on encyclopedia subscriptions in the 1770s. To account for a potentially direct effect of pre-revolution schools, we control for the number of philosophy chairs in the local college.

4.6.2 *Encyclopédie* Subscriptions and Enrolment in Science

Table 4.8 shows the results of regressions of enrolment shares as of 1799 in a technical curriculum (in the four technical subjects, including drawing), or in a predominantly scientific curriculum (in the three scientific subjects, excluding drawing) on encyclopedia sales in the 1770s. Since the enrolment data are only available on the level of *départements*, encyclopedia sales in these regressions have been aggregated to the *département* level as well.[26] The results show that a higher prevalence of codified knowledge entails a greater demand for technical or scientific education. In particular, a 10-percent higher subscription to the encyclopedia was associated with a 3-4 percent higher enrolment rate in technical or scientific subjects. This holds while controlling for the full set of geographic and socio-economic controls aggregated at the department level.[27]

While encyclopedia subscriptions have significantly positive effect on the demand for scientific education, the presence of several philosophy chairs, with some dedicated to physics, prior to the revolution does not significantly affect the enrolment to a scientific curriculum. Similarly, including literacy rates in 1786 has no significant effect. This supports the conjecture that it is the availability of codified knowledge that determines the demand for the relevant embodied knowledge rather than some diffuse persistence of educational institutions.

4.7 Implications for Economic Development

Having provided evidence for the hypothesis that embodied scientific knowledge was a prerequisite for the demand for codified knowledge, and that a greater availability of codified knowledge increased the demand for embodied scientific knowledge as reflected by enrolment in corresponding subjects, this section explores the question whether this interaction had implications for economic development.

4.7.1 Empirical Strategy

In this section we test the hypothesis that school-based education was conducive to (regional) economic development by allowing for the adoption of frontier knowledge. Hence, the conjecture is that it was the interaction between embodied knowledge and the sudden expansion in the availability of codified knowledge through the publication of the encyclo-

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[26] In particular, we compute the weighted average of encyclopedia sales per capita on the *département* level, with city population sizes as weights.

[27] The regression results for the full set of controls are contained in Appendix Table 4.23.

pedia that generated an acceleration in growth. An important aspect is again that education content should have mattered and that, in particular, the prevalence of scientific literacy as compared to any literacy (or proficiency in ancient languages) was key for the adoption and adaptation of frontier knowledge.

The problem with providing evidence for the growth implications is twofold. On the empirical side, in the absence of reliable statistics on regional or town-specific production or value added, the analysis will necessarily have to rely on imperfect proxies for economic development. On the historical side, the turmoil related to the French Revolution makes it difficult to single out particular factors related to growth during the late 18th century in France. To overcome these problems, we present several pieces of evidence that, in combination, provide a largely coherent picture of the development patterns during this time.

The empirical strategy to test the relevance of the interaction of human capital and codified knowledge for economic growth is based on a similar logic as the strategy adopted in Section 4.5. In particular, we treat the cross-sectional distribution of development across towns in 1750 as predetermined and not affected by the widespread availability of codified knowledge in terms of the encyclopedia. Since income dynamics in the largely Malthusian context prior to the demographic transition in France are largely reflected in population dynamics (Ashraf and Galor, 2011; Galor, 2012), we measure the implications for development by considering the difference in city population growth over the period when codified knowledge became widely available, 1750–1800, relative to before, 1700-1750. In terms of human capital, we again apply an intention-to-treat logic, using the exposure to colleges and their curriculum and structure of chair denominations (professors for philosophy, logic, and physics) as proxy. As shown in the evidence regarding the determinants of schools in Section 4.4, schools and their curriculum were largely predetermined around 1750, before the publication of the encyclopedia. This publication made codified knowledge available everywhere, but demand was particularly high in towns with schools offering modern scientific education as suggested by the evidence presented in Section 4.5.

The testable implication from these considerations is that schools with scientific curriculum were conducive for development particularly once they enabled the adoption of codified knowledge, i.e., after 1750. We test this conjecture using a differences-in-differences logic, using cross-sectional variation in the differences of growth rates before and after 1750, as well as using a panel specification interacting cross-sectional variation in the availability of schools with time variation in the availability of codified knowledge, in a specification with city and period fixed effects.

4.7.2 Schools, Codified Knowledge, and Development

As a first test of this conjecture, we regress the difference in city population growth over the period 1750-1800, when the encyclopedia became available, relative to the period 1700-1750, when codified knowledge in terms of the encyclopedia was not widely available, on an indicator variable for the presence of a college in a city, or on the education content, proxied by the curriculum in the college or the availability of philosophy or physics chairs. The results in Table 4.9 reveal that the growth acceleration was more pronounced in cities with a college. As with subscriptions, this effect is mainly related to humanistic or philosophy education being offered and the largest effect is found for cities with colleges that had distinct chairs for physics and logic.

We next consider panel regressions for the period 1500 to 1850. This allows us to include fixed effects for towns and periods, thus controlling for time invariant city-specific factors and for a general trend related to industrialization or demographic development. Moreover, this allows us to test the conjecture of the importance of the interaction between embodied knowledge and codified knowledge, keeping in mind that codified knowledge only became widely available with the publication of the encyclopedia in the second half of the 18th century. To test this, we adopt a differences-in-differences strategy, coding the period after 1750 as the treatment period. The results in Table 4.10 deliver a similar picture. Education in terms of the number of philosophy chairs has no effect on population growth before the expansion of the stock of available knowledge in terms of the publication of the encyclopedia, whereas a higher number of philosophy chairs implies faster growth after 1750.

4.7.3 Robustness: Alternative Specifications and Outcomes

Alternative Specification. The results are similar when considering variation in city growth over the period 1750-1850. Towns with a college exhibited significantly faster population growth than other towns, even when accounting for the full set of controls for city characteristics, see 4.24. Also with this specification, the curriculum offered in the colleges matters for development, with the number of philosophy chairs, and particularly the existence of distinct chairs for physics and logic, indicating a decidedly scientific curriculum, were associated with faster economic development after 1750, see Table 4.25.

Wealth. In order to rule out that the presence of full colleges and colleges with a scientific curriculum picks up variation in the initial distribution of wealth that itself correlates with growth, we also estimated extended specifications with controls for the number of famous people in business occupations, born 1700–1799, paralleling the analysis in Section 4.5. The results indeed reveal a significant effect of the presence of famous business people on growth, but the effects of the school variables remain unaffected (see Appendix Table 4.26.

Alternatively, we control for the the density of nobles at the département level. Again, the presence of more nobles is associated with faster growth, without affecting the results for the school variables (see Appendix Table 4.27.

Non-linear Growth Effects. To rule out that population growth exhibits non-linear dynamics with respect to the initial population size of a town, for instance as consequence of the demographic transition (Cervellati, Matteo, and Sunde, 2011), we also estimated an extended specification accounting for a fourth order polynomial in log population size in 1750. Again, this leaves the estimation results regarding the growth effects of the schooling variables unaffected (see Appendix Table 4.28).

Falsification. To rule out additional concerns of potential endogeneity of the education variables, we also conducted a placebo analysis. This analysis is based on the idea that, in order to account for the estimation results, a third factor would have to be correlated with school and chair foundations during 16th and 17th century; would have to be correlated with city growth only after 1750 but not before; and must not be captured by any of the other control variables included in the empirical specification. The presumably hardest test for the hypothesis of the crucial role of the interaction between school-based human capital and codified knowledge for economic development is therefore to rule out that schools predict growth before the dissemination of codified knowledge through the encylopedia. This motivates the falsification test that, to support the conjecture of the interaction, schools should not predict city growth before the availability of the encyclopedia. We implement this test by estimating the same specification as before, but using city growth over the period 1700–1750 as the dependent variable. The conjecture is that, if the hypothesis is true, then the coefficient on schools and curricular content should be not significantly different from zero. The empirical analysis indeed delivers no evidence for an effect of the availability of schools with scientific education, providing further evidence in support of the role of the interaction between embodied knowledge and the availability of codified knowledge (see Table 4.29).

Alternative Outcomes. To further explore the implications for long-run development, we collected alternative data on income per capita at the level of *départments* for the 19th century from various sources. While these data provide direct measures of income and do not rely on the assumption of a Malthusian dynamics, they do not exhibit variation over time as they are only available for various points in time during the 19th century.

Nevertheless, we believe the analysis is insightful as variation in incomes during the 1860s reflects development differences. With controls for development levels earlier in the 19th century, this provides us with the possibility to grasp some of the development dynamics.

Table 4.30 presents the results for the regression of four different measures of log income per capita in 1861 on the availability of philosophy education in 1750 (aggregated to the level of *départments* using population shares of towns as weights). The results show that, even conditioning on other geographic and socio-demographic controls, in particular schooling enrolment in 1837 and population density in 1851, the access to full colleges with a curriculum in philosophy in 1750 is associated with significantly higher income levels more than a century later.

4.7.4 Additional Results: Evidence on the Channel

As the final step of the analysis, we test directly whether school-based human capital affects growth through its interaction with codified knowledge. In particular, we demonstrate the consequences of the interaction between the available human capital and the adaptation of codified knowledge for economic development in two ways. The first leverage the data structure and presents the results of a two-stage regression framework, and the second leverages novel data on innovation from patents filed during the early 1800s in France.

Two-stage analysis. The two-stage analysis makes use of the particular data structure, with historically determined cross-sectional variation in the existence of schools with a scientific curriculum and time variation in the availability of codified knowledge related to the publication of the encyclopedia. Notice that subscriptions to the encyclopedia are a reflection (or an outcome) of this interaction by measuring the demand for codified knowledge once it is available. This implies that simply running a regression of growth on an interaction term of school variables and subscriptions is not able to identify the role of the interaction of embodied and codified knowledge for development.[28]

Instead, we proceed in two steps. First, we demonstrate that encyclopedia subscriptions indeed correlate with subsequent city growth. This correlation is shown in Column (1) of Table 4.12 and has been documented previously by Squicciarini and Vogtländer (2015), who interpreted subscriptions to the encyclopedia as manifestation of the existence (and size) of knowledge elites. In view of the previous results shown here, an alternative interpretation is

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[28] Moreover, unreported pooled regressions of city growth on subscriptions to the encyclopedia and school variables suggest that encyclopedia subscriptions are the main correlate of city growth, while the existence of colleges or scientific education facilities show no significant independent association with city growth once subscriptions are accounted for, which in a way confirms the findings of Squicciarini and Vogtländer (2015).

that subscriptions reflect the (realized) demand for codified knowledge that became widely available for the first time in the form of the encyclopedia. Moreover, in view of the crucial role of access to school-based education, and particularly a scientific curriculum, for this demand, we can explore the interaction between embodied and codified knowledge by using the encyclopedia subscriptions that are predicted by the school infrastructure. Columns (2)-(5) of Table 4.12 present the results for different school characteristics as instrument for encyclopedia subscriptions. Throughout, the first stage relationship is strong, and the coefficient of encyclopedia sales in the outcome equation is larger than in the OLS specification. Additional analysis reveals qualitatively similar results for the alternative measures of development in terms of income levels per capita in the 1860s (see Appendix Table 4.31).

To further illustrate the implication of the interpretation of subscriber density as demand for codified knowledge instead of a proxy for upper-tail knowledge, one would expect that knowledge elites subscribing to the Encyclopedia were present also prior to 1750. Moreover, there is little reason to believe that the spatial distribution of knowledge elites has changed dramatically around the middle of the 18th century. This raises the question whether subscription density indeed has an independent effect on economic development, or whether it is the existence of colleges that provide scientific education that primarily determine economic development. Regressions for growth during the placebo period 1700-1750 reveal no significant coefficients for the OLS and for the IV estimations (see Appendix Table 4.32), in line with the hypothesis of an interaction between school-based education and the dissemination of codified knowledge.

It should be noticed that this IV strategy is not meant to identify the causal effect of encyclopedia subscriptions on growth. In fact, it is unlikely that the exclusion restriction that would have to hold in this case is indeed satisfied, even in the specifications with an extensive set of control variables. Nevertheless, the results are insightful as they document that the (historically determined) variation in schools and curricula accounts for the demand for codified knowledge and exhibits a correlation with subsequent economic development that works *through* this demand for codified knowledge.

Generation of new knowledge: Patents. The literature on technology-driven endogenous growth stipulates an important role of human capital for innovation (Mokyr, 2002; Jones, 2005), but evidence for such a link during the early phases of development is scant. Moreover, the conjecture that embodied knowledge, particularly of a scientific curriculum, affected innovation and patenting activity has not been tested as consequence of the lack of data. Here, we leverage novel data on patenting during the first half of the 19th century in

France to document a correlation between scientific education and patenting dynamics. In particular, we make use of city-level data on patenting over time using newly digitized data on patents between 1791 and 1855. Before the French Revolution, patents were granted discretely by royal "*privilèges*" and no data are available (see also Section 4.3).

The analysis shows that patents grew faster in cities with a college that offered a scientific curriculum, as reflected by the existence of a designated chair for physics prior to 1789, see Figure 4.5 and Table 4.13.

4.8 Concluding Remarks

This paper has provided novel evidence for an interaction between embodied knowledge and codified knowledge in the process of development. We first set out by exploring the determinants of secondary education institutions in pre-revolution France, documenting that college foundations were closely linked to historical factors related to the church, whereas the adoption of a scientific curriculum was related to religious competition between protestants and Jesuits in the phase of the counter-reformation. This implies that the availability of schools with scientific particular curriculum was predetermined at the time of the enlightenment. Our second set of results shows that the availability of an appropriate basis of human capital, as reflected by schools with scientific curriculum, was a key requirement for the adoption of codified knowledge as reflected by subscriptions to the Encyclopedia. The third set of results provides evidence for the reverse direction of the interaction between embodied and codified knowledge, by documenting that the demand for scientific education, reflected in course enrolment in post-revolution education institutions, has been influenced by the availability of codified knowledge, reflected in Encyclopedia subscriptions. Our last set of results indicates that the interaction between embodied and codified knowledge had implications for economic development and innovation.

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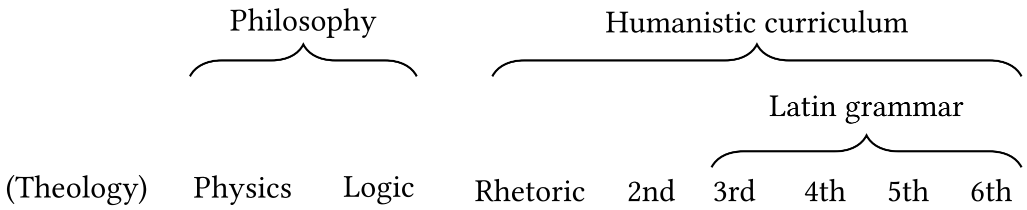
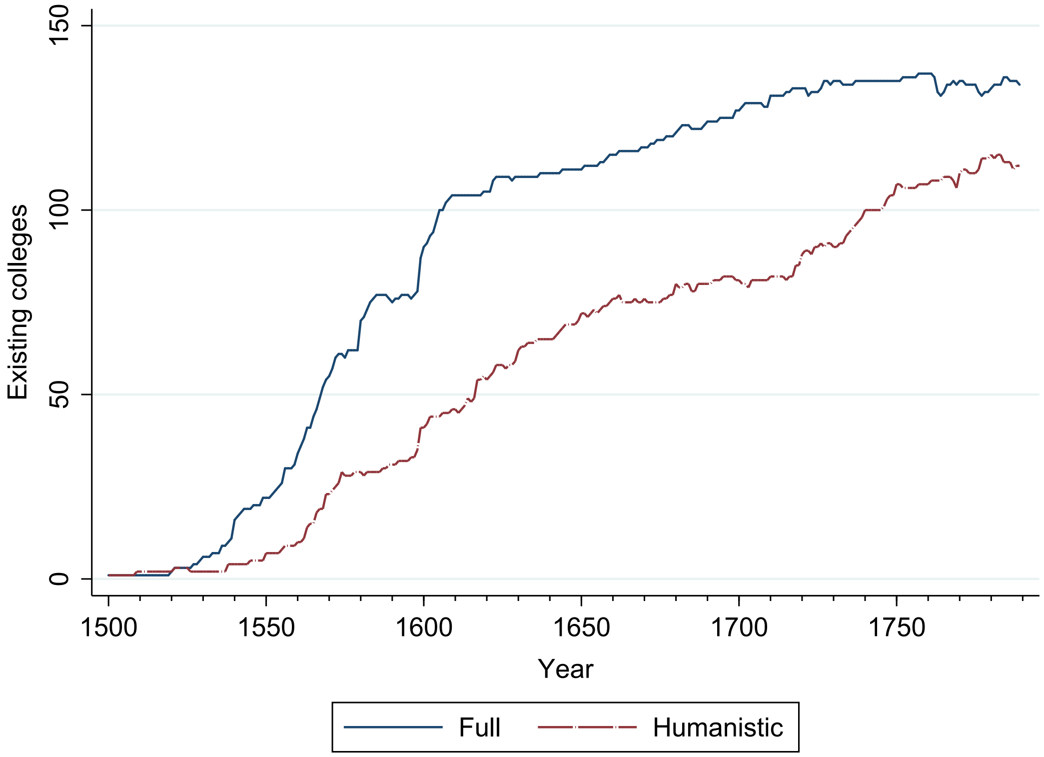
Figures and Tables



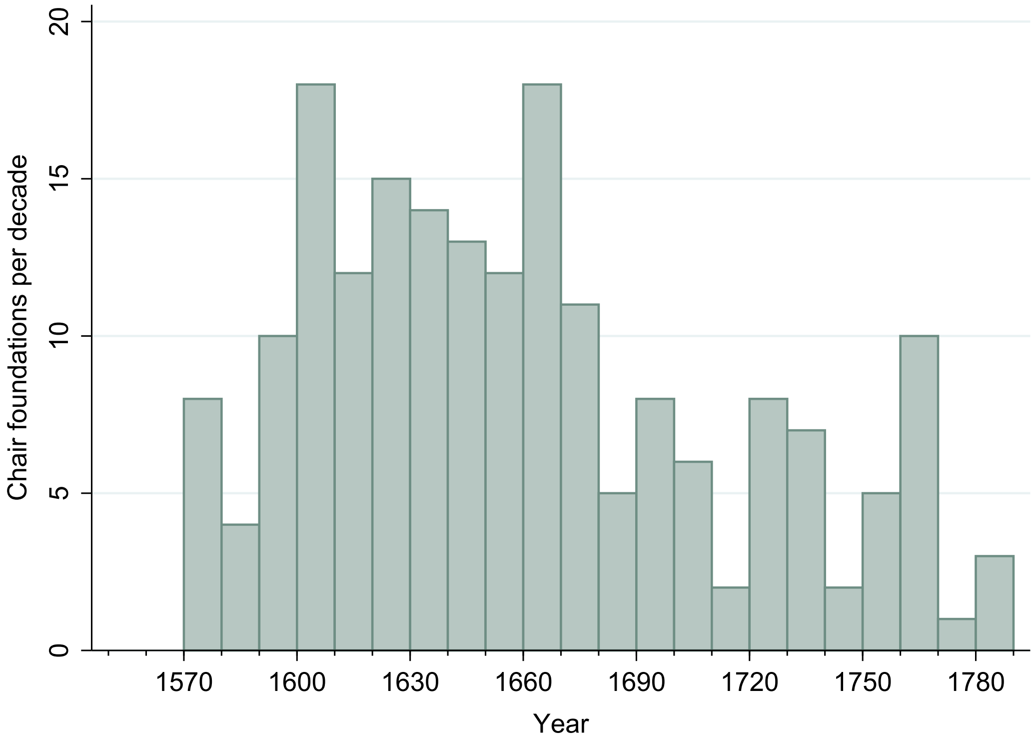
Small Latin schools offered the introductory curriculum (6th grade up to 3rd). Humanistic colleges offered the complete Latin curriculum, grammar as well as composition (2nd) and rhetoric (1st). Full colleges offered philosophy additionally to the humanistic Latin curriculum. Some full colleges offered on top a three-year course in theology. Colleges with sufficient funding employed one teacher per class. Colleges with less funding either employed one teacher per two Latin classes, or dropped the 6th and sometimes even 5th class. Schools with very limited funding offered only the lower Latin grammar classes.

Figure 4.1: French education system before the Revolution



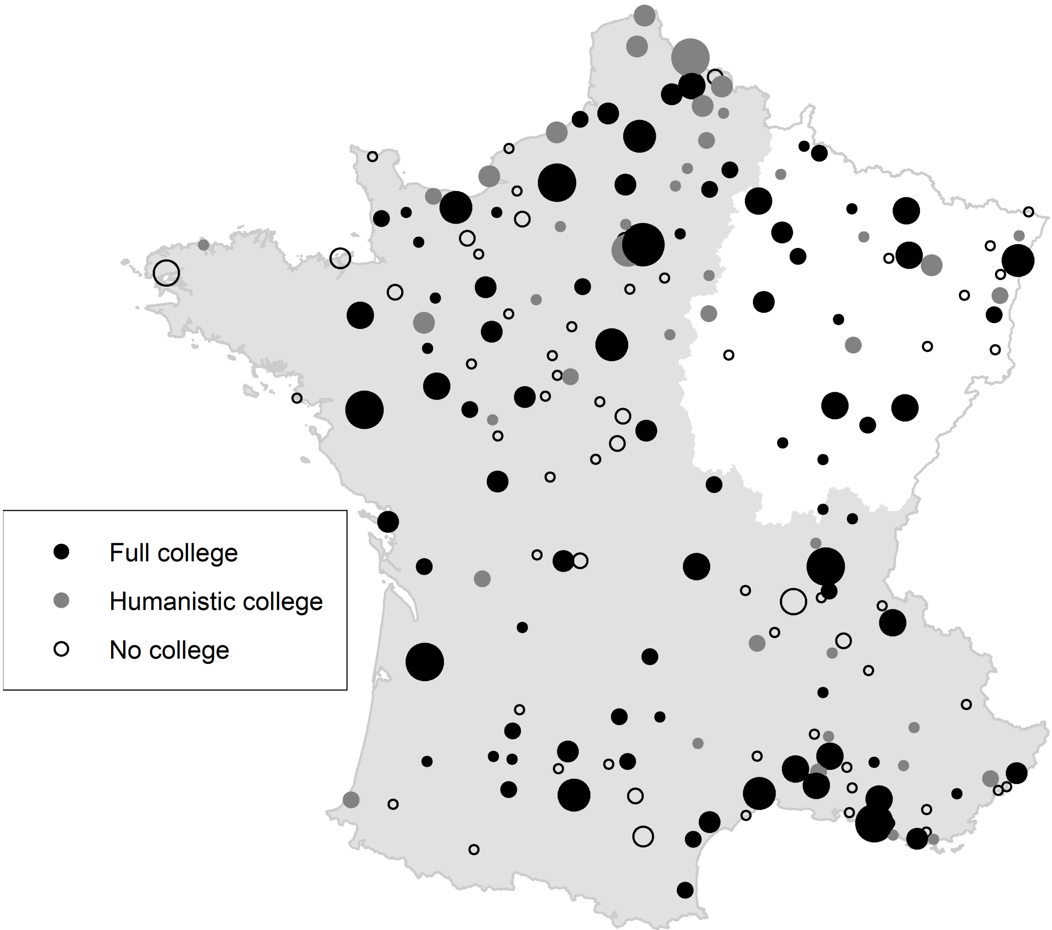
The graph shows that most French colleges which existed at the time of Enlightenment had been founded by 1650. The sample excludes colleges in Paris and the East of France. Humanistic colleges offered humanistic and Latin grammar education and had at least three permanent teachers. Full colleges offered philosophical education in addition to humanistic and Latin grammar education. The distinction between humanistic and full colleges is not always sharp until about 1600. The jump at 1600 occurs because college foundations during 16th century without exact information have been dated on 1599.

Figure 4.2: College Foundations in France, 1500–1789



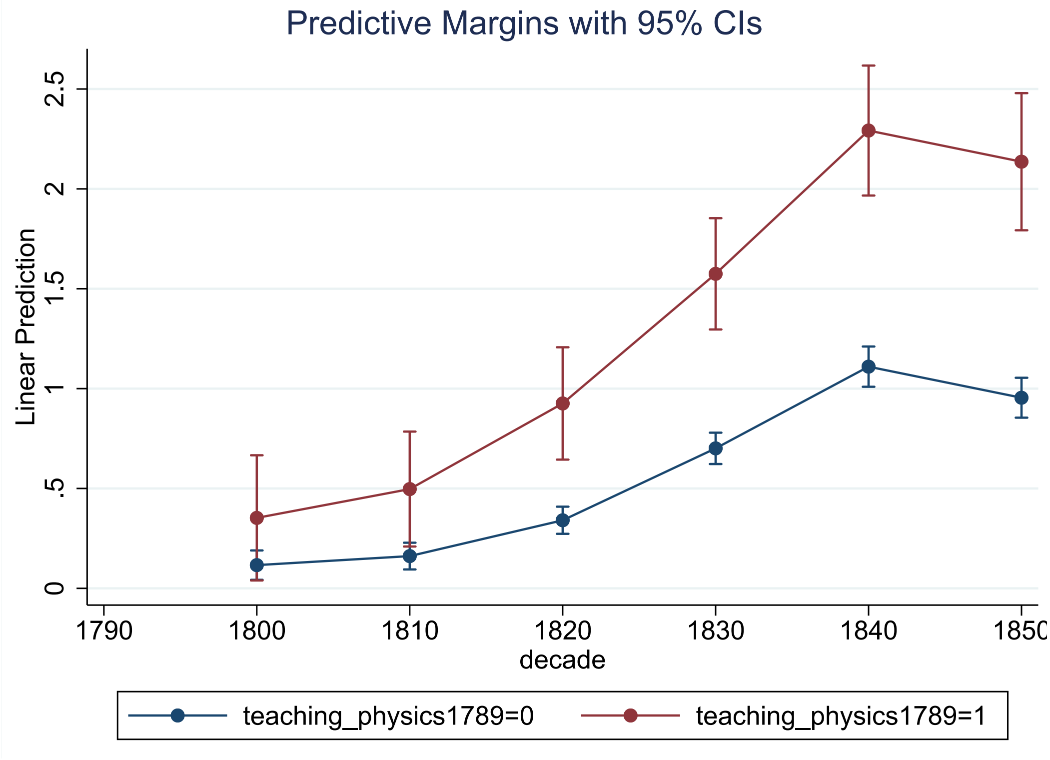
The graph shows that, similar to the establishment of colleges, the foundation of chairs for philosophy at French colleges largely preceded the time of Enlightenment. The sample excludes chairs for philosoph in Paris and the East of France. Chairs dedicated to subdisciplines logic or physics are included. Philosophy education may have started prior to the foundation of a chair.

Figure 4.3: Foundations of Chairs for Philosophy



The map reports the presence of a college for 189 cities with reported population in 1750 from Bairoch et al. (1988). The cities constitute the sample of the main regression in section ??. The marker size is positively monotonically related to city size. The white area is the region East, for which we do not have more detailed information on colleges. The map shows (i) that larger towns were more likely to have a college, and (ii) that the variation in full vs humanistic vs no college is not clustered regionally.

Figure 4.4: Cities in France



The graph shows the linear prediction of the number of patents during a decade separately for cities with a college that had a designated chair for physics and cities with no such college. The prediction is based on regressions with decade and city fixed effects and the plot represents the estimated decade dynamics.

Figure 4.5: Dynamics of Patents by School Type

Table 4.1: Determinants of College Foundations

	Any college	Full college	Humanistic college
Bishop's see	0.328***	0.421***	−0.092
	(0.046)	(0.062)	(0.058)
Latin school by 1500	0.211***	0.002	0.209***
	(0.052)	(0.066)	(0.066)
University in 1500	−0.009	0.169*	−0.178**
	(0.068)	(0.102)	(0.080)
Printing Press by 1500	0.101	0.049	0.051
	(0.063)	(0.087)	(0.079)
Huguenots (16th cent.)	0.119**	0.111**	0.008
	(0.052)	(0.050)	(0.048)
Log Population 1550	0.057**	0.081***	−0.025
	(0.023)	(0.028)	(0.026)
Controls	Yes	Yes	Yes
Observations	332	332	332
Adjusted R^2	0.250	0.302	0.024
Mean of dep. var.	0.614	0.404	0.211

Sample excludes Paris and East of France. Controls: see text.

Table 4.2: Determinants of Curriculum

	# philo chairs	Physics	Theology
Bishop’s see	0.420***	0.086	0.247***
	(0.148)	(0.068)	(0.081)
Latin school by 1500	−0.122	0.079	−0.046
	(0.148)	(0.070)	(0.078)
University in 1500	0.381	0.088	0.132
	(0.270)	(0.156)	(0.144)
Printing Press by 1500	0.131	0.126	0.073
	(0.239)	(0.131)	(0.130)
Huguenots (16th cent.)	0.210	0.057	0.069
	(0.156)	(0.070)	(0.085)
Log Population 1550	0.178**	0.064*	0.046
	(0.075)	(0.035)	(0.042)
Controls	Yes	Yes	Yes
Observations	158	158	158
Adjusted R^2	0.184	0.128	0.121
Mean of dep. var.	1.063	0.215	0.361

Estimates conditional on any college. Sample excludes Paris and East of France. Controls: see text.

Table 4.3: Determinants of Curriculum

	# philo chairs		Physics		Theology	
	(1)	(2)	(3)	(4)	(5)	(6)
Jesuit college	0.493***	−0.068	0.182**	−0.044	0.208**	0.045
	(0.146)	(0.265)	(0.073)	(0.109)	(0.087)	(0.138)
Jesuits x Huguenots (16th)		0.828***		0.333**		0.240
		(0.297)		(0.135)		(0.171)
Huguenots (16th cent.)	0.284*	−0.088	0.077	−0.073	0.108	−0.000
	(0.160)	(0.212)	(0.072)	(0.079)	(0.087)	(0.112)
Log Population 1550	0.111	0.082	0.036	0.024	0.023	0.014
	(0.080)	(0.077)	(0.036)	(0.035)	(0.042)	(0.042)
Knowledge demand controls	Yes	Yes	Yes	Yes	Yes	Yes
Geography controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	156	156	156	156	156	156
Adjusted R^2	0.22	0.25	0.18	0.20	0.10	0.11
Mean of dep. var.	1.077	1.077	0.218	0.218	0.365	0.365

Estimates conditional on any college. Sample excludes Paris and East of France. Controls: see text.

Table 4.4: College Education and the Diffusion of Codified Knowledge

	Dep. variable: Log Encyclopedia sales p. c.			
	(1)	(2)	(3)	(4)
Any college	0.740***	0.476***	0.428***	
	(0.089)	(0.109)	(0.116)	
Number of teachers				0.054***
				(0.017)
Log Population 1750		0.105	0.208*	0.104
		(0.107)	(0.117)	(0.126)
University in 1750		0.338	0.334	0.278
		(0.229)	(0.249)	(0.257)
Latin school by 1500		−0.109	−0.068	−0.021
		(0.144)	(0.148)	(0.145)
Printing Press by 1500		0.343*	0.320	0.319
		(0.189)	(0.224)	(0.223)
Roman road		0.263**	0.207*	0.199
		(0.113)	(0.124)	(0.125)
Atlantic Port		0.109	−0.017	0.053
		(0.209)	(0.210)	(0.214)
Mediterranean Port		0.265	0.228	0.242
		(0.380)	(0.390)	(0.380)
Navigable River		−0.113	−0.147	−0.123
		(0.202)	(0.207)	(0.192)
Non French Speaking		−0.302*	0.065	0.163
		(0.162)	(0.171)	(0.192)
Observations	187	187	154	154
Adjusted R^2	0.163	0.241	0.250	0.251

Table 4.5: Education Content and the Diffusion of Codified Knowledge

	Dep. variable: Log Encyclopedia sales p. c.			
	(1)	(2)	(3)	(4)
Philosophy education	0.478^{***}	0.270	0.186	0.186
	(0.156)	(0.174)	(0.218)	(0.218)
Humanistic education	0.504^{***}	0.419^{***}	0.378^{**}	0.378^{**}
	(0.124)	(0.130)	(0.145)	(0.145)
Latin grammar education	-0.156^{**}	−0.168	−0.160	−0.160
	(0.075)	(0.102)	(0.106)	(0.106)
Theology education			0.137	0.137
			(0.208)	(0.208)
Knowledge demand controls		Yes	Yes	Yes
Geography controls		Yes	Yes	Yes
Observations	187	187	154	154
Adjusted R^2	0.21	0.25	0.25	0.25
Mean of dep. var.	0.602	0.602	0.569	0.569

Table 4.6: The Number of Philosophy Chairs and the Diffusion of Codified Knowledge

	Dep. variable: Log Encyclopedia sales p. c.			
	(1)	(2)	(3)	(4)
Number of philosophy chairs	0.492^{***}	0.347^{***}	0.508^{***}	0.495^{***}
	(0.062)	(0.120)	(0.150)	(0.146)
Humanistic education		0.258^{**}	0.563^{***}	0.549^{***}
		(0.116)	(0.196)	(0.184)
Latin grammar education		−0.157	−0.032	
		(0.102)	(0.113)	
Theology education		−0.085	0.005	−0.006
		(0.191)	(0.188)	(0.174)
Number of teachers			-0.082^{**}	-0.103^{***}
			(0.040)	(0.038)
Year of first college/Latin school				-0.004^{***}
				(0.001)
Knowledge demand controls		Yes	Yes	Yes
Geography controls		Yes	Yes	Yes
Observations	154	154	154	128
Adjusted R^2	0.316	0.312	0.328	0.353

Table 4.7: Scientific Education and the Diffusion of Codified Knowledge

	Dep. variable: Log Encyclopedia sales p. c.			
	(1)	(2)	(3)	(4)
One philosophy chair	0.282*	0.101	0.241	0.297
	(0.156)	(0.194)	(0.224)	(0.216)
Two philosophy chairs	0.822***	0.548*	0.765**	0.816***
	(0.201)	(0.285)	(0.318)	(0.304)
Physics and Logic chairs	1.173***	0.844***	1.080***	1.128***
	(0.173)	(0.274)	(0.316)	(0.313)
Humanistic education		0.346***	0.563***	0.478**
		(0.126)	(0.197)	(0.187)
Latin grammar education		−0.146	−0.056	
		(0.102)	(0.112)	
Theology education		−0.101	−0.034	−0.029
		(0.196)	(0.199)	(0.188)
Number of teachers			−0.060	−0.090**
			(0.039)	(0.038)
Age of college (in 1750)				0.002***
				(0.001)
Knowledge demand controls		Yes	Yes	Yes
Geography controls		Yes	Yes	Yes
Observations	154	154	154	154
Adjusted R^2	0.310	0.314	0.321	0.344

Table 4.8: Codified Knowledge and the Demand for Scientific Education

	Technical enrolm. share			Science enrolm. share		
	(1)	(2)	(3)	(4)	(5)	(6)
Log Encyclopedia sales p.c.	0.298**	0.266**	0.273**	0.303**	0.357***	0.358***
	(0.135)	(0.120)	(0.117)	(0.115)	(0.108)	(0.110)
Log Philosophy chairs p.c.		2.192	2.172		−3.763	−3.987
		(3.667)	(3.313)		(3.843)	(3.806)
Literacy 1786			−0.099			−0.014
			(0.109)			(0.113)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	53	53	51	53	53	51
Adjusted R^2	0.11	0.09	0.12	0.07	0.06	0.04
Mean of dep. var.	0.68	0.68	0.68	0.52	0.52	0.52

Observation: *département.*

Table 4.9: College Education, Curriculum, and Dynamics of City Growth

	Dep. variable: Log city population			
	(1)	(2)	(3)	(4)
Number philosophy chairs	−0.005 (0.068)	−0.044 (0.069)	−0.043 (0.069)	−0.031 (0.071)
Number philosophy chairs x *post 1750*		0.068* (0.036)	0.074* (0.041)	
Number philosophy chairs x *post 1700*				0.033 (0.047)
City FE	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes
Controls			Yes	Yes
Observations	893	893	893	893
Adjusted R^2	0.768	0.769	0.779	0.778

Table 4.10: College Education, Codified Knowledge, and Development: Panel Estimation

	Dep. variable: Log city population			
	(1)	(2)	(3)	(4)
Number philosophy chairs	−0.005 (0.068)	−0.044 (0.069)	−0.043 (0.069)	−0.031 (0.071)
Number philosophy chairs x *post 1750*		0.068* (0.036)	0.074* (0.041)	
Number philosophy chairs x *post 1700*				0.033 (0.047)
City FE	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes
Controls			Yes	Yes
Observations	893	893	893	893
Adjusted R^2	0.768	0.769	0.779	0.778

Table 4.11: Implications for Development in the 19th Centuries: Alternative Measures

	Dep. variable: Log Income per capita 1861			
	Delefortrie & Morice (1959)	Combes et al. (2011)	Bazot (2014)	Diéz-Minguela & Llopis (2017)
Philosophy education (pop. share)	0.119**	0.127**	0.156**	0.163**
	(0.055)	(0.062)	(0.061)	(0.063)
Schooling rate 1837	0.421***	0.450***	0.536***	0.520***
	(0.097)	(0.115)	(0.111)	(0.110)
Log population density 1851	−0.024	0.173***	0.204***	0.243***
	(0.058)	(0.063)	(0.069)	(0.067)
Mediterranean Port	0.126	0.222***	0.418***	0.363***
	(0.090)	(0.062)	(0.053)	(0.080)
Navigable River	0.166***	0.183***	0.284***	0.190***
	(0.044)	(0.056)	(0.056)	(0.055)
Non-french speaking	−0.188***	−0.205***	−0.115	−0.114*
	(0.059)	(0.048)	(0.083)	(0.059)
Paris	1.408	−4.231**	−4.906**	−5.974***
	(1.698)	(1.813)	(2.000)	(1.939)
Constant	−1.053***	−1.153***	−1.310***	−1.285***
	(0.064)	(0.079)	(0.073)	(0.074)
Controls	Yes	Yes	Yes	Yes
Observations	80	80	80	80
Adjusted R^2	0.439	0.480	0.605	0.593

Table 4.12: The Interaction between Schools, Demand for Codified Knowledge, and City Growth 1750-1850

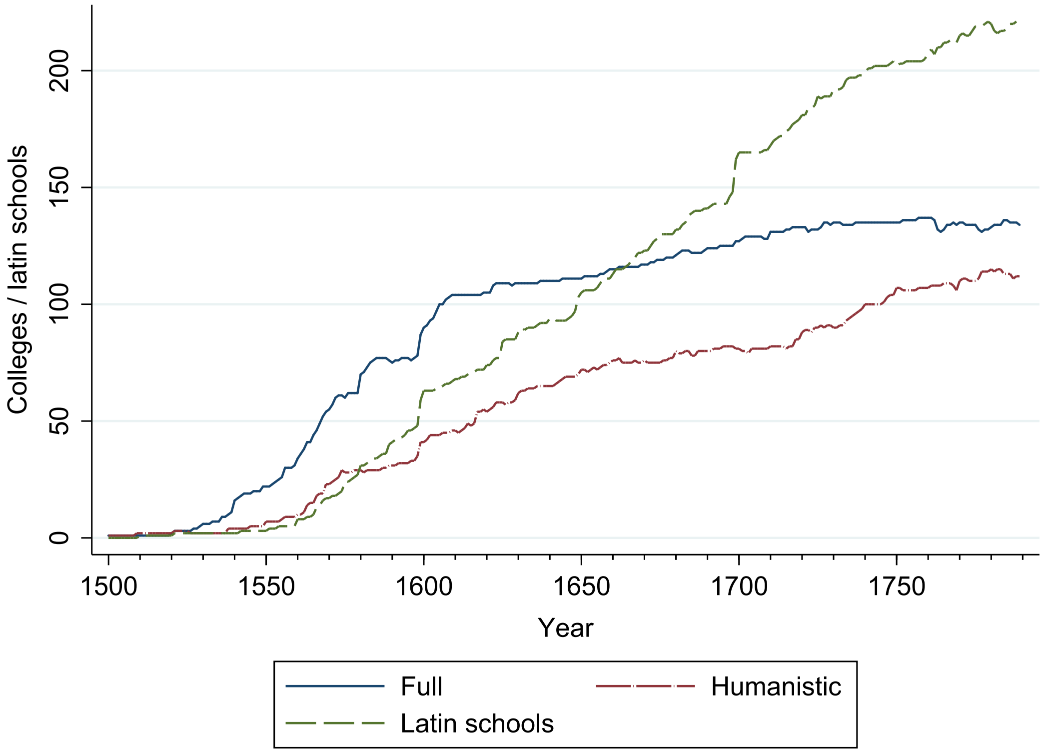
	OLS	IV			
	(Squicciarini & Voigtländer)	Any college	Education types	Number chairs	Physics & Logic
Log Encyclopedia sales p.c.	0.184***	0.404*	0.291**	0.225***	0.192**
	(0.040)	(0.223)	(0.132)	(0.086)	(0.088)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	154	154	154	154	154
First stage F		15.8	10.7	32.7	8.3

Table 4.13: Schools, Curriculum, and Patents 1800-1850

	Dep var: Log (patents of invention + 1)			
	Philo chairs	Encyclopedia	Encyclopedia= Philo chairs	Physics by 1789
1800	0.110*	0.121	0.299	0.244
	(0.066)	(0.075)	(0.185)	(0.181)
1810	0.145**	0.158**	0.389**	0.346**
	(0.062)	(0.075)	(0.175)	(0.168)
1820	0.314***	0.353***	0.914***	0.605***
	(0.061)	(0.074)	(0.172)	(0.166)
1830	0.374***	0.586***	1.021***	0.914***
	(0.063)	(0.073)	(0.169)	(0.166)
1840	0.504***	0.709***	1.331***	1.232***
	(0.071)	(0.084)	(0.195)	(0.188)
1850	0.477***	0.648***	1.285***	1.229***
	(0.075)	(0.093)	(0.208)	(0.197)
City FE	Yes	Yes	Yes	Yes
Decade FE	Yes	Yes	Yes	Yes
Observations	1869	1351	1078	1869
R^2	0.723	0.800	0.014	0.725

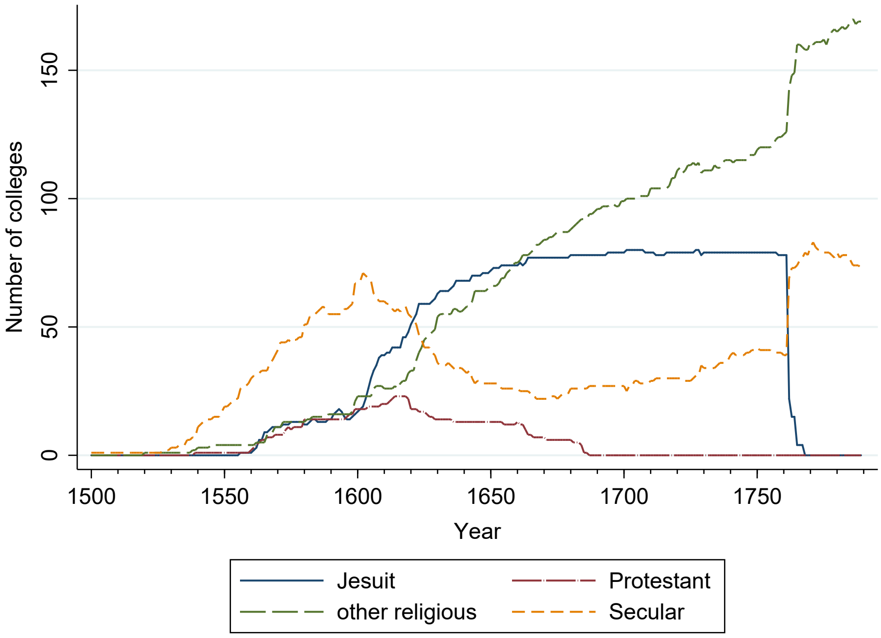
4.A Additional Evidence and Robustness

This section provides attional graphs, maps, and figures as well as robustness analyses in suppport of the main argument.



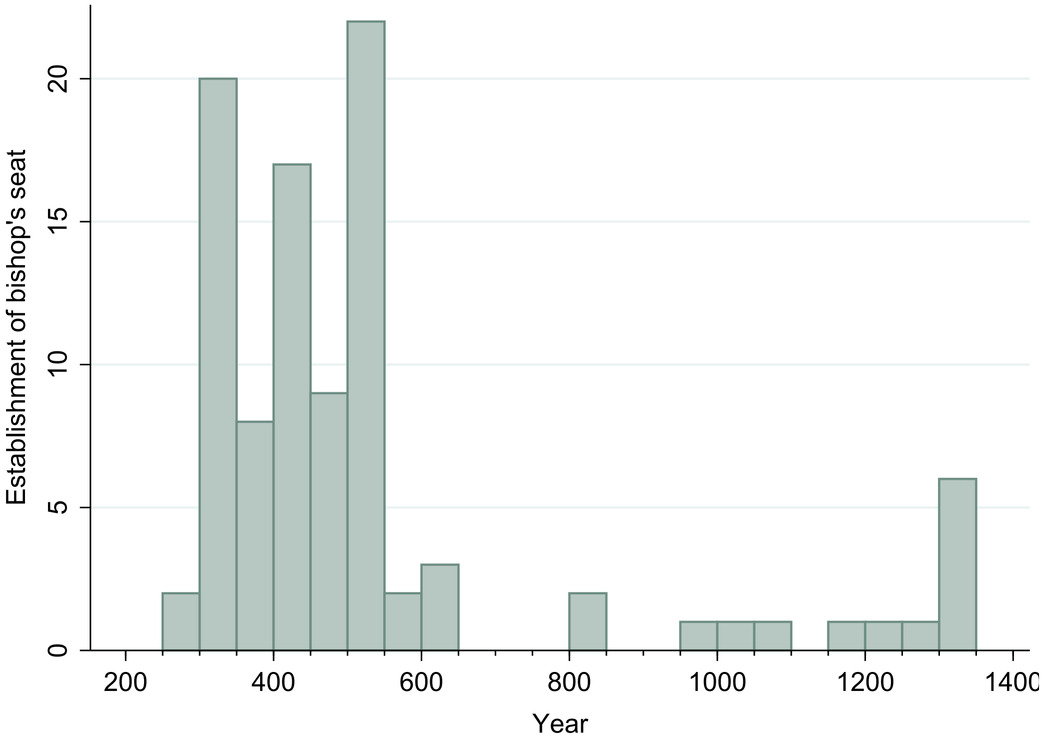
The graph shows the number of existing French colleges between 1500 and 1789, excluding Paris and the East of France. Latin schools were small schools offering latin education in the "style of Paris" which had one or two permanent teachers. Humanistic colleges had at least three permanent teachers for latin. Full colleges offered education in philosophy in addition to the humanistic curriculum.

Figure 4.6: College and latin school foundations, 1500–1789



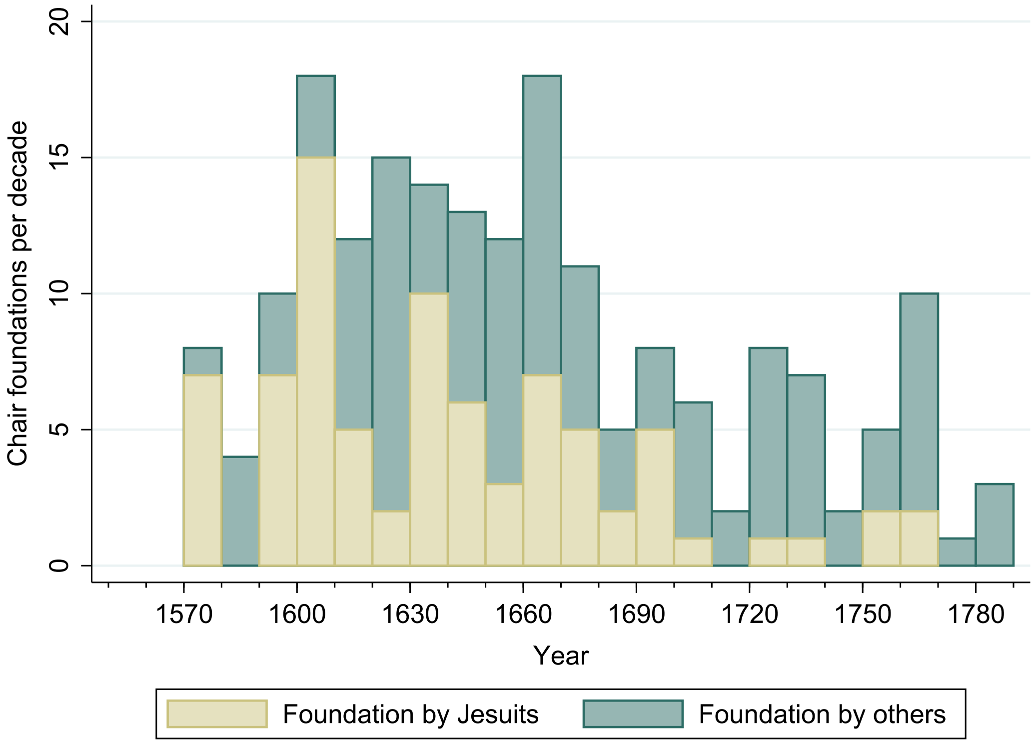
The graphs show the affiliation of the teachers in French full and humanistic colleges between 1500 and 1789, excluding Paris and the East of France. “Other religious” includes professional teaching orders other than Jesuits (e. g., Oratorians and Doctrinairies), religious orders (e. g., Benedictines or Augustinian Canons), and priests.

Figure 4.7: Teaching institutions in France, 1500–1789



The graph shows that most bishoprics have been founded in the late Roman period between 300 and 550 CE. Michaels and Rauch (2017) show that the Roman city network persisted in France, and that the locational characteristics which determined city location during the Roman period were suboptimal for city growth and prosperity during the Medieval and Early Modern period.

Figure 4.8: Dates of Establishment of Bishop's Sees in France



The graph shows the foundations of chairs for philosophy (including the subdisciplines logic and physics) at French colleges under the Jesuit order, excluding Paris and the East of France. Philosophical education may have started prior to the foundation of a chair.

Figure 4.9: Jesuit foundations of chairs for philosophy

Table 4.14: Scientific Education and Knowledge Generation

	Any fam. scientist born 1650–1749			
	(1)	(2)	(3)	(4)
Any college	−0.101 (0.099)			
Philosophy education		0.177* (0.092)		
Numb. philosophy chairs			0.134** (0.057)	
One philosophy chair				0.026 (0.106)
Two philosophy chairs				0.266** (0.133)
Physics and Logic chairs				0.297** (0.149)
Humanistic education		−0.194 (0.128)	−0.203 (0.126)	−0.172 (0.129)
Latin grammar education		−0.023 (0.152)	−0.023 (0.151)	−0.024 (0.152)
Controls	Yes	Yes	Yes	Yes
Observations	125	125	125	125
Adjusted R^2	0.237	0.245	0.264	0.259

Table 4.15: Robustness: Controlling for Huguenot Influence

	Dep. variable: Log Encyclopedia sales p. c.				
	(1)	(2)	(3)	(4)	(5)
Huguenot community 18th	0.888***	0.634***	0.612***	0.705***	0.743***
	(0.216)	(0.213)	(0.220)	(0.228)	(0.235)
Any college		0.503***			
		(0.110)			
Philosophy education			0.303*		
			(0.161)		
Number of philosophy chairs				0.424***	
				(0.112)	
One philosophy chair					0.273
					(0.202)
Two philosophy chairs					0.731***
					(0.247)
Physics and Logic chairs					0.989***
					(0.268)
Controls		Yes	Yes	Yes	Yes
School controls			Yes	Yes	Yes
Observations	189	189	189	154	154
Adjusted R^2	0.094	0.264	0.278	0.383	0.385

Table 4.16: Robustness: Controlling for Wealth: Famous Business People

	Dep. variable: Log Encyclopedia sales p. c.				
	(1)	(2)	(3)	(4)	(5)
Log (business people +1)	0.381***	0.238*	0.232*	0.351***	0.333**
	(0.086)	(0.134)	(0.133)	(0.134)	(0.139)
Any college		0.538***			
		(0.109)			
Philosophy education			0.324*		
			(0.166)		
Number of philosophy chairs				0.460***	
				(0.112)	
One philosophy chair					0.294
					(0.213)
Two philosophy chairs					0.769***
					(0.271)
Physics and Logic chairs					1.004***
					(0.259)
Controls		Yes	Yes	Yes	Yes
School controls			Yes	Yes	Yes
Observations	189	189	189	154	154
Adjusted R^2	0.111	0.237	0.253	0.358	0.348

Table 4.17: Robustness: Controlling for Wealth: Nobles

	Dep. variable: Log Encyclopedia sales p. c.				
	(1)	(2)	(3)	(4)	(5)
Log Nobles p. c.	0.504^{**} (0.234)	0.764^{***} (0.220)	0.724^{***} (0.224)	0.562^{**} (0.242)	0.579^{**} (0.247)
Any college		0.512^{***} (0.108)			
Philosophy education			0.227 (0.175)		
Number of philosophy chairs				0.396^{***} (0.115)	
One philosophy chair					0.213 (0.216)
Two philosophy chairs					0.574^{**} (0.258)
Physics and Logic chairs					0.920^{***} (0.271)
Controls		Yes	Yes	Yes	Yes
School controls			Yes	Yes	Yes
Observations	183	183	183	154	154
Adjusted R^2	0.027	0.281	0.287	0.345	0.342

Table 4.18: Robustness: Controlling for Book Sales

	Dep. variable: Log Encyclopedia sales p. c.				
	(1)	(2)	(3)	(4)	(5)
Log STN book sales p. c.	0.255***	0.200***	0.198***	0.233***	0.238***
	(0.041)	(0.047)	(0.045)	(0.052)	(0.050)
Any college		0.457***			
		(0.106)			
Philosophy education			0.315**		
			(0.159)		
Number of philosophy chairs				0.403***	
				(0.105)	
One philosophy chair					0.286
					(0.202)
Two philosophy chairs					0.607**
					(0.247)
Physics and Logic chairs					0.972***
					(0.236)
Controls		Yes	Yes	Yes	Yes
School controls			Yes	Yes	Yes
Observations	189	189	189	154	154
Adjusted R^2	0.268	0.343	0.358	0.467	0.469

Table 4.19: Robustness: Controlling for Male Literacy

	Dep. variable: Log Encyclopedia sales p. c.				
	(1)	(2)	(3)	(4)	(5)
Literacy 1786	0.162 (0.255)	0.155 (0.230)	0.222 (0.221)	0.452* (0.250)	0.442* (0.251)
Any college		0.590*** (0.118)			
Philosophy education			0.327* (0.175)		
Number of philosophy chairs				0.413*** (0.118)	
One philosophy chair					0.278 (0.219)
Two philosophy chairs					0.617** (0.270)
Physics and Logic chairs					0.978*** (0.277)
Controls		Yes	Yes	Yes	Yes
School controls			Yes	Yes	Yes
Observations	176	176	176	149	149
Adjusted R^2	−0.003	0.228	0.242	0.348	0.341

Table 4.20: Scientific education and scientific societies

City	Philosophy chair at *collège*	Scientific society
Paris	.	1666
Nîmes	1582	1682
Angers	1675	1685
Lyon	1592	1700
Caen	1580	1705
Montpellier	1595	1706
Bordeaux	1573	1712
Pau	1623	1718
Béziers	1599	1723
Orléans	1617	1725
Dijon	(east)	1725
Marseille	1616	1726
Toulouse	1577	1729
Montauban	1600	1730
La Rochelle	1571	1732
Rouen	1604	1736
Arras	1665	1737
Amiens	1636	1745
Besançon	(east)	1748
Auxerre	1622	1749
Châlons-Sur-Marne	(east)	1750
Nancy	(east)	1750
Brest	-	1752
Cherbourg	-	1755
Bourg-En-Bresse	1661	1755
Metz	(east)	1757
Clermont-Ferrand	1635	1759
Grenoble	1640	1772
Agen	1591	1776
Valence	-	1784

The table displays all French cities that had a scientific society before the Revolution. Paris was the first town where philosophy was taught at colleges from the late 15th century. The reported dates are the first year for which their is definitive information that a chair was established. That means, philosophy may have been taught already before the reported date. With few exceptions, all cities had established chairs for philosophy at the local college before the foundation of a scientific society. In many cities, the establishment of philosophy predates the foundation of a scientific society by more than 100 years. All cities in the East of France had a full college, but the exact date of the establishment of chairs for philosophy is unknown.

Sample conditional on any college

Table 4.21: Robustness: Controlling for Bishop's See

	Dep. variable: Log Encyclopedia sales p. c.			
	(1)	(2)	(3)	(4)
Bishop's see	0.374^{**}	0.205	0.117	0.149
	(0.157)	(0.182)	(0.160)	(0.162)
Philosophy education		0.194		
		(0.217)		
Number of philosophy chairs			0.317^{***}	
			(0.116)	
One philosophy chair				0.041
				(0.202)
Two philosophy chairs				0.460^{*}
				(0.266)
Physics and Logic chairs				0.759^{***}
				(0.277)
Humanistic education		0.389^{***}	0.267^{**}	0.361^{***}
		(0.144)	(0.112)	(0.125)
Latin grammar education		-0.213^{**}	-0.198^{**}	-0.193^{*}
		(0.098)	(0.097)	(0.098)
Controls	Yes	Yes	Yes	Yes
Observations	154	154	154	154
Adjusted R^2	0.217	0.251	0.310	0.313

Table 4.22: Robustness: Controlling for Religious Competition Between Jesuits and Huguenots

	Dep. variable: Log Encyclopedia sales p. c.		
	(1)	(2)	(3)
Jesuits x Huguenots	0.182	−0.139	−0.232
	(0.379)	(0.393)	(0.399)
Huguenots (16th cent.)	0.284	0.279	0.301
	(0.286)	(0.283)	(0.288)
Jesuit college	0.056	0.085	0.164
	(0.323)	(0.328)	(0.335)
Number of philosophy chairs		0.332^{***}	
		(0.122)	
One philosophy chair			0.118
			(0.206)
Two philosophy chairs			0.498^{*}
			(0.296)
Physics and Logic chairs			0.829^{***}
			(0.285)
Controls	Yes	Yes	Yes
Observations	103	103	103
Adjusted R^2	0.072	0.145	0.140

Table 4.23: Codified Knowledge and the Demand for Scientific Education: Full Specification

	Technical enrolm. share		Science enrolm. share	
	(1)	(2)	(3)	(4)
Log Encyclopedia sales p.c.	0.313**	0.308**	0.422***	0.402***
	(0.132)	(0.132)	(0.136)	(0.136)
Log Philosophy chairs p.c.	−1.683	−0.826	−9.218	−7.928
	(4.914)	(4.458)	(6.181)	(5.854)
Literacy 1786		−0.059		0.033
		(0.119)		(0.132)
City Pop - Department	−0.002	−0.001	−0.001	−0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Atlantic Port	0.007	0.015	−0.053	−0.053
	(0.050)	(0.055)	(0.064)	(0.069)
Mediterranean Port	0.122*	0.094	0.076	0.058
	(0.068)	(0.065)	(0.092)	(0.088)
Navigable River	0.085	0.050	0.108*	0.060
	(0.057)	(0.047)	(0.064)	(0.046)
Non-french speaking	0.049	0.058*	0.100**	0.096*
	(0.033)	(0.034)	(0.049)	(0.049)
Constant	0.669***	0.666***	0.555***	0.528***
	(0.053)	(0.040)	(0.058)	(0.053)
Observations	57	54	57	54
Adjusted R^2	0.033	0.001	0.044	−0.013

Table 4.24: College Education Predicts City Growth

	Dep. variable: City growth 1750–1850		
	(1)	(2)	(3)
Any college	0.230^{**}	0.290^{***}	0.312^{***}
	(0.091)	(0.088)	(0.091)
Log Population 1750		-0.163^{***}	-0.112^{*}
		(0.057)	(0.059)
University in 1750		−0.007	−0.045
		(0.083)	(0.087)
Printing Press by 1500		0.122	0.210^{**}
		(0.107)	(0.105)
Log Books printed by 1500		0.043	0.001
		(0.035)	(0.035)
Atlantic Port		0.374^{**}	0.431^{**}
		(0.171)	(0.178)
Mediterranean Port		0.837^{***}	0.848^{***}
		(0.197)	(0.198)
Navigable River		0.136^{*}	0.089
		(0.080)	(0.089)
Non French Speaking		0.323^{*}	0.102
		(0.173)	(0.157)
Constant	0.206^{**}	0.396^{***}	0.241^{*}
	(0.085)	(0.126)	(0.132)
Observations	189	189	154
Adjusted R^2	0.043	0.176	0.192

Table 4.25: Role of Education Content for Growth

	Dep. variable: City growth 1750–1850		
	(1)	(2)	(3)
Philosophy education	0.047 (0.079)		
Humanistic education	0.277** (0.123)		
Latin grammar education	0.016 (0.164)		
Number of philosophy chairs		0.110*** (0.040)	
One philosophy chair			0.187* (0.113)
Two philosophy chairs			0.172* (0.098)
Physics and Logic chairs			0.226*** (0.075)
Controls	Yes	Yes	Yes
Observations	154	154	154
Adjusted R^2	0.182	0.139	0.130

Table 4.26: Growth robustness: Log business people (city)

	Dep. variable: City growth 1750–1850				
	(1)	(2)	(3)	(4)	(5)
Log (business people +1)	0.193*** (0.057)	0.122* (0.063)	0.129** (0.062)	0.145** (0.062)	0.145** (0.061)
Any college	0.285*** (0.086)	0.305*** (0.090)			
Philosophy education			0.063 (0.076)		
Humanistic education			0.252** (0.125)		
Latin grammar education			0.033 (0.164)		
Number of philosophy chairs				0.114*** (0.037)	
One philosophy chair					0.191* (0.107)
Two philosophy chairs					0.193** (0.093)
Physics and Logic chairs					0.221*** (0.072)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	189	154	154	154	154
Adjusted R^2	0.208	0.201	0.193	0.155	0.145

Table 4.27: Growth robustness: Log nobles p.c. (département)

	Dep. variable: City growth 1750–1850				
	(1)	(2)	(3)	(4)	(5)
Log Nobles p. c.	0.290^{**}	0.324^{**}	0.323^{**}	0.339^{**}	0.348^{**}
	(0.121)	(0.124)	(0.129)	(0.134)	(0.135)
Any college	0.283^{***}	0.281^{***}			
	(0.088)	(0.092)			
Philosophy education			0.005		
			(0.084)		
Humanistic education			0.279^{**}		
			(0.124)		
Latin grammar education			−0.003		
			(0.160)		
Number of philosophy chairs				0.078^{*}	
				(0.042)	
One philosophy chair					0.151
					(0.112)
Two philosophy chairs					0.093
					(0.106)
Physics and Logic chairs					0.173^{**}
					(0.075)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	183	154	154	154	154
Adjusted R^2	0.187	0.217	0.206	0.166	0.158

Table 4.28: Growth robustness: City size polynomial

	(1)	(2)	(3)	(4)	(5)
Log Population 1750	-1.856^{***}	-2.912^{**}	-2.814^{**}	-4.404^{***}	-4.094^{***}
	(0.465)	(1.335)	(1.394)	(1.420)	(1.504)
Log population squared	0.809^{***}	1.572^{*}	1.503	2.535^{**}	2.330^{**}
	(0.290)	(0.925)	(0.963)	(0.987)	(1.018)
Log population cubed	-0.159^{**}	−0.367	−0.349	-0.620^{**}	-0.564^{**}
	(0.070)	(0.261)	(0.270)	(0.278)	(0.283)
Log population to the fourth	0.012^{**}	0.031	0.029	0.054^{*}	0.048^{*}
	(0.006)	(0.026)	(0.026)	(0.027)	(0.028)
Any college	0.327^{***}	0.294^{***}			
	(0.088)	(0.090)			
Philosophy education			0.041		
			(0.079)		
Humanistic education			0.262^{**}		
			(0.123)		
Latin grammar education			0.019		
			(0.166)		
Number of philosophy chairs				0.103^{***}	
				(0.039)	
One philosophy chair					0.149
					(0.114)
Two philosophy chairs					0.154
					(0.101)
Physics and Logic chairs					0.224^{***}
					(0.075)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	189	154	154	154	154
Adjusted R^2	0.222	0.184	0.173	0.140	0.128

Table 4.29: City Growth Regressions: Placebo Period

	Dep. variable: City growth 1700–1750			
	(1)	(2)	(3)	(4)
Any college	−0.100 (0.115)			
Philosophy education		0.019 (0.072)		
Humanistic education		−0.018 (0.195)		
Latin grammar education		−0.191 (0.185)		
Number of philosophy chairs			−0.008 (0.036)	
One philosophy chair				0.023 (0.078)
Two philosophy chairs				0.061 (0.087)
Physics and Logic chairs				−0.085 (0.078)
Controls	Yes	Yes	Yes	Yes
Observations	120	120	120	120
Adjusted R^2	0.175	0.177	0.162	0.179

Table 4.30: Channel: Income per capita (reduced form)

	Dep. variable: Log Income per capita 1861			
	Delefortrie & Morice (1959)	Combes et al. (2011)	Bazot (2014)	Diéz-Minguela & Llopis (2017)
Philosophy education (pop. share)	0.119**	0.127**	0.156**	0.163**
	(0.055)	(0.062)	(0.061)	(0.063)
Schooling rate 1837	0.421***	0.450***	0.536***	0.520***
	(0.097)	(0.115)	(0.111)	(0.110)
Log population density 1851	−0.024	0.173***	0.204***	0.243***
	(0.058)	(0.063)	(0.069)	(0.067)
Mediterranean Port	0.126	0.222***	0.418***	0.363***
	(0.090)	(0.062)	(0.053)	(0.080)
Navigable River	0.166***	0.183***	0.284***	0.190***
	(0.044)	(0.056)	(0.056)	(0.055)
Non-french speaking	−0.188***	−0.205***	−0.115	−0.114*
	(0.059)	(0.048)	(0.083)	(0.059)
Paris	1.408	−4.231**	−4.906**	−5.974***
	(1.698)	(1.813)	(2.000)	(1.939)
Constant	−1.053***	−1.153***	−1.310***	−1.285***
	(0.064)	(0.079)	(0.073)	(0.074)
Controls	Yes	Yes	Yes	Yes
Observations	80	80	80	80
Adjusted R^2	0.439	0.480	0.605	0.593

Table 4.31: Channel: Income per capita (IV)

	Dep. variable: Log Income per capita 1861			
	Delefortrie & Morice (1959)	Combes et al. (2011)	Bazot (2014)	Diéz-Minguela & Llopis (2017)
Panel A: OLS				
Log Encyclopedia sales p.c.	0.064**	0.058*	0.077**	0.084**
	(0.028)	(0.034)	(0.036)	(0.033)
Controls	Yes	Yes	Yes	Yes
Observations	81	81	81	81
Adjusted R^2	0.448	0.458	0.602	0.581
Panel B: IV				
Log Encyclopedia sales p.c.	0.097**	0.103**	0.127***	0.133***
	(0.042)	(0.047)	(0.048)	(0.046)
Controls	Yes	Yes	Yes	Yes
Observations	80	80	80	80
First stage F	44.2	44.2	44.2	44.2

Table 4.32: City Growth Regressions (IV): Placebo Period

	OLS	IV			
	(Squicciarini & Voigtländer)	Any college	Education types	Number chairs	Physics & Logic
Log Encyclopedia sales p.c.	−0.036	−0.198	−0.044	−0.020	−0.072
	(0.039)	(0.228)	(0.141)	(0.084)	(0.090)
Controls	Yes	Yes	Yes	Yes	Yes
Observations	120	120	120	120	120
First stage F		12.5	7.3	21.6	5.4

4.B Data Appendix

4.B.1 Summary statistics and data overview

Table 4.33: Summary statistics: regression dataset

	Mean	Std.Dev.	Min	Max
Latin grammar education	0.83	0.38	0.00	1.00
Humanistic education	0.67	0.47	0.00	1.00
Philosophy education	0.45	0.50	0.00	1.00
Number of philosophy chairs	0.75	0.92	0.00	3.00
One philosophy chair	0.15	0.36	0.00	1.00
Two philosophy chairs	0.13	0.34	0.00	1.00
Physics and Logic chairs	0.16	0.37	0.00	1.00
Number of teachers per capita	2.64	1.97	0.00	11.54
Year of first college/Latin school	1596.55	54.40	1499.00	1734.00
Subscriptions per 1000	1.62	2.92	0.00	16.25
Famous scientist born 1600–1750	0.29	0.46	0.00	1.00
Huguenot community 17th	0.18	0.38	0.00	1.00
Huguenot community 18th	0.11	0.31	0.00	1.00
Business people born 1700–99	1.16	2.48	0.00	19.00
Noble Families 1750, dept level	15.10	7.77	4.00	39.00
STN Books	427.14	2041.70	0.00	20874.00

$N = 154$ (Cities of Bairoch dataset whose population in 1750 is observed, excluding East and Paris.)

Table 4.34: Summary statistics: full colleges

	Mean, full college	Mean, no full college	Difference	t-statistic
Positive subscriptions	0.56	0.18	0.37***	(7.33)
Subscriptions per 1000	2.94	0.76	2.18***	(4.88)
Log Population 1750	2.48	1.89	0.58***	(5.07)
pop_1550	7.39	3.45	3.93*	(2.36)
Atlantic Port	0.04	0.08	−0.03	(−1.19)
Mediterranean Port	0.02	0.01	0.01	(0.84)
Navigable River	0.10	0.03	0.07*	(2.54)
Non French Speaking	0.04	0.08	−0.04	(−1.73)
University in 1750	0.16	0.01	0.15***	(4.53)
Printing Press by 1500	0.22	0.04	0.18***	(4.59)
Log Books printed by 1500	0.54	0.11	0.43***	(3.42)
Bishop’s see	0.56	0.11	0.46***	(9.49)
Huguenot community (17th or 18th)	0.26	0.15	0.11*	(2.48)
I_Scient.Societies>0	0.19	0.02	0.17***	(4.87)
Observations	135	198	333	

Table 4.35: Overview of variables

Variable	Definition	Source
New variables		
Full college	Dummy for full college	Compère and Julia (1984, 1988); Julia and Pressley (1975)
Humanistic college	Dummy for humanistic college	Compère and Julia (1984, 1988); Julia and Pressley (1975)
Latin school	Dummy for Latin school or small college with two permanent teachers maximum	Compère and Julia (1984, 1988); Julia and Pressley (1975)
Number of philosophical chairs	Sum of chairs for philosophy, including logic and physics	Compère and Julia (1984, 1988)
Number of teachers per capita	Number of permanent teaching positions at college(s) about 1750, per city population in thousands	Compère and Julia (1984, 1988); Bairoch et al. (1988)
Year of first college/Latin school	Year when college or latin school first offered education in “style of Paris”	Compère and Julia (1984, 1988)
Two philosophy chairs	Dummy for two chairs for philosphy but not seperately for logic and physics	Compère and Julia (1984, 1988)
Physics and Logic chairs	Dummy for seperate chairs for logic and physics	Compère and Julia (1984, 1988)
Technical chair	Dummy for chair in maths or related subject	Compère and Julia (1984, 1988)
Theology education	Dummy for chair for theology at college or seminary	Compère and Julia (1984, 1988)
Scientists	Dummy for any famous French scientist born in town	De la Croix and Licandro (2015)
Entrepreneurs	Dummy for any famous French entrepreneur born in town	De la Croix and Licandro (2015)
Huguenot community (17th c.)	Dummy for Huguenot community in 17th century (safety place or church)	Mours (1958)
Huguenot community (18th c.)	Dummy for clandestine Huguenot church in 18th century	Mours (1958)
Jesuit full college	Dummy for full college run by Jesuits in 1750	Compère and Julia (1984, 1988); Delattre (1940)
Other full college	Dummy for whether full college run by oher religious or secular institutions in 1750	Compère and Julia (1984, 1988)
Bishop and cathedral chapter	Dummy for bishop’s seat with cathedral and attached cathedral chapter	Lienhard and Morice (2016)

University in 1750	Dummy for active University around 1750	Brockliss (1987)
Population ca. 1550 (log)	Log of average population 1500 and 1600 in thousands; if either missing, other; if both missing, 1000 assumed	Bairoch et al. (1988)
Existing variables		
Log subscriptions per capita	Log (Subscriptions to Encyclopedia / city population 1750 in thousands + 1)	Squicciarini and Vogtländer (2015)
City growth 1750–1850	Log difference of city population 1850 and 1750	*idem*
Atlantic Port	Dummy for cities with port on Atlantic	*idem*
Mediterranean Port	Dummy for cities with port on Mediterranean	*idem*
Navigable River	Dummy for city located on navigable river	*idem*
Non French Speaking	Dummy for départments which spoke different language in 18th century	*idem*
Printing Press in 1500	Dummy for printing press established by 1500	*idem*
Log Books Printed 1500	Log (number of editions printed by 1500 + 1)	*idem*
Literacy 1786	Département level; Percentage of men signing wedding certificate	*idem*
Pays d'Election	Dummy for regions where French king exerted particularly strong control over tax collection	*idem*
Log Pre Industry p. c.	Département level; Log (Number of mines, forges, iron trading locations, and textile manufactures before 1500 / total city population 1750 in thousands)	*idem*
Log Nobles p. c.	Département level; Log (Number of noble families / total city population 1750 in thousands)	*idem*
Log Distance Coal	Log distance (in km) from the closest coal field mined in 19th century	*idem*
Log STN book sales p. c.	Log (book purchases from publishing house Société Typographique de Neuchâtel (STN) 1769–1794 / city population 1750 in thousands + 1)	*idem*
Log Huguenot Density 1670	Département level; Log (Huguenot population in 1670 / total city population in 1750 + 1)	*idem*

4.B.2 Details on variable construction

Existence and type of school in 1750 (full, humanistic, Latin). Data on the existence of a school in 1750 and the offered curriculum was collected from Compère and Julia (1984, 1988). This source covers the North of France, the West, and the Midi. Paris had an order of magnitude more colleges than a normal city in France and is covered by a separate volume (Marie-Madeleine, 2002). Because Paris is special, Paris was excluded from all regressions and is not part of the data presented here. For the East of France, the forth and last volume of the series of French colleges before the Revolution has not yet been completed. Thus, we complete information on school type and activity in 1750 in the East of France by Julia and Pressley (1975).

Year of first college/Latin school. The year of the first college or Latin school is the year when for the first time education in the style of Paris was established, that is, education organized in a class system that followed the nationwide curriculum. In some places, it coincides with the year when a public school opened for the first time, in other places, it marks the date when an older Latin school in the town was refurbished and headmaster and teachers hired who were able to teach the nationwide curriculum. The primary data source is Compère and Julia (1984, 1988).

Number of teachers. The number of teachers is the number of Latin grammar and rhetoric teachers, professors for physics, logic, and philosophy, professors for other subjects including mathematics and theology, and administrative staff like principals and sub-principals, summed up across all colleges in a city. Additional staff attached to boarding houses is not counted, as their existence varies greatly across schools and through time.[29] The information for teachers comes from a nationwide survey conducted in 1789/1792 (??). We correct the number for any reported change of college type between 1750 and 1789 (e. g., from Latin school to humanistic college), the establishment of a chair for a particular subject (e.g., a chair for mathematics or design), or the transformation in an elite boarding school replacing the former college in the 1770ies (this happened in the sample of the empirical analysis in La Fleche, Tournon, and Vendôme). Latin schools had either one teacher (in the data source, *régence latin*) or two teachers (*petit collège*). Where in few cases information for humanistic colleges misses, we assume the number of teachers equals the minimum of three. The primary data source is Compère and Julia (1984, 1988).

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[29] The instability of boarding houses across time is also the reason why we do not use their existence as another control variable. Further, the non-existence of a boarding house does not signal that there were no boarding students: Traditionally, the principal would have living quarters in the school building and his wife would provide for boarders there.

Number of chairs for philosophy, physics, and logic in 1750. In some cities with two chairs for philosophy, one of the chairs was explicitly dedicated to logic and the other to physics. For the number of philosophy chairs in 1750, we count all professors for philosophy, including professors for logic and physics. As the number of teachers, the information comes from the survey in ??. Thus, we correct the number by any reported foundations or closures after 1750. If the separation into physics and logic chair was reported to happen after 1750, we coded the city as having two philosophy chairs. If one of the two chairs (e. g., a chair for physics) was established after 1750, we coded the city as having one philosophy chair. The primary data source is Compère and Julia (1984, 1988).

Technical chair in 1750. The technical chairs comprise mainly chairs for mathematics and a few chairs for design and after 1750 also chemistry. In some coastal towns, the chair for mathematics was specifically dedicated to hydrography, a field of applied mathematics. The variable is a dummy for whether a town had in 1750 at least one technical chair at the college. The primary data source is Compère and Julia (1984, 1988); de Dainville (1954).

Theology education in 1750. Some full colleges had one or two additional chairs for theology. The course in theology offered was tailored towards the philosophy graduates and prepared them for becoming a priest or acquiring a university degree in theology. In some towns, theology was not taught at the college but in separate seminaries (schools for future priests). The variable is a dummy for whether a town had in 1750 either a chair for theology at the college or a seminary. The primary data source is Compère and Julia (1984, 1988).

Teaching institutions. The data on teaching institutions comes from Compère and Julia (1984, 1988). Data on whether Jesuits ran a college were cross-validated against Delattre (1940). Almost all Jesuit colleges were founded or taken over by the order before 1700 and run until 1762/63, when the order was expelled from France for reasons unrelated to education and enlightenment. There is only one case in the sample were a Jesuit college was closed earlier (in Chambéry, 1729). Other religious teaching institutions include other teaching congregations like the Jesuits, in particular the Oratorian and Doctrinary orders, religious orders like Benedictines or Augustinian Canons, and priests, which were members of the diocesan clergy. There were no secular teaching institutions as such—the category covers teachers, often times university graduates, in particular graduates of the University of Paris, who were not affiliated to any religious institution and directly employed by the college board.

Huguenot community in 17th century. We code Huguenot communities in the 17th century if there exists at least one of two pieces of evidence: First, evidence for a Huguenot church in the town at least once during the 17th century; Second, evidence whether the king had granted Huguenots special rights in the town, including the right to maintain their own armed forces for their safety (these so-called "security places" were granted to prevent a second St. Bartholomew's Day massacre). In towns with special rights the Huguenots were often in the majority and had a strong influence on local institutions. The rights ceased to exist with the revocation of the Edict of Nantes (1685). The primary data source is Mours (1958).

Huguenot community in 18th century. After the revocation of the Edict of Nantes in 1685, Huguenots were officially forbidden to practice their religion publicly and thus to have their own churches. The ban, however, was not strictly enforced during the 18th century. In the cities where their presence was generally tolerated, they could de facto have unofficial, private churches (the so-called "desert churches," (*églises du désert*). The variable is a dummy for whether there was a "desert church" during the eighteenth century in the town. The primary data source is Mours (1958).

Bishop's sees and cathedrals. A bishop's see measures not only the presence of a bishop, but also of a cathedral chapter, which was involved in the administration of the bishopric and, in the Middle Ages, offered Latin education at the episcopal choir school. The primary data source is Lienhard and Morice (2016). Except in the case of Perpignan (around 1600) and few small towns not in the regression dataset, the bishop's seat was definitely established by 1317, but in many cases much earlier (during late antiquity and early Middle Ages).

University (active) 1750. Dummy variable for whether a university was active around 1750. The first universities in France were founded during the 12th century (Paris and Montpellier). Most universities that existed during the Ancien Regime had been founded at the end of the 16th century. Nancy saw the only university foundation after 1750 (in 1768 when the Jesuit university at Pont-a-Mousson was closed). The university of Cahors closed 1751 and coded as inactive. The measure differs from that by Squicciarini and Vogtländer (2015), who measure if a city ever hosted a university before 1750. The primary data source is Brockliss (1987).

Famous scientists. The data on famous scientists comes from De la Croix and Licandro (2015), who digitized the *Index Bio-bibliographicus Notorum Hominum*. We match persons identified as French by place of birth to the city-level dataset. Following De la Croix and Licandro (2015), we code individuals as as scientist if he or she had at least one of the following professions: Agronomist, Archaeologist, Astronomer, Botanist, Cartographer, Chemist, Economist, Engineer, Geograph, Geologist, Inventor, Mathematician, Naturalist, Pharmacist, Philosopher, Physician, Physicist, Zoologist.[30]

Subscriptions to the *Encyclopédie*. A main outcome variable of the analysis is the number of subscriptions to the Quarto edition (1777–79) of the *Encyclopédie* in a town, which were originally compiled by Darnton (1979) and digitized by Squicciarini and Vogtländer (2015). The Quarto edition comprised 36 volumes of text three volumes of illustrative plates. Since these were typically not delivered in one chunk, readers of the *Encyclopédie* are commonly referred to as "subscribers." The Quarto edition was designed to be affordable for middle-class readers and cost only one fifth of the original folio edition(s). The complete list of subscriptions survived in the archives of the publishers, the Société Typographique de Neuchâtel. Of the total 8011 subscriptions to the Quarto edition, 7081 were sold in 118 French cities. Most of the sales went to local booksellers. Because the purchase of several subscriptions at once demanded the investment of not unsubstantial capital on the side of booksellers, they often had collected advance payments from their customers. Thus, it is likely that the subscriptions were sold locally and that the sales of subscriptions to the *Encyclopédie* reflect a local demand for the *Encyclopédie*. In all specifications, subscriptions to the *Encyclopédie* are standardized by city population to account for the fact that larger towns had on average more subscriptions because of a larger population. Figure 4.4, panel (b) shows that the demand for the *Encyclopédie* was heterogeneous across France and across France. In comparison to panel (a), it shows that after the standardization, subscriptions per capita capture demand for the *Encyclopédie*. Figure 4.4, panel (b) also shows the distribution of colleges across French towns. Both colleges with and without philosophy colleges are spread equally across France.

4.C Additional historical background data

This section provides additional data to better describe the historical background. The social composition of students and catchment area gives a better idea of who attended the colleges. The data on Encyclopedia subscribers in Besançon may not be representative, but are the only available.

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[30] We slightly deviate from De la Croix and Licandro (2015) and chose to not classify "doctors" as scientific, because doctors were in principle any persons who obtained a doctorate from a university, including doctorates in theology and law.

4.C.1 Social composition of college students

Table 4.36: Social composition of students in Auch around 1600

Profession of father	local		foreign		all	
	total	%	total	%	total	%
Clerics	1	0.2	1	0.2	2	0.1
Nobles, landowners	9	2.2	182	14.3	191	11.3
Middle and higher officials, lawyers, physicians	27	6.4	94	7.4	121	7.1
Subordinate officials, lower liberal professions	52	12.3	115	9.0	167	9.9
Bourgeois	46	10.9	220	17.3	266	15.7
Merchants, innkeepers	101	23.9	218	17.1	319	18.8
Artisans	143	33.9	124	9.7	267	15.8
Farmers, ploughmen	43	10.2	319	25.1	362	21.3
Day labourers	0		0		0	
Total	422		1273		1695	

Source: Full college, Frijhoff and Julia (1975, p. 14).

Table 4.37: Social composition of students in Bordeaux, collège de la Madeleine

Profession of father	total	%
Nobles	29	9.1
Bourgeois	35	11.0
Higher officials and liberal professions	95	29.8
Lower officials and liberal professions	72	22.6
Merchants	67	21.0
Artisans	16	5.0
Farmers	2	0.6
Soldiers	3	0.9
Total	319	

The full Jesuit collège de la Madeleine was an elite institution and thus provides an upper bound for social exclusivity. The data relates to the academic years 1644–1646. In other Jesuit collèges at the time, the share of students from a lower social background was considerably higher. For example, in Billom between 1610 and 1625, the share of students whose father's profession is worker was 27%. In Châlons-sur-Marne, in the period 1618–1634 about 20% of students had artisans as father, and in 1654–1661 about 15%.

Source: Compère and Julia (1984, pp. 151–2).

Table 4.38: Social composition of students by school class in Le Mans

Profession of father	Philo.	Rhet.	2	3	4	Total	%
Nobles	2	7	5	4	24	42	7.2
Higher officials and liberal professions	29	17	26	22	21	115	19.5
Bourgeois	23	5	9	12	19	68	11.6
Lower officials and liberal professions	9	21	28	26	32	116	19.7
Merchants	15	20	19	28	27	109	18.5
Artisans	15	8	13	15	23	74	12.6
Farmers, ploughmen	5	12	22	16	9	64	10.9
All known	98	90	122	123	155	588	
Unknown	14	18	1	15	7		
Total	112	108	123	138	162	634	

Le Mans had a collège since 1600, run by Oratorians from 1625 to 1792. A first chair for philosophy was established in 1624, a second in 1652. The data are from 1668. There were further 125 students in 5th class, for which information on father's occupation is missing.

Source: Compère and Julia (1988, p. 418).

Table 4.39: Social composition of students by school class in Mauriac

Profession of father	Phys.	Log.	Rhet.	2	3	4	5	Total	%
Nobles		1	1	1		2		5	2.8
Higher officials and liberal professions			3		1	1		5	2.8
Bourgeois		1	2	6	9	6	1	25	13.7
Lower officials and liberal professions	5	1	1	2	4	2	2	17	9.3
Merchants, innkeepers	5		10	3	3	7	10	38	20.8
Artians	2	2	2			1		7	3.9
Workers	15	13	7	6	20	19	5	85	46.7
Total	27	18	26	18	37	38	18	182	

Mauriac had a full Jesuit collège from 1563 to 1762. Data refers to academic year 1762–1763, when teaching had been taken over by (secular) priests. Richer parents would be underrepresented if they sent their children to some boarding school or collège in Paris with higher reputation.

Source: Compère and Julia (1984, p. 433).

4.C.2 Catchment area of colleges

Table 4.40: Origin of students at Arras

Origin	count	%
Town of Arras	59	24.7
Within 30km of Arras	72	30.1
Further than 30km from Arras	69	28.9
From Austrian Netherlands	38	15.9
Total	239	

Arras had a collège since 1561, run from 1603 to 1762 by Jesuits. A chair for philosophy was founded 1665–66. The data comes from ca. 1770. It is not specified whether it covers all students of the academic year. The collège had 400 students in December 1766 and 400 to 500 in 1789.

Source: Compère and Julia (1988, pp. 57–62).

Table 4.41: Origin of students at Carpentras

Origin	1609–1613		1709–1713	
	count	%	count	%
Town of Carpentras	44	25.6	55	30.6
Bishopric of Carpentras	20	11.6	67	37.2
Rest of Comtat Venaissin[1]	35	20.4	35	19.4
Neighbouring bishoprics	36	20.9	18	10
Alpine bishoprics	32	18.6	5	2.8
Other	5	2.9		
Origin known	172		180	
Origin unknown	17		24	
Total	189		204	

Carpentras had a collège since the 16th century. Since 1608 it was run by Jesuits, since 1676 it had a chair for philosophy. The numbers likely relates to all students in rhethoric and 2nd class during the two periods.

[1] Bishoprics Avignon, Cavaillon, Vaison

[2] Aix, Apt, Arles, Die, Orange, St-Paul-Trois-Châteaux, Uzès, Valence, Viviers

[3] Digne, Embrun, Fréjus, Gap, Glandèveps, Grasse, Riez, Senez, Sisteron, Turin

Source: Compère and Julia (1984, p. 198).

Table 4.42: Origin of students at Saint-Omer

Origin	1683/84		1709/10		1740/41	
	count	%	count	%	count	%
Saint-Omer	173	60.2	180	56.8	138	60.8
1 to 20 km	40	13.8	53	16.7	36	15.8
21 to 40 km	45	15.6	45	14.2	28	12.4
More than 40 km	30	10.4	39	12.3	25	11
Origin known	288		317		227	
Origin unknown	38		43		18	
Total	326		360		245	

The data refers to the humanistic collège wallon (since 1762 collège français). It was founded in 1567 and run by Jesuits until 1762.

Source: Compère and Julia (1984, p. 630).

Table 4.43: Origin of students at Lisieux

Origin	count	%
Town of Lisieux	39	27.7
Other towns and townlets of bishopric	19	13.5
Countryside of bishopric	77	54.6
Other	6	4.2
Total	141	

Lisieux had a collège since 1572, which between 1677 and 1714 was transformed into a full collège. Since 1654, teachers were from the Congregation of Jesus and Mary (Eudistes). The data comes from 1782 and does not include the origin of the 20 philosophy students.

Source: Compère and Julia (1988, pp. 442–4).

Table 4.44: Origin of students at Vannes

Origin	count	%
Town of Vannes	79	18.7
Other towns of bishopric	78	18.4
Countryside of bishopric	258	61
Other	8	1.9
Total	423	

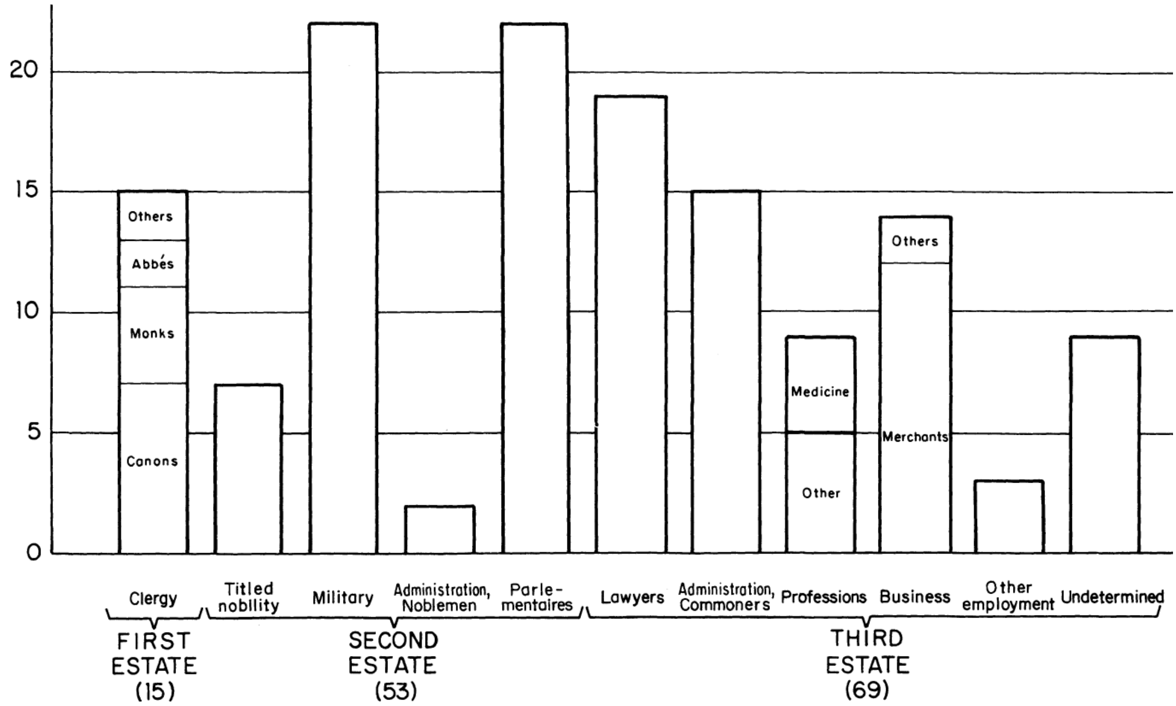
The collège in Vannes was founded between 1574 and 1580 and run by Jesuits from 1630 to 1762. A first chair for philosophy was founded in 1637 and a second in 1674. The data comes from 1782 and does not include the origin of the 20 philosophy students.

Source: Compère and Julia (1988, p. 682).

4.C.3 Subscribers to Encyclopedia in Besançon

Besançon was among towns with most subscribers (~340). It was one of a douzen towns with *parlement*, the provincial appellate courts which were the highest legal authority under the king. It hosted a relatively large population of clergy (1/40 of about 32,000 total population). And, it had a full college with two professors of philosophy.

Subscribers came from all three estates: Clergy, nobility, and commoners. Among the nobility, most subscribers were either military officers or parlementaires. Among the commoners, many were lawyers or worked in administration, or were professionals (medicine or other, normally studied) or merchants. The category “professonials–other” includes as subscriber the principal of the full college.



Source: Darnton (1979, p. 291), Figure 6

Figure 4.10: Subscribers to Encyclopedia in Besançon

Eidesstattliche Versicherung

Ich versichere hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sowie mir gegebene Anregungen sind als solche kenntlich gemacht. Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht. Sofern ein Teil der Arbeit aus bereits veröffentlichten Papers besteht, habe ich dies ausdrücklich angegeben.

München, 16. September 2022

Lukas Rosenberger