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Doctoral Thesis

On the Shoulders of Science – Early Science as a Driver of Innovation During the Early Industrial Revolution

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Abstract

Abstract

The thesis investigates the knowledge economy of early modern England. It studies mechanisms of knowledge transmissions, knowledge spillovers, and the formation of upper-tail human capital. The thesis concludes that throughout the seventeenth and eighteenth century, early science and technology started to increasingly interact with each other. At the end of the eighteenth century, this interaction led to increased innovativeness in technological progress.

First, the thesis investigates teacher-directed scientific change at the universities of Oxford and Cambridge in the seventeenth century. It shows that the direction of the English Scientific Revolution was partly determined by teacher-student exposure at universities. This finding highlights the importance of universities and the composition of the teaching force at universities for a country's long-run research trajectory. Next, the thesis investigates how the knowledge generated within the Scientific Revolution interacted with technological knowledge. Specifically, the thesis tests Mokyr's theory of a feedback mechanism between propositional and prescriptive knowledge. Using natural language processing techniques, it shows that throughout the seventeenth and eighteenth century the strength of feedback signals between propositional and prescriptive knowledge increased continuously. Additionally, the thesis investigates how local industrialization led to an increase in local human capital formation, thereby highlighting a mechanism for access to science in places where it was needed most. In a last step, the thesis investigates the role of scientific knowledge for practical innovations. It shows that patents with a high similarity to science were more innovative than other patents. Investigating the mechanism between science and technology, the paper argues that systematic quantification and precise measurement were at the heart of the connection between early science and technology.

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Contents

1 Linking material

1.1 Introduction

The early modern period witnessed two structural breaks of an unprecedented dimension. First, the Scientific Revolution created the basis for modern science. Before the early-modern period, scientific discoveries had stagnated for centuries. Now, with the Scientific Revolution, they started to appear with unparalleled speed and fundamentally altered humanity's understanding of its own place in nature and the universe (Wootton, 2015). Second, the Industrial Revolution created the first regime of modern growth. Before, growth had been largely determined by the extensive use of land and the division of labour. Now, for the first time in history, economic growth started to be driven by technological innovations enabling sustained exponential growth (Kuznets and Murphy, 1966; Landes, 1969; Mokyr, 1992, 2002).

Comparing both revolutions, the Industrial Revolution has received most interest in economic history (Deane and Cole, 1969; Pomeranz, 2000; Lucas, 2002; Clark, 2007; Allen, 2009; Broadberry et al., 2015). And it seems that the Industrial Revolution stands out for good reasons: It created the possibility of modern living standards, including an abundance of food, warm living spaces, fast transport, and modern health care. It further changed the distribution of wealth and sources of wealth income (Piketty, 2014, 2020). Yet, many of the conditions of modern life do not only find their origin in improved economic production, but in scientific progress as well. This includes our modern understanding of pathogens, an idea of where we are (cartography, and GPS), and a belief in the predictability and formability of nature. Furthermore, scientific knowledge underlies most of modern technology, ranging from microwaves and car-engines to modern day computers and cell phones. Given our knowledge about the interconnectedness between science and technology in our modern world, it is natural to wonder about its origins in the past. Especially, we should ask how much science and technology owed to each other.

This thesis goes back to seventeenth and eighteenth century England, the birth place of the Industrial Revolution, to investigate how science and technology influenced each other. It is not the first to do so. Within the economic history literature, seventeenth and eighteenth century England has become an established battleground for key debates on the impact of early science and technology and development. The seminal contributions setting the stage for the debate were Schofield (1957, 1963) and Musson and Robinson (1969) who studied the intellectual environment of Birmingham and Manchester entrepreneurs and found strong connections to early science. They argue that the technological progress behind the English Industrial Revolution was fuelled by insights from eighteenth century science. Furthermore, they argue that it was the logical outcome of a culture of applied science that was specific to Britain. Since then, this proposed link between industrial entrepreneurship, technological innovations, and science has been attacked from many sides. Mathias (1972) and Hall (1974) argue that early science was too immature to yield useful predictions for practical technology. Ó Gráda (2016) further questions the extent to which entrepreneurs were actually connected to scientific circles. However, there are also multiple scholars who have defended the importance of science for the Industrial Revolution (Stewart, 1986*a*,*b*, 1992, 2007; Jacob, 1997, 2014).

A special place in the debate belongs to the lifeworks of Joel Mokyr. While his 1992 *Levers of Riches* still argued that technological development within the eighteenth century developed without major inputs from science, his 2002 *Gifts of Athena* introduced a new framework that considerably broadened the phenomena of interest. Crucially, he introduces the concept of propositional knowledge, knowledge about the world, and prescriptive knowledge, knowledge how to change the world. His definition of propositional knowledge is broader than the field of scientific inquiry. This broader definition also allows him to capture the changes in knowledge creation that came with the Scientific Revolution and Baconian program, but were not part of "high science". This includes the collection of facts in encyclopaedias or societies trying to improve the state of knowledge within a local place. Here, he introduces the concept of useful knowledge – that becomes important for technological improvements. Useful knowledge includes simple collections of facts, small recipes of how to solve a practical problems as well as advanced mechanics or chemistry. Hence, his conception of the interaction between science and technology breaks with the narrow categories and mechanisms of high science, prediction, and technological improvement. In the end, his argument rests on the observation of the emergence of a feedback loop between prescriptive and propositional knowledge that led to modern self-sustained growth. Yet, both the strength and the existence of this mechanism have been questioned within the literature (McCloskey, 2016; Allen, 2009). Hence, the debate on the interaction between science and technology remains open and fiercely contested.

Yet, despite the debate's importance for our understanding of the origin of modern growth, it has been mostly carried out within the historical literature without much quantitative evidence being brought to weigh in. There is a limited literature that has quantified inventors connections to science (Khan and Sokoloff, 1993; Meisenzahl and Mokyr, 2011; Hanlon, 2022, 2023). Furthermore, there is a burgeoning literature on the role of upper-tail human capital on growth and innovation (Squicciarini and Voigtländer, 2015; Hanlon, 2022; Kelly, Mokyr and Ó Gráda, 2023). Yet, there is hardly any quantitative evidence that investigates the role of ideas and knowledge transmission.

This thesis sets out to use recent advances in natural language processing to produce first quantitative evidence on mechanisms of knowledge spillovers within and between early science and technology. The fundamental idea of the thesis is that most of the contested ideas in the prior debate rest on assumptions about knowledge spillovers. For example, did ideas from early science "spill" into areas of technological improvement? If so, did they help to make the technology better? Moreover, a feedback loop between two types of knowledge as in Mokyr (2002) is essentially a combination of subsequent knowledge spillovers that run into two directions. Hence, being able to quantify knowledge spillovers means being able to empirically test most of the hypotheses at heart of the debate on the importance of early science of technology. Finally, knowledge spillovers also lay at the heart of the intergenerational transmission and dispersion of knowledge. Hence, they can also account for the process of knowledge creation and the direction of a country's direction of research. Built on the quantification of knowledge spillovers, the thesis investigates the following themes that are central to the debate on early science and technology: First, was the direction of research within the Scientific Revolution shaped by social factors? Second, was there a positive feedback mechanism between propositional and prescriptive knowledge that could enable self-sustained growth? Third, was scientific knowledge in itself a driver of technical innovations? And fourth, how did technological innovations, growth, and upper-tail human capital interact?

Many of these questions are so broad that the thesis does not and cannot aim to answer them comprehensively. Instead, the thesis focuses on a few case studies that allow for the quantification and identification of the mechanisms of interest. Thus, the thesis creates first empirical findings that can challenge the state of the existing debate. Furthermore, one of its main contributions is the development a methodology that can be applied to other places or other types of knowledge that were relevant for the Scientific Revolution and Industrial Revolution. Hence, it is hoped that the thesis opens up a new pathway for productive research on the interaction between early science and technology. In the following this chapter gives an overview over the research question and findings of each of the four papers of this thesis as well as their contribution to the literature.

Paper 1: Teacher-directed scientific change: The case of the English Scientific Revolution

The first paper of the thesis tests whether teachers at the universities of Oxford and Cambridge in the seventeenth century were able to shape the direction of their students' research towards the Scientific Revolution. Here, the thesis does not take the Scientific Revolution as a monolithic block of new knowledge, but stresses that the very direction of research that led to the Scientific Revolution was a product of multiple social and economic factors. The paper introduces a new dataset on 111,242 students and teachers a the universities of Oxford and Cambridge. It further matches students and teachers to the universe of British publications between 1600 and 1800 from the English Short Title Catalogue (ESTC). Applying machine learning and natural language processing techniques to their publications, the paper creates a measure of students' and teachers' direction of research. This makes it possible to estimate whether teachers' direction of research had an impact on their students' direction of research.

To account for bias through students' self-selection towards similar teachers, the paper introduces two identification approaches. First, it exploits a quasi-natural experiment based on the expulsion and appointment of new teachers following the English Civil War in a difference-in-differences design. Second, the paper exploits the historically strong links between English regions and colleges within the universities for an instrumental variable approach. The instrumental variable is then based on to predicting students' choice of college based on a student's place of birth. Altogether, the paper finds that teachers' working on the Scientific Revolution successfully shifted their students' direction of research towards the topics of the Scientific Revolution.

The paper makes several contributions to the literature. First, some historians have argued that the English universities of the seventeenth century were strongholds of tradition and did not contribute to the Scientific Revolution (Hill, 1965, 1968; Manuel, 1968; Westfall, 1983). Others have argued that teachers had some significant room outside the admittedly traditional curriculum to expose their students to the ideas of the Scientific Revolution (Curtis, 1959; Shapiro, 1969; Jacob and Jacob, 1980; Gascoigne, 1985, 1990; Jacob, 1997; Feingold, 1997). Both branches of the literature are non-quantitative and non-causal. This paper provides new quantitative data on students and teachers and introduce two identification strategies to obtain causal estimates of teacher-student effects that allow us to settle this debate quantitatively. The results from the paper contradict the historical literature that has argued that the English universities did not contribute to the Scientific Revolution. Instead it finds that teachers successfully shifted their students' direction of research towards the Scientific Revolution. Hence, the paper allows us to revise some of the history on the role of English universities for the Scientific Revolution based on quantitative estimates.

Furthermore, the paper also contributes to the literature on directed technical and scientific change. Especially the recent literature on directed change has increasingly concentrated on the role of social factors in determining the direction of technical and scientific change (Acemoglu, 2023; Acemoglu and Johnson, 2023). One important social factor is teacher-directed change that accounts for teachers' influence in shifting the direction of their students' research in the long-run. The paper provides estimates for teacher-directed change for the Scientific Revolution, one of the largest shifts in the direction of science in history.

Lastly, in order to provide estimates for teacher-directed change, the paper introduces a new measure of the direction of research using natural language processing of historical publications. Hence, the paper introduces a new method of measuring individuals' direction of research, a key concept within the literature on directed technical and scientific change.

Paper 2: Did a feedback mechanism between propositional and prescriptive knowledge create modern growth?

The second paper of the thesis tests Mokyr's (2002) hypothesis that a feedback loop between propositional and prescriptive knowledge in the eighteenth century led an increasing stock of useful knowledge and self-sustained economic growth. Mokyr (2002) defines propositional knowledge as knowledge about the world and prescriptive knowledge as knowledge about how to change the world. The paper sets out to empirically test Mokyr's hypothesis based on the knowledge economy of Britain between 1600 and 1800. For this, the paper creates new measures of knowledge spillovers based on natural language processing techniques applied to the universe of published titles from the English Short Title Catalogue (ESTC). Practically, the paper tests whether titles that received knowledge spillovers from fields within propositional or prescriptive knowledge were more likely to create feedback loops as well.

The paper focuses on feedback loops between applied physics and techniques in trades, applied physics and techniques in agriculture, mathematics and technical instructions in trades, and astronomy and navigation. On average across all fields, the paper finds that at the beginning of the seventeenth century the coefficients for the feedback loop processes were still negative. Hence, publications that incorporated ideas from other fields were less likely to create spillovers. Effectively, this shows that e.g. false facts from early propositional knowledge or insufficient codification of early prescriptive knowledge created disbenefits rather than benefits to the composite product. Yet, throughout the seventeenth century negative feedback loops disappeared across all fields. The paper further finds evidence of positive feedback loops for a select number of fields at the end of the eighteenth century. Yet, the paper also finds a large heterogeneity across fields, including still some mildly negative feedback loops.

Overall these results point towards the beginning of a structural break in knowledge production throughout the seventeenth and eighteenth century. Yet, the results also show that the end of the eighteenth century only witnessed the beginning of positive benefits from knowledge spillovers for a select some fields, indicating that the process might only have started and might only have created limited benefits. Yet, for titles in technical instructions that received knowledge spillovers from applied physics, the paper finds a positive effect on similarity to patents. Hence, it appears that knowledge spillovers already contributed to innovations in the real economy. These results are compatible with Mokyr's (2002) narrative of a gradually increasing integration between propositional and prescriptive knowledge. Extending the publication data to a later time frame will be desirable for future work.

The paper contributes to our understanding of the origins of the Industrial Revolution by providing the first empirical test-case for Mokyr's (2002) hypothesis of the emergence of a feedback loop between propositional and prescriptive knowledge. The results are compatible with Mokyr's hypothesis. Yet, we should note that the analysis mainly reports associations between knowledge spillovers. Hence, technically the results might be driven by other deep-running processes of societal change. Yet, finding associational evidence compatible with Mokyr's (2002) hypothesis already significantly extends our prior knowledge of feedback loop processes within the British knowledge economy of the eighteenth century. Most importantly, this paper is the first one to quantitatively assess the presence of knowledge spillovers and feedback loop processes during the time of the early Industrial Revolution.

Paper 3: Attracting Science: The Impact of Industrialisation on Upper-Tail Human Capital during the Early English Industrial Revolution

The third paper of my thesis studies the effect of industrialisation on the local presence of upper-tail human capital. It investigates whether industrialisation opened up career opportunities for people within the upper-tail of the human capital distribution or whether negative externalities of industrialisation led to out-migration from industrialising centres. This question is also relevant if we believe that access to knowledge was an important input for industrial growth and that upper-tail human capital enabled access to knowledge as has been argued in the literature (Squicciarini and Voigtländer, 2015; Dowey, 2017; Hanlon, 2022). Then, if industrialisation itself led to an increased presence of local upper-tail human capital, it would endogenously strengthen access to knowledge, and thereby lead to a virtuous cycle. One the other hand, if the negative externalities of industrialisation led to out-migration of upper-tail human capital, the lack of access to knowledge might have slowed down or even stalled early industrialisation.

In order to quantify the presence of upper-tail human capital, the paper draws on two datasets on knowledge elites within England during the seventeenth and eighteenth century. First, the paper introduces a novel dataset on the lifetime movements and occupations of the fellows of the Royal Society, England's first and foremost scientific society of the seventeenth and eighteenth century. Second, the paper draws on a dataset of knowledge elites of people with a Wikipedia entry from Laouenan et al. (2022)

To capture an exogenous shock to local industrialisation, the paper uses the activation of coal reserves following the introduction of steam engines and new mining technology. To further account for the endogeneity of coal-mining sites, the paper uses the activation of carboniferous strata starting in 1740—1760. Yet, we should note that carboniferous strata is heavily spatially clustered in the North of England. Since the North of England was also the traditionally poorer and less fertile part of England, we would expect to see different pre-trends between areas with and without carboniferous strata. To construct a control group that is similar to the treated areas with carboniferous strata, the paper relies on a synthetic difference-in-differences (Arkhangelsky et al., 2021) approach that re-weights individual units according to their pre-trends of the presence of upper-tail human capital.

The paper finds that coal-based industrialisation increased the presence of local upper-tail human capital both for the members of the Royal Society as well as for notable people from Laouenan et al. (2022). Next, the paper decomposes this effect into the formation and the net-migration of upper-tail human capital. The paper finds that the increased net presence of upper-tail human capital was entirely due to an increased local formation of upper-tail human capital. In contrast, knowledge elites were more likely to move out of industrialising areas, thereby counteracting the effect of an increased formation of local upper-tail human capital. Yet overall, the paper finds that the effect of an increased formation of local upper-tail human capital was stronger than the effect of out-migration. Hence, the results indicate that early coal-based industrialisation did lead to an increased local stock of knowledge elites within the upper-tail human capital distribution that would have provided substantial access to knowledge.

The paper contributes to a long-standing literature on upper-tail human capital (Mokyr, 2002, 2016; Squicciarini and Voigtländer, 2015; Hanlon, 2022; Cinnirella, Hornung and Koschnick, 2022). While this literature has mainly focused on the effects of upper-tail human capital, this paper provides new evidence on the formation and mobility of upper-tail human capital following coal-based industrialisation. It further makes it likely that there was a self-reinforcing link between industrialisation as access to knowledge as assumed in many models of endogenous growth theory (Romer, 1986, 1990; Galor and Tsiddon, 1997). This paper applies these aggregate models to the local economy of Britain, showing that industrialisation increased the local presence of upper-tail human capital.

Paper 4: Science and patenting: An analysis of English patents, 1700–1820

There is a long-standing debate on the impact of early science on technological innovations during the Industrial Revolution. While some historians have highlighted the connections between entrepreneurs and scientific culture (Schofield, 1957, 1963; Musson and Robinson, 1969; Jacob, 2014), others have questioned the practical applicability of eighteenth century science (Mathias, 1972; Hall, 1974; Ó Gráda, 2016). This paper quantitatively assesses this old question by constructing a natural language processing (NLP) based measure of proximity between patent texts between 1700–1820 and scientific publications from the seventeenth and eighteenth century. The paper then estimates whether patent proximity to science is associated with patent innovativeness.

To capture the actual incorporation of scientific concepts in contrast to superficial similarities in language, the paper adopts a placebo-approach. For each scientific field, the paper creates a list of industries that could have been plausibly affected by knowledge spillovers. It further creates a list of unrelated industries that are used as a placebo group. Using this approach, the paper finds that proximity to scientific fields was positively associated with a select number of industries. First, it finds that the field of applied physics was associated with patent innovativeness within textile industries. Furthermore, the field of mathematics and scientific instruments in science were associated with patent innovativeness in textile industries and instrument industries. Lastly, proximity to the scientific field of chemistry was associated with patent similarity in chemical industries.

The results indicate a positive association between proximity to applied physics and patent innovativeness within textile industries might appear surprising. Afterall, textile innovations have often been characterized as simple inventions that mainly profited from practical tinkering and gradual improvements (Mokyr, 1992; Cardwell, 1994). To further investigate this puzzle, the paper investigates two different hypotheses on the nature of knowledge spillovers from early science in textile industries. First, it follows the hypothesis that Newtonian physics proved useful in practical mechanical applications (Jacob, 2014). Second, it follows the hypothesis that borrowing systematic quantification and precise measurement from science was a key-driver of practical progress (Kelly and Ó Gráda, 2022). To test these hypothesis, the paper uses natural language processing to map key-words from these theories into a text embedding space. Then, it uses patent text proximity to these text embeddings as additional regressors in a horse race approach. The analysis reveals that most of the association between applied physics and patent innovativeness within textile industries can be explained by systematic quantification and precise measurement, while the impact of Newtonian physics carries less explanatory power.

The paper contributes to the long standing debate on the impact of early science on technological innovations during the Scientific Revolution. The associations found in this paper are compatible with the presence of productive spillovers from science to technology. It further sheds new light on the mechanism of how early science led to innovations in technology: For innovations in textile industries, it highlights the importance of the scientific method with its emphasis on empirical experimentation, systematic quantification, and precise measurement. In contrast, it finds less evidence a productive impact from the application of mechanical theories.

Common threads and overall findings

Overall, the thesis follows the determinants and dynamics of the two great structural breaks in early modern economic history, the Scientific Revolution and the Industrial Revolution.

The thesis first explores the role of social factors contributing to the Scientific Revolution by studying the specific case of teacher-student interaction at the Universities of Oxford and Cambridge in the seventeenth century. It finds evidence of teacher-directed scientific change that shifted students' research trajectories towards the fields of the Scientific Revolution.

The thesis then investigates the knowledge dynamics that were created by the Scientific Revolution and the Enlightenment. By the beginning of the eighteenth century, the stock of propositional knowledge had significantly increased, yet it is well established that it only brought about limited technical applicabilities. Still, multiple studies claim that by the time of the Industrial Revolution (approx. post 1750 or 1760), inventors increasingly relied on scientific knowledge (Schofield, 1957, 1963; Musson and Robinson, 1969; Jacob, 1997, 2014). The fourth paper of the thesis empirically investigates the validity of these claims. It finds that patents in a select, but important, number of fields were more innovative if their patent text was also more similar to scientific texts. Exploring multiple mechanism for patents in textile industries shows that patents mainly profited from the use of the scientific method with its focus on systematic quantification and precise measurement and relied less on predictions from theoretical mechanics. Overall, these findings indicate that by the end of the eighteenth century, science had become relevant for technical innovations, although through a less direct channel than sometimes posited.

Yet, then what changed between 1700 and 1760 that suddenly allowed for the useful application of science to industry? The second paper of the thesis follows Mokyr's (2002) hypothesis that the Scientific Revolution and Enlightenment brought about an increasing feedback loop between propositional and prescriptive knowledge. By quantifying knowledge spillovers between scientific and technical fields, the paper finds evidence compatible with Mokyr's (2002) hypothesis of a gradually increasing feedback loop, although the strength of the feedback loop process was still very heterogenous across different fields. This mechanism is a potential candidate to explain how scientific knowledge became useful to practical inventors. As both fields grew tighter and incorporated more ideas from each other, new knowledge became tested, refuted, improved, and finally applicable. An important input for this process is the presence of local upper-tail human capital that could access new knowledge when it was needed. The third paper of the thesis shows that local industrialisation led to an increase in the presence of local upper-tail human capital, thereby also improving local possibilities of accessing relevant knowledge.

All in all, the evidence shown in this thesis is compatible with the narrative of a structurally changing knowledge economy based on new propositional knowledge from the Scientific Revolution and an increasing feedback loop between propositional and prescriptive knowledge. The thesis further finds that these changes in the knowledge economy led to positive spillovers into technical fields that increased the innovations in the real economy. However, the thesis cannot answer to the final question of the how much science accounted for technological innovations and economic growth during the Industrial Revolution. Yet, quantitative evidence of structural breaks in the feedback loop processes of Britain's knowledge economy and quantitative evidence of productive knowledge spillovers from science to technology during the Industrial Revolution are already significant findings. It appears that Britain was on the breaking point of achieving self-sustained technological growth based on a modern knowledge economy. The exact moment of this breaking point still remains object to future research.

1.2 The literature in economics

1.2.1 Science, technology, and growth: Early advances

This section gives a brief overview over seminal contributions to the study of early science, technology, and growth within the literature of economic history. The section does not attempt to be comprehensive, but highlights works that are especially related to the material discussed in this thesis.

The modern discussion of technology, innovation, and growth starts with the rise of innovation economics that owed much to the discussion of creative destruction in Schumpeter (1943). For Schumpeter, economic growth is driven by the disruptive market entries of entrepreneurs that replace prior market structures and create new and more efficient ways of production. However, Schumpeter's (1943) argument mainly ignores the technological aspect of innovation. Hence, it was only in the 1950s and 1960s that a new consensus on technology's central role for long-run growth was formed and integrated into the neoclassical synthesis. This idea finds its most basic representation within a Solow-Swan growth model where technological progress is the only source for self-sustained long-run growth. Yet, within the model it remains an exogenous factor. All in all, the prominence of technological growth within the neoclassical paradigm only showed that economics did not yet have a theory of the dynamics and origin of technological growth.

One answer to this challenge, was the arrival of endogenous growth theory (Romer, 1986, 1990) as well as unified growth theory (Galor, Moav and Vollrath, 2009; Galor, 2011) in the 1990s and early 2000s. Yet, the 1960s already produced a set of seminal works on growth and technological progress from a historical perspective. They elucidated key facts about the interaction between early science, technology, and economic growth.

One seminal contribution is Landes' *The Unbound Prometheus* that stylizes itself as a history of the "cumulative, self-sustaining advance in technology whose repercussions would be felt in all aspects of economic life" (Landes, 1969, p. 3). Landes sketches out a history of technological improvements based on a wide array of factors such as a higher level of technical skills (Landes, 1969, p. 69), political fragmentation as a driver for scientific and technological competition (Landes, 1969, p. 31), as well as a larger interest in the natural world and the systematic application of "empirical searching" (Landes, 1969, p. 69). However, regarding the Scientific Revolution's influence on the Industrial Revolution, Landes marks out only an "extremely diffuse" connection (Landes, 1969, p. 61). Successful applications of scientific theories are hard to find and the timing of technological progress seems to lag significantly behind the timing of scientific progress. Furthermore, Landes marks out that there were larger flows in knowledge from technology to early science than vice versa (Landes, 1969, p. 61, 101). Instead, Landes chooses to make a heightened Western rationality the key driver of his narrative. From a modern background that concept appears heavily Whiggish and teleological. Furthermore, in so far as rationality is usually defined as a successful ordering and manipulation of nature, using rationality to explain the successful manipulation of the world appears circular. Yet, despite these shortcomings, Landes' overall focus on technological growth set the precedent for recent studies of technology and economic growth.

When it comes to the impact of science and technology on growth during the early Industrial Revolution, it is also important to reflect on the magnitudes of the explanandum, growth rates in Britain during the Industrial Revolution. Here, Crafts and Harley (1992) have shown that the Industrial Revolution of the late eighteenth century only featured relatively small growth rates of ca. 1.5% (Crafts and Harley, 1992). Hence, these magnitudes also reflect back on the explanans. To explain growth rates of 1.5%, we would not require the presence of radical changes in technology or a very successful application of scientific concepts, methods, and ideas. It seems that early growth was still stunted, adoption of technology was imperfect, and many technological innovations were dead ends. This should not question that the Industrial Revolution was a deep structural break, both in terms of technology and growth rates. Yet, in the beginning it seems that even if the break was structurally radical, it still remained quantitatively small.

1.2.2 The Mokyrian turning point

The rise of endogenous growth theory in the 1990s brought about a renewed interest in human capital, knowledge, and technological growth (Romer, 1986, 1990) (Romer 1986, 1990). Yet, these models of aggregate structural change begged a key set of questions: Why did the transition towards a modern regime of growth happen within Western Europe? Why was Britain first in Europe? Why were other societies in history with a high number of knowledge elites, such as Ancient Greece, the Arabic Caliphates, or Song dynasty China, unsuccessful in eliciting self-sustained growth?

Furthermore, it appeared that Britain as the frontrunner of the Industrial Revolution was not better endowed with basic human capital than other nations in Western Europe; nor did literacy levels rise before the Industrial Revolution (Mitch, 1999). Hence, the study of basic human capital alone did not seem to carry the full explanatory force needed to tackle the prior questions.

Yet, it appeared that there was one factor that was special about the early knowledge economy of Europe: The Scientific Revolution of the sixteenth and seventeenth century had transformed European science and European culture. Margaret Jacob (1997) used this observation to argue that scientific culture transformed European culture and created the necessary toolsets to radically move the technology frontier. Yet, the linkages between science and technology had already been debated within the history of science and technology literature without ever reaching a clear consensus (Schofield, 1957, 1963; Musson and Robinson, 1969; Mathias, 1972; Hall, 1974). Hence, Jacob's (1997) analysis seemed to open a new set of challenges that were needed to be addressed.

Against this background of shifts in the literature, Mokyr's (2002) *Gifts of Athena*, provided a synthesis of prior approaches that added significant explanatory power. In a first step, Mokyr (2002) argues that the Scientific Revolution changed the basic fundamentals of the European knowledge economy. He then argues that the enlightened spread of applied science and useful knowledge in the eighteenth century (Mokyr, 2002, p. 29) culminated in an "industrial enlightenment" (Mokyr, 2002, pp. 28–77) and a new regime of self-sustained knowledge.

The heart of Mokyr's theory is the introduction of a theory of knowledge creation. For this, he introduces a distinction between propositional knowledge as knowledge about the world and prescriptive knowledge as a set of instructions how to change the world (Mokyr, 2002, pp. 1–26). While propositional and prescriptive knowledge had increased in waves before, these waves had always been stifled again by economic and social checks. During the Industrial Revolution knowledge suddenly started to increase permanently (Mokyr, 2002, pp. 29–32). Mokyr's explanation for this permanent change in the production function of knowledge is a feedback mechanism between propositional and prescriptive knowledge (Mokyr, 2002, p. 33): New propositional knowledge not only started to become useful for propositional techniques, but applying propositional knowledge in practical schemes also provided real-world feedback to improve the original set of propositional knowledge. Thus, propositional and prescriptive knowledge started to interact in a virtuous feedback mechanism. Mokyr (2002) argues that this positive feedback mechanism became possible through the empirical mindset of the scientific program that passed from scientists to improvers. Crucially, the feedback mechanism rests on a communicative link between theorists, inventors and practitioners. Mokyr (2002) argues that the program of the enlightenment created these communicative links. He further argues that it brough down the costs of access to propositional knowledge (Mokyr, 2002, p. 296). In the end, "useful knowledge could only become economically significant if it was shared, and access was shaped by institutions, attitudes and communications technology" (Mokyr, 2002, p. 288).

Hence, for Mokyr, the origin of self-sustained growth lies in an "industrial enlightenment" (Mokyr, 2002, p. 28) building on the conviction of applied scientists like John Desaguliers, or the authors of the *Encyclopédie* "that the mapping from propositional to prescriptive knowledge and their continued interaction held the key to economic progress" (Mokyr, 2002, p. 42).

In contrast, earlier arguments against a link between the Scientific Revolution and the Industrial Revolution were looking for a "direct, unitary, [and] simple" (Mathias, 1972, p. 15) channel between science and technology. Mokyr, however opened the door of analysis to the interaction between different spheres of epistemic knowledge - within the space of ideas as well as in changes in physical access to these ideas. Hence, Mokyr's work stands out as a turning point that created a new research program with a new set of research questions within economic history.

1.2.3 Upper-tail human capital

A key implications from Mokyr's work is that a smaller number of educated people played an important role in creating new, transmitting, and applying new knowledge to useful applications. Furthermore, it was important that these groups at the upper-tail of the human capital distribution were part of the culture of the industrial enlightenment – open about scientific innovations, interested in collecting useful knowledge and convinced that new knowledge could be used for improvements in the economy (see also Slack, 2014).

The central role of knowledge elites in Mokyr's (2002) analysis gave rise to a new literature on upper-tail human capital and early economic growth. The first key contribution were Squicciarini and Voigtländer (2015) who investigated the impact of the local presence of subscribers to the *Encyclopédie* on long-run growth in France. The *Encyclopédie*, published by Diderot and d'Alembert between 1751 and 1772 was a key-project of the French enlightenment that systematically collected the stock of eighteenth century knowledge across broad disciplines such as philosophy, science, and the arts. Notably, the *Encyclopédie* stood out for its extensive portrayal of the mechanical arts (Pannabecker, 1998). It further incorporated a Newtonian view of the world. Given the broad enlightenment agenda of the *Encyclopédie*, Squicciarini and Voigtländer (2015) argue that subscribers to the *Encyclopédie* are a good proxy for knowledge elites at the heart of Mokyr's analysis. They find that the density of local subscribers to the Encyclopédie are a strong predictor for growth and the adaptation of innovative technology in manufactories. Hence, they argue that the upper-tail of the human capital distribution was a key driver of technological progress and growth.

In their wake, there has been a broad range of papers that have provided evidence on the growth-enhancing role of upper-tail human capital. Yet, each study has laid their focus on different societal and occupational groups. Hanlon (2022) argues that the creation of the occupation of the engineer in Britain contributed to high-quality patenting. Likewise, Maloney and Valencia Caicedo (2022) argue that the presence of engineers during the Second Industrial Revolution in the US led to persistently higher levels of local income in the long-run. Relatedly, Mokyr, Sarid and van der Beek (2022) lay their emphasis on millwrights and their engineering skills as a contributor to early industrialization in Britain.

In contrast, Kelly, Mokyr and Ó Gráda (2014) adopt a wide interpretation of upper-tail human capital arguing that the quality of skilled workmen was higher in eighteenth century Britain than on the continent. Likewise, Kelly, Mokyr and Ó Gráda (2023) lay their emphasis on the presence of occupations with mechanical skills. In a more general approach, Cabello and Rojas (2016) study the number of researchers in given city based on Wikipedia entries for the sixteenth to early nineteenth century. They document a stable relationship between the presence of scientists and economic growth.

Another angle in the literature on upper-tail capital is to study the institution that provided access to knowledge and either formed or interacted with upper-tail human capital. Dowey (2017) quantifies "knowledge access institutions" in eighteenth century Britain, such as scientific societies, libraries or masonic lodges. He shows that knowledge access institutions were associated with higher rates of patenting. Moreover, Cinnirella, Hornung and Koschnick (2022) study the impact of eighteenth century economic societies in the German lands. Economic societies were founded with the explicit aim of promoting useful knowledge. The study finds that the presence of economic society members had a relevant effect on the level and the direction of patenting in the nineteenth century.

Effects of upper-tail human capital have also been documented in earlier history. Cantoni and Yuchtman (2014) show how university educated lawyers contributed to medieval market expansion. Cantoni, Dittmar and Yuchtman (2018) document that the Protestant Reformation increased the number of arts degrees at universities and decreased the number of degrees in theology. Additionally, Dittmar (2019) documents that the introduction of the printing press increased the wages of faculty at early modern universities within the sciences but not in other subjects. These results speak to the importance of the early formation of upper-tail human capital and to early contributing factors to the Scientific Revolution.

All in all, the literature has produced substantive evidence of the effects of multiple layers of upper-tail human capital on economic growth and innovation. Yet, there exists some ambiguity on the exact definition of upper-tail human capital and heterogenous effects across different groups of upper-tail human capital. Yet, we can note that many of the different occupational groups investigated in the literature were connected by their role in facilitating access to knowledge. The following section will argue that the knowledge-component in human capital remains understudied.

1.2.4 Epistemic capital

As a final note on the discussion of early science, technology, and economic growth within the domain of economics, this section critically discusses the notion of human capital in contrast to epistemic capital.

It is perhaps surprising that Mokyr's *Gifts of Athena* (2002) only influenced the study of upper-tail human capital within economics. Afterall, *The Gifts of Athena* gives a narrative account of a growth model that is based on the production of different types of knowledge. Similar to e.g. capital and labour in a Solow model, useful knowledge serves as an input that determines the final output of an economy. Useful knowledge in turn is determined by the growth of propositional and prescriptive knowledge that stand in interaction with each other as well as other economic forces. Hence, the most direct implication of Mokyr's thesis relates to society's stock of knowledge, its epistemic capital.

Mokyr's main contribution on epistemic capital lies in highlighting the importance of the composition of epistemic capital. While in e.g. endogenous growth models there usually only exists a uniform stock of ideas, Mokyr stresses the importance of the distinction between propositional and prescriptive knowledge. He further highlights the distinction between useful knowledge and knowledge that does not help us to interact with nature. Effectively, society relies on both the stock and the composition of epistemic capital.

Instead, most of the literature has focused on (upper tail-) human capital that is invested in individual agents. The two notions are not incompatible with each other. To the opposite, they fundamentally rely on each other. Agents are needed to produce, disseminate, and apply epistemic capital. At the same time, an agent's hard-won skills would be quite useless in a modern society if they did not come along with the means to assess a society's stock of epistemic capital.

Yet, both notions are different in their implications and operationalisation. Let me illustrate this with an example. Let us imagine two islands far away in the ocean. Through a deus ex machina operation, we transfer a population with access to the stock of knowledge from ancient Greece to island A and a population with access to the stock of knowledge from a modern society to island B. We further assume that the population from island A only features agents with high upper-tail human capital. Their island is literally composed of the Aristotles, Platos, and Pythagorases of the ancient days and has a fully stocked Alexandrian library. In contrast, island B only has a handful of highly-skilled individuals with access to a large library that includes the full stock of modern knowledge. The rest of the population of island B is largely illiterate and broadly unskilled.

It is easy to see that if we were to predict long-run growth, island B would have an advantage over island A. Yet, if we were to restrict our analysis to upper-tail human capital, we would be likely to give island A an advantage over island B. Yet, island B's true advantage comes from their access to the stock of modern knowledge. It does not matter how many people with high upper-tail human capital we would add to island A or how many ancient books we would add to the library on island A, island B would still be able to command superior levels of technology. While the shortage of human capital on island B would likely lead to slow but steady growth, in the long-run island B would be stuck in a significantly lower equilibrium of technology and the production of goods than island A.

The key implication from this thought experiment is that epistemic knowledge is not embedded in the upper-tail human capital of the skilled people on island B. No one of them knows much about quantum mechanics, the composition of fertilizers, or the best way how to build an electric engine. Yet, their advantage is their ability to look this up. Visually speaking, their advantage is their library on island B. This library constitutes their epistemic capital.

This way epistemic capital is similar to physical capital. It is not embedded in individual agents but in physical objects. Epistemic capital it is usually embedded in books, journals, or newspapers. Just as physical capital, the stock of epistemic capital can deprecate or even be destroyed (e.g. the burning of the library of Alexandria). Just as with physical capital, operating epistemic capital takes different degrees of human capital. Yet in contrast to physical capital and to the notion of ideas in macroeconomics, epistemic capital consists of different types of knowledge. It is structured across the lines of propositional and prescriptive knowledge, across different subject field and across the question of how different types of epistemic capital interact with other types of epistemic capital.

The call for an inclusion of epistemic capital into growth theory goes back to Kuznets (1965). For Kuznets, a major key for the operationalisation of the stock of knowledge as an economic concept is the classification of knowledge into different types (Kuznets, 1965, p. 61). Furthermore, he highlights that "social decisions that affects these conditions may have the most profound effect on economic growth" (ibid.).

Kuznets' latter point is important for making the case for epistemic knowledge as an addition to human capital. There are various social forces that affect the direction of epistemic knowledge production that are independent of human capital. Hence, the concept of epistemic knowledge ceaselessly links to the study of directed technical change (Acemoglu, 2002, 2023; Acemoglu and Johnson, 2023).

There has been a range of studies that have advanced the quantification and classification of epistemic knowledge in economic history. Recently, Baten and van Zanden (2008) have produced measures of the total production of books throughout European history. Moreover, Lehmann-Hasemeyer, Prettner and Tscheuschner (2023) have expanded an endogenous growth model to include knowledge as a production factor. They further use the Scientific Revolution as a shock that drives the transition towards modern growth. Curtis and de la Croix (2023) classify the publications of European scholar between 1000–1800 into different subject fields and test implications for economic growth. Lastly, Hallmann, Hanlon and Rosenberger (2023) explore an additional dimension of epistemic knowledge by quantifying the centrality of British and French inventions within the innovation network.

Following the spirit of Kuznets (1965) and Mokyr (2002), a fruitful road for future research will be the further quantification of epistemic knowledge across different subject classes. Having a broad body of evidence of different subject classes of knowledge will allow for estimating different dynamics of knowledge production. These estimates will enable a better understanding of directed technical and scientific growth.

This thesis hopes to advance the study of epistemic capital by applying recent techniques from natural language processing to the classification of the universe of English publication between 1600 and 1800. The thesis further differentiates subject fields across the dimensions of propositional and prescriptive knowledge. Based on this distinction, it investigates the effects of knowledge spillovers between propositional and prescriptive knowledge on the production function of epistemic capital. It estimates knowledge spillovers both in the form of teacher-student interactions and across different fields. Through this approach, the thesis follows the empirically under-researched topic of the role of epistemic capital for society's transition towards modern growth.

1.3 The literature in history

This section begins by locating the third and fourth paper of this thesis within the historical literature on the impact of science on technology. It further locates these two papers within the literature on different paradigms of science and knowledge production in Britain and on the continent. Then, the section provides an overview over the concept of the Scientific Revolution. It introduces a basic periodisation, discusses challenges in classifying fields within the Scientific Revolution, and provides a brief historiography for the Scientific Revolution.

1.3.1 Science and technology

Scientific applicability disputed

The original contributions on eighteenth century science and technology originate from the works of Musson and Robinson (1969) and Schofield (1957, 1963). These studies first highlighted entrepreneurs' early interest in natural philosophy. Provincial societies like the Lunar Society in Birmingham often bridged the gap between savants and entrepreneurs, often without an extensive education on their own (Wedgwood was apprenticed as a potter and Boulton was attended a Grammar school while simultaneously involved in his father's firm (Tann, 2013; Schofield, 1963)).

But just being able to point to a relationship between inventors and scientists is not yet conclusive. After Musson and Robinson (1969), the subsequent literature has often explored individual case studies and asked whether their scientific contacts had any bearing on their original inventions. Thus, some paradigmatic examples of the fusion of science and technology have started to sway: For examples, Josiah Wedgwood's wide-ranging scientific correspondence is not disputed, but it seemed to have emerged after the development of his "Wedgwood" ceramic ware (McClellan III and Dorn, 2015, p. 289).[1] Hall (1974) further looks at the new propositions from famous scientists themselves, e.g. Newton's definition of a solid of least resistance or Huygen's solution for the curve of a fired projectile, and then concludes that all of these were inapplicable in their own time (Hall, 1974, p. 145 f.).[2] He further questions that the inventive process started with scientific input, arguing that both students and inventors of

[1] There exists a further list of case studies working on individual inventors that attempt to understand how much these inventors were drawing on science (Berend, 2013; Jewkes, Sawers and Stillerman, 1958; Lane, 2019).

[2] However note that Euler and Robin successfully advanced the appliance of theoretical gunnery between 1742 and 1753 theory through taking account of the sound barrier and rotation during flight (Wootton, 2015, p. 479).

machines did not start with the laws of motion although (sic) being familiar with them (Hall, 1974, p. 149).

The same argument is made by Mathias (1972), although concluding that

> "(...)it was the same Western European society which saw both great advances in science and in technological change in the great sweep of time and region across the fifteenth to the nineteenth centuries. It would be carrying nihilism to the point of dogma to write this off as a mere accident (...)" (Mathias, 1972, p. 15)

Indeed, he concludes that this argument is directed against "The simplest assumptions of causation flowing directly and in one direction (...) [the] presumption that connexions between science and industry were direct, unitary, simple." (Mathias, 1972, p. 15).

New evidence

Stewart (1986*b*) uncovers a wide array of links between Newtonian public lecturers and commercial enterprise. These could end up in a partnership between scientist and artisan to register a patent, e.g. in the case of Desagulier, Vream and Niblet (Stewart, 1986*b*, p. 185). Other commercial projects actively thought the consultation of Newtonian scientists, e.g. the New River Company involving Sir James Lowther and John Theophilus Desagulier (Stewart, 1986*b*, p. 183 f.). Furthermore, Stewart and Weindling (1995) use the Spitalfields mathematical society as a case study to trace artisans' interest in mathematics and experiments. They further show that such groups of artisans were not disclosed from contact to the gentlemanly circles of science, with two of their members later becoming fellows of the Royal Society (Stewart and Weindling, 1995, p. 41 f.).

Thus, in contrast to Musson and Robinson and the revisionist literature, Stewart and Weindling (1995) show that scientific knowledge permeated into wider circles than previously assumed. Thus, metallurgy, traditionally seen as dependent on practical and oral traditions has resurfaced in a new light: Jones (2008*b*) follows the traditional view that the smelting, cementation, annealing and tempering were independent from scientific development, as found e.g. in the early (Mokyr, 1992, pp. 92–96). In contrast, (Jones, 2008*b*, p. 134) paints a more multi-faceted picture of metallurgy in the eighteenth century by illustrating the theoretical research undertook by man like Keir or Boulton for the manufacture of metal alloys.

Other contemporary views, close to the idea of Mokyr's idea of an "industrial enlightenment" are found in Jacob (1997) and Wootton (2015). Wootton argues that the "Industrial Revolution can be seen as merely an extension of the Scientific Revolution" (Wootton, 2015, p. 476). For him, a deep conceptual change of ideas and language is important. Wootton argues that "What was needed was not just new machines but also a new language for discussing machinery." (Wootton, 2015, p. 445). Jacob (1997) comes to a similar conclusion by highlighting the importance of the spread of Newtonianism and mechanical engineering. For her, the spread of Newtonian ideas from the circles of the savant, into wider circles, finally reaching the entrepreneur or fabricant and leading to a "shared technical vocabulary" (Jacob, 1997, p. 115) (Jacob, 1997, p. 115). Additionally, (Jones, 2008*a*, p. 17) argues that often the savant and fabricant could be found in the same person.

The fourth paper of this thesis contributes to this long-standing debate on the impact of science on technological innovations. Based on an NLP-based index of patent proximity to applied physics, the paper investigates the association between patent proximity to applied physics and patent innovativeness. The paper finds a positive and significant association showing that there were large knowledge spillovers from science to patents. Furthermore, these knowledge spillovers are associated with an increase in patent innovativeness. Yet, the paper also finds that these findings can mostly be explained by an adoption of the scientific method including systematic quantification and exact measurement rather than by the impact of theoretical models or exact predictions.

Furthermore, the third paper of this PhD thesis shows that amongst scientific knowledge elites, coal-based industrialisation only led to a local increase in the presence of the occupational group of entrepreneurs. These results lend empirical support to Jacob (1997) and Jones (2008*a*) who have argued that entrepreneurs fulfilled a special role in connecting the spheres of high science and the practical requirements on the shop-floor.

Britain and the continent

There is another side to the Mokyrian argument. Provided that we accept the crucial role of the industrial enlightenment for inventive capacity and industrialization, can we also explain why Europe was late? There is another puzzle inherently connected to this question: If technological progress was slower on the continent than in Britain, then we also need an explanation for what shaped the continent's "backwardness". Afterall, the sciences flourished no less in continental Europe, we only have to think of the likes of Huygens, the Bernoullis, Euler, Laplace or Lavoisier.

Jacob (1997) provides an argument based on countries' different direction of research within science. Jacob (1997) argues that the early dominance of Aristotle, Descartes, and Leibniz on the content and the aristocratic domination of science and state promoted research hindered the development of active knowledge spillovers into technology. As a first observation, Jacob observees a late transmission of Newtonianian to France. For her Newtonianism, in contrast, to deductive Cartesianism, implied the basis for a wide dissemination of mechanical applied knowledge. It is well worth reflecting her argument in the light of the history of the universities and academies.

France was by no means isolated from the interest in the new sciences. The abbé Nollet (1700-1770) was one of first lecturers on Newtonianism. Voltaire later lend the Newtonians an even more popular voice and Diderot's monumental Encyclopédie starting in 1751 remained a beacon for Newtonian thought throughout the 18th century (Jacob, 1997, p. 139). Yet, there also was strong opposition to Newtonianism in France. The University of Paris, only took up Cartesianism in the 1690s (Brockliss, 1981). The first Newtonian lecturers only emerged in the 1740s (Jacob, 1997, p. 135 f.). Moreover, until the abolition of the Jesuit order in 1764, the Jesuits strongly opposed the adoption of Newtonianism. They were well placed to do so, with substantial influence on many of the colleges. The final shift in French education seemed only to have occurred in the 1760s (Jacob, 1997, p. 134 ff.). Indeed, the above timing seems to be compatible the late start of French technological adoption and well in line with the patterns of growth found in (Squicciarini and Voigtländer, 2015).

Was England more progressive? In contrast to the University of Paris, the English universities of Oxford and Cambridge never abandoned their Aristotelian curriculum. Yet, the first paper of this thesis shows that English universities were places where new and innovative ideas from teachers had a lasting impact on their students. This contrasts with the relatively strong role of censorship at the University of Paris (Brockliss, 1981). To gain an understanding of the role of universities for a) the adoption of Newtonianism and b) the overall direction of their countries' research it would be desirable to extend the methods of analysis developed in the first paper of this thesis to other countries on the continent.

We should also ask whether Newtonianism was really the driver of technological progress in Britain. The fourth paper of the PhD thesis analyses the association between applied physics and patent innovativeness. It finds that applied physics was positively associated with patent innovativeness in industries such as textiles or instrument making. It further shows that most of this channel can be explained through the adoption of the scientific method of systematic quantification and exact measurement. In contrast, Newtonian physics or laws of motion seem to explain only a smaller part of patent innovativeness. Hence, the evidence found in the fourth paper of this thesis does not support a sufficient link between high Newtonian physics and new patent innovations. However, it remains an open question whether Newtonian and Cartesian science would have had a different impact on technological innovations through other channels than the application of physical models.

Jacob (1997) and Jones (2008*a*) provide an additional argument for the continent's "backwardness" in technological innovations. They argue that the social of order of the ancien régime inhibited the social dynamic necessary for economic change. Jacob (1997) describes a rich set of institutions build around a powerful state, around which different social spheres were hierarchically arranged (Jacob, 1997, pp. 165–172). Here, her argument is less concerned with the three estates, but with the separation of professional spheres: The state employed Royal engineers carrying the authority of the state, the savant carrying the authority of its state-sponsored academy, and the entrepreneur fighting for industrial privileges and state-support, and did not see the need for cooperation (Jacob, 1997, p. 184) (Jacob, 1997, p. 184 f.).[3]

In contrast to France, the case of the German lands is characterized through diversity rather than similarity. The multitude of states within the Holy Roman Empire led to diverging policies. Many academies flourished, with the Prussian Academy of Sciences, the Bavarian Academy of Sciences, and the Erfurt Academy of Sciences as the largest. Jones (2008*a*, p. 141) highlights that most of the mining operations were in the hands of the states. Furthermore, population losses in the Seven Years War motivated many of the belligerent states to encourage the promotion of explicitly useful knowledge through new schools and societies: Saxony founded its "Bergakademie" in 1765 (Jones, 2008*b*, p. 142) and Saxony, Prussia, Hannover, and Karlsruhe all founded their own economic societies in the wake of Seven Years War (Rübberdt, 1934; Braun, 1980; Stapelbroek and Marjanen, 2012; Cinnirella, Hornung and Koschnick, 2022).

To understand the actual effects of state centralization on the incentives of knowledge elites and entrepreneurs it would be desirable to estimate the responsiveness of the formation and attraction of knowledge elites in response to supply shocks from industry. This thesis provides a first contribution for this research program by testing the effect of industrialisation in Britain on the formation and migration of British knowledge elites. It would be desirable to extend this analysis to knowledge elites in other countries to have a basis for a cross-country comparison of the dynamics of knowledge elites in response to industrial supply shocks.

1.3.2 The Scientific Revolution

The first paper of the thesis investigates the effects of teachers in directing their students' research towards the Scientific Revolution. Furthermore, the second paper of this thesis investigates knowledge spillovers driven by the expansion of scientific knowledge through the Scientific Revolution. Yet, our conception of the Scientific Revolution needs further clarifi-

[3] We should note that some authors have also discussed the virtues of the French system. For example, focussing on Lyon's silk industry, Foray and Perez (2006) argue that local and central governments actually promoted inventive practices. They contrast Spitalfields, characterized by "individualism and secrecy, and patents" (Foray and Perez, 2006, p. 9) with "open technology" at Lyon.

cation. This section provides a basic periodisation and discusses the challenges in the use of anachronistic concepts, especially when classifying scientific works into different sub-fields. The section then provides a short historiographical overview over the concept of the Scientific Revolution.

Periodisation

Conceptions of historical time periods are usually built around a few great events. This also holds for the Scientific Revolution. We can list Copernicus' *De revolutionibus* in 1543, Galilei's *Dialogo* in 1632, the foundation of the Royal Society in 1660 and of the Académie des sciences in 1666, as well as the publication of Newton's *Principia* in 1687 and *Opticks* in 1704. Yet, none of these events are sudden events of radical change. Instead, the Scientific Revolution consisted of a wide array of gradual shifts, with historians sometimes dating its start as early as 1300 and its end as late as 1800 (Wootton, 2015, p. 18). The thesis follows Wootton's (2015) periodisation of the English Scientific Revolution that places the English Scientific Revolution within the time-frame of the beginning of the seventeenth century to the early eighteenth century. As an illustration of the force of change, Wootton (2015, pp. 6–12) takes two exemplary points, 1600 and 1733. For him 1600 still represents a time where for educated men of the age the name of Galilei was unheard of and superstitious beliefs were common (Wootton, 2015, pp. 6–10). He contrasts this with 1733, the year of the publication of Voltaire's, *Letters Concerning the English Nation* or *Lettres philosophiques*, where scientific culture had successfully permeated the educated circles (Wootton, 2015, pp. 10–12), namely Voltaire's "polite and learned Company" (Voltaire, 1733, p. 83). In 1733 the world looked different, "Magic was replaced by science, myth by fact, the philosophy and science of ancient Greece by something that is still recognizably our philosophy and our science" (Wootton, 2015, p. 11). See Cohen (1994) for a detailed discussion of different conceptions and implied periodisations of the Scientific Revolution.

Hence, pragmatically following Wootton, we can locate the emergence of the English "new sciences" between the early seventeenth and early eighteenth century. We can distinguish between two major stages. First, while the "new sciences" slowly started in the hands of a small informal research community and slowly developed themselves throughout the first half of the seventeenth century, they managed to reach a form institutionalized research with the foundation of the Royal Society in 1660. Then, in a second stage, between the "1680s to the 1720s (...) Mechanically based science left the hands of the mathematically adept and went into the everyday conversations of journalists, learned societies, coffee house lectures, and church sermons" (Jacob, 1997, p. 73). We might add a third stage of the final transmission of scientific ideas and practices to industries and the shop floor (Stewart, 2007), an open ended process starting about the 1720s. Hence, to study knowledge transmissions during the Scientific Revolution, the first paper of the thesis concentrates on the period between the early seventeenth to early eighteenth century. To study the full knowledge dynamics between propositional and prescriptive knowledge, the second paper studies the full period between 1600 and 1800, from the beginning of the Scientific Revolution to the early Industrial Revolution. Lastly, the third and fourth paper concentrate on the eighteenth century to understand the impact of industrialisation on the presence of knowledge elites and to estimate the effects of knowledge spillovers on patent innovativeness during the Industrial Revolution.

Defining science and scientific fields

When discussing science in the seventeenth and eighteenth century, we face two challenges in defining "science". First, the modern term "science" lacks a corresponding counterpart in seventeenth century vocabulary. Second, and more substantially, notions of what constituted science were changing over time. Hence, it is important to be avoid anachronisms that stem from projecting our modern notion of science onto the seventeenth and eighteenth century.

First, the seventeenth century lacked a clear definition of science. Usually, projects we associate with "early science" were historically referred to as "natural philosophy", "mechanical philosophy", or "natural knowledge". Some of these terms are associated with specific movements within the Scientific Revolution, such as e.g. "mechanical philosophy" that carried a corpuscular association. Other terms such as "natural philosophy" were used very broadly to describe any study of nature, including older Aristotelian explanations of natural phenomena (and could include law as well).[4] "Science" itself carried an equally broad meaning and could also be applied to other faculties of reason, such as e.g. "the science of philosophy" or "the science of ideas and propositions".[5][6]

Hence, our modern notion of "science" did not have a stable corresponding concept in the seventeenth century. Hence, a more straightforward way movement of the Scientific Revolution (a concept that was only created after the Scientific Revolution was over, see next subsection) is to classify knowledge into single fields of science that find a closer correspondence to historical definitions. Yet, working with single fields of science, such as astronomy, applied physics, mathematics, geography etc., comes with its own challenges. First, it should be assessed in how far these fields would have been recognized by scientific practitioners of the day. Second, we should critically consider how much the definition of these fields changed over time.

For this, the paper contrasts the list of scientific fields used in this thesis with the classification of knowledge by Francis Bacon (1620, 1623) and Diderot and D'Alembert (1751) in the first volume of the *Encyclopédié* in table 1 and 2. These two works capture two influential views of the classification of knowledge during the early Scientific Revolution and at the end of the Scientific Revolution. Both are closely interlinked, with Diderot and d'Alembert (1751) adopting the basic classification system of Francis Bacon that assigns fields of human knowledge to the three faculties of the mind, memory, reason, and imagination (Sandoz, 2016). We can see substantive changes between these time periods and classification systems. First, Diderot and d'Alembert's classification system uses about four times as many categories as Bacon's. Furthermore, we can discern some rearrangements that capture the particular rationalist spirit of the *Encyclopédie*. For example the fields of physics have been reassigned from

[4] The distinction between "science" as a general term for the academic universe and "natural science" as the hard sciences still survives in the German use of "Wissenschaft" and "Naturwissenschaft".

[5] Likwise, the word the term "technology" was not used in the seventeenth century. "Technology" was borrowed from the German "Technologie" in the late 18th century and was soon used to describe the crafts and arts (Jones, 2008b, p. 113). Insofar, the word still keeps close to its Greek origin of τεχνικός , technikós, meaning arts, crafts, or skill, differences in meaning are perhaps minor. We can think about technology as the machinery related subset of the arts and crafts.

[6] Additionally, the term "scientist" was not yet in use in the seventeenth and eighteenth century. It was coined by William Whewell at a meeting of the British Association for the Advancement of Science in 1833 (Janiak, 2019; Snyder, 2011). Throughout the seventeenth and eighteenth century practitioners of science found themselves working in a wide range of occupations ranging from the clergy and academics to merchants and simple craftsmen.

the faculty of memory to the faculty of reason – in contrast to the arts that remained in the faculty of memory.

Yet, mapping the scientific fields used in this thesis to the classification systems from Bacon (1620, 1623) and Diderot and D'Alembert (1751) (table 1 and 2) reveals a relatively straightforward lineage. First, comparing the scientific fields used in this thesis, *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*, to Diderot and D'Alembert (1751) reveals the closest match. Most fields correspond directly. The only differences arise from a) the thesis's distinction between astronomy and almanacs and b) the field of scientific instruments. Distinguishing between astronomy and almanacs is a distinction that is based purely on publication practises and different uses of astronomical science. Hence, we would not expect to see this reflected in a basic classification system of knowledge. Second, *scientific instruments* is an ambiguous field that might as well be subsumed under astronomy or practical methods. Given its importance in the historiography of the Scientific Revolution (esp. Zilsel and Zilsel, 2003), the thesis includes this fields even though it might correspond less closely to historical classification systems. Furthermore, the meaning of scientific instruments was and is less ambiguous than the more abstract fields of knowledge production, hence the addition is appears defendable.

Comparing the scientific fields used in this thesis to Bacon's (1620; 1623) classification system is more complex. This derives mainly from the fact that Bacon distinguishes between the histories of fields (descriptive science) and speculative reasoning (laws of nature). As would be expected in the 1620s, some fields like, geography, medicine, and biology are only listed as descriptive fields. Physics, applied physics, mathematics, and chemistry find an entry as both a descriptive and theoretical fields. Furthermore, fields are listed by separate objects of studies. Thus, e.g. biology is matched to a selection of the fields of *History of Plants, Vegetables, Fishes, Birds, Quadrupeds, and Serpents, Worms, Flies, and other Insects.* Yet, given the more complex framework of Bacon's classification system, the mapping still appears to be relatively straightforward and only excludes almanacs and scientific instruments.

Table 1: Comparison of classification system of this thesis to Diderot and D'Alembert (1751)

Encylopédie	**This thesis**
Geometric astronomy	Astronomy
	Almanacs
Optics, mechanics	Applied physics
Pure mathematics	Mathematics
Chemistry	Chemistry
Zoology, Botany	Biology
Geography	Geography
Medicine	Medicine
	Scientific instruments

Notes: The table shows the results of matching the scientific fields used in this thesis, *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*, to the tree of knowledge at the beginning of the first volume of the *Encyclopédié* from Diderot and D'Alembert (1751).

We might further wonder whether changes in the content of these fields cause problems for the classification exercise. For example, many of the fields listed in Bacon (1620, 1623) would still be attached to pre-modern beliefs (we find gold and metals listed in the field of History of Species as e.g. animals or plants). Without doubt, the content of the fields changed dramatically over the next two centuries.

Hence, it has been argued that science was still often convoluted with alchemy and superstitious beliefs — the foremost example being Newton himself who practised alchemy besides studying mathematics, light, and the heavens (Hannaway, 1975; Webster, 1977, 1982). For Newton both, alchemy, and mathematics would have been a valid way to gaze into the laws of god's creation. Yet, as can be seen by the case of Newton who kept his alchemical works secret, ist still holds that contemporaries were aware of the distinction between the spheres they were operating in. Hence, it appears that we need to distinguish between knowledge spillovers

Table 2: Comparison of classification system of this thesis to Bacon (1620, 1623)

Histories (descriptive science)	**Speculative reasoning (laws of nature)**	**This thesis**
Astronomical History and Cosmographical History	Speculative physics of heavens, meteors, earth, sea	Astronomy
		Almanacs
	Speculative physics of simple mot., summs of mot., measures of mot.	Applied physics
History of Mathematics	Mathematics	Mathematics
Chemical History of Metals and Minerals; History of Metals, Gold, and Silver; History of Air; History of Flame; History of Water; History of Earth	Speculative physics of hot, dense, grave., light, Speculative physics of elements	Chemistry
History of Plants, Vegetables, Fishes, Birds, Quadrupeds, and Serpents, Worms, Flies, and other Insects		Biology
Natural History of Geography		Geography
Physiognomical History; Anatomical History; History Medicinal of Diseases and Treatments (etc.)		Medicine
		Scientific instrument

Notes: The table shows the results of matching the scientific fields used in this thesis, *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*, to the classification of knowledge along different faculties in **?** and a list of natural histories in Bacon (1620).

and differences between classifications. For example, it has been established that some occult qualities found their way into established physical concepts, e.g. magnetism or gravity – forces that interacted without physical contact (for more context see Hutchison, 1982). These appear to be knowledge spillovers rather than substantive changes in the definition of fields. Hence, the thesis introduces a framework that explicitly models knowledge spillovers between different fields, but takes the basic definition of scientific fields for granted. This simple mapping exercise shows that classifying publications into relatively broad scientific field is sufficiently time consistent. Hence, the approach of this thesis to use stable subject classes to estimate knowledge spillovers seems to be historically appropriate.

A short overview of the historiography of the Scientific Revolution

This section closes by providing a short account of the historiographical development of the concept of the Scientific Revolution. Thus, while the previous section has investigated the historical definitions of scientific fields, this section focuses on the modern scholarly understanding of the nature of scientific change in the seventeenth century. In other words, what did scholars across time believe to be the defining element of the Scientific Revolution?

First, classic accounts like Voltaire (Voltaire, 1733, p. 88) have stressed the experimental method of the "new sciences" as constituting a general break between the ancients and moderns. Kant (1787) was one of the earliest thinkers to have identified a "revolution" in science, based on a new relationship between theory and empirical method:

> "Thus even physics owes the advantageous revolution in its way of thinking to the inspiration that what reason would not be able to know of itself and has to learn from nature, it has to seek in the latter (though not merely ascribe to it) in accordance with what reason itself puts into nature. This is how natural science was first brought to the secure course of a science after groping about for so many centuries" (Kant, 1787, p. 109)

In other words, for Kant, the revolution in the "way of thinking" (ibid) consists of the combination of a priori reasoning and synthetical empirical enquiry.

The classic tradition of Butterfield (1957) and Koyré (1957) in the history of science has characterized the Scientific Revolution as an epistemological break through the mathematization of nature. The mathematization of nature then gave rise to key-concepts of the Scientific Revolution such as a geometrical idea of space (Cohen, 1994, p 73 f.; Wootton, 2015, p. 19). All in all, these accounts stress the importance of the epistemological conception of nature, while relativising the role of the experimental method (ibid.).[7]

At the same time another strain of the literature has investigated the material and societal origins of the Scientific Revolution. One strain of the literature has stressed the role of European discoveries and how an increasing commercialization fuelled the demand for technical and scientific innovations (Hessen, 1931) and connected the spheres of the skilled craftsmen with the learned savants of the age (Zilsel and Zilsel, 2003). Another strain of the literature stresses the role of Puritanism for the origin of English science (Merton, 1938; Hill, 1964).

Recently, these theories that either focus on one epistemogological break or one material cause of the Scientific Revolution have come under critique from the recent literature on the history of science. Instead, recent contributions have stressed the heterogenous nature of scientific inquiry and focussed on localized histories of the Scientific Revolution (Porter, 1986; Shapin, 1996). For example, Shapin and Schaffer (1985) reconstruct the conflict between Thomas Hobbes and Robert Boyle about the validity of Boyle's experimental air-pump experiments with a vacuum. The work highlights that the production of theories and facts were influenced by social context. It further and explores the social process in the adoption of knowledge. In the same way, these studies also started to include intellectual traditions as part of the Scientific Revolution that had previously been seen as pseudo-science, such as alchemy (Hannaway, 1975; Webster, 1977, 1982). The common thread to these more recent relativist studies is a denial of any common "scientific method" behind the Scientific Revolution. Stronger positions even adhere to an epistemological relativism towards science in general. Instead of the rela-

[7] The scepticism about the experimental method is based on many historical episodes where competing theories sucessfully explained the same set of facts. Indeed, problems created by the impossibility of an experimentum crucis between theories with different world views permeates the whole literature of the history of science, from Koyré (1957) to Kuhn (1962), to Shapin and Schaffer (1985).

tion between scientific theory and nature, the relationship between scientific theory and social power has moved into the foreground of inquiry.

This direction has been methodologically criticized as well. (Jacob, 1999, p. 106) highlights the danger of a decontextualization of history as an effect from “localization” practices. Wootton further accuses Shapin (1988) of Whiggishnes by turning historical figures like “Hobbes into a seventeenth-century Wittgensteinian, someone who believes that all knowledge is conventional and constructed” (Wootton, 2015). Kuhn himself has criticized the assumption within the sociology of science “that power and interest are all there are. Nature itself, whatever that may be, has seemed to have no part in the development of beliefs about it” (Kuhn, 1992, p. 8 as quoted in Brush 2000, p. 43). Thus, recently more traditional histories of the Scientific Revolution have re-emerged in the literature. One example is Wootton (2015) who centres his story around the invention of one new scientific world-view, constrained by nature and contingent on historical developments.

Given these differing perspectives from the history of science, this thesis has the privilege of being agnostic towards the intrinsic “functioning of science”. Yet, the thesis also contributes to the empirical aspects of this literature by providing quantitative estimates of the effects of social influence on the direction of research. The first paper of this thesis finds that teachers interested in the Scientific Revolution successfully shifted their students’ research interests towards the Scientific Revolution. Hence, the thesis provides evidence of how social factors could determine the direction of research, thereby relativising accounts that see rationality and a new epistemic conception of nature as the sole drivers of the direction of scientific change that would culminate in the Scientific Revolution.

2 Teacher-directed scientific change: The case of the English Scientific Revolution

Abstract

While economic factors in directed technical and scientific change have been widely studied, the role of teacher-directed scientific change has received less attention. This paper studies teacher-directed scientific change for one of the largest changes in the direction of research, the Scientific Revolution. Specifically, the paper considers the case of the English Scientific Revolution at the English universities of Oxford and Cambridge. It argues that exposure to different teachers shaped students' direction of research and can partly account for the successful trajectory of English science. For this, the paper introduces a novel dataset on the universe of all 111,242 students at English universities in the seventeenth and early eighteenth century and matches them to their publications. Using machine learning, the paper is able to quantify personal interest in different research topics. To derive causal estimates of teacher-student effects, the paper exploits a natural experiment based on the expulsion of fellows following the English Civil War and uses an instrumental variable design that predicts students' choice of college based on their home regions. The paper finds strong empirical evidence of teacher-directed change in the English Scientific Revolution. These results illustrate how teacher-directed change can contribute to paradigm change.[8]

Keywords: Directed Technical Change, Knowledge Diffusion, Innovation, Human Capital, Natural Language Processing

JEL Classification: N33, I23, O33, O31, O43, O14

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2.1 Introduction

"whenever I am thinking of a character, in public life it may be, or in literature, I always ask 'What was happening in the world when he was twenty?' (...) To the twenties I go for the shaping of ideas not fully disclosed: to the forties for the handling of things already established"

(George Malcolm Young 1949, p. 49 as cited in Hunter, 1995)

"If I have seen further it is by standing on ye sholders of Giants"

(Isaac Newton, 1675)

Can teachers influence the direction of scientific change? Until recently, the literature on directed technical and scientific change has focused on economic factors such as factor prices or market size (Acemoglu, 2002; Allen, 2009). Recently, Acemoglu and Johnson (2023) have argued that the direction of technical and scientific change also depends on institutional and ideological factors (see also Acemoglu, 2023). Acemoglu and Johnson (2023) further argue that teachers at universities play an important role in shaping the direction of technology and science that their graduates will pursue. While the curriculum at universities is known to be an important factor in shaping the beliefs of graduates (Cantoni et al., 2017; Acemoglu, He and Le Maire, 2022), the mechanism of teacher-directed scientific change is significantly understudied. Yet, the role-model effect of individual researchers might be especially important for the adoption of new ideas and new paradigms that are not part of the official curriculum yet.

As an ideal test case for the role of individual teachers on students' adoption of new ideas and new paradigms, the paper studies one of the largest shifts in the direction of research, the Scientific Revolution. Specifically, the paper studies how university teachers at the English universities of Oxford and Cambridge that adopted ideas from the Scientific Revolution influenced the direction of their students' research. Between, 1600 and the early 1700s, these universities educated hundreds of important innovators in science, such as e.g. Isaac Newton, Robert Hooke, John Flamsteed, or Edmond Haley. They crucially changed our understanding of natural science by innovating on topics such as laws of motion, universal gravitation, optics, and the appliance of early microscopes. Doing this, they broke with traditional ideas about how to approach nature, how to generate knowledge, and how to perceive the world. Altogether, the new ideas from the Scientific Revolution laid the foundation for science driven-growth and industrialization (Mokyr, 2002, 2016; Jacob, 1997, 2014; Hanlon, 2022). Understanding how much innovations in science were impacted by teacher influence is important for both our understanding of directed scientific change in general as well as our understanding of the history of the English Scientific Revolution.

To quantify teachers' and students' direction of research, the paper matches novel data on the universe of all students at the English universities of Oxford and Cambridge to the universe of all publication titles in Britain.[9] By applying an automatic text-processing routine to the registers of the university of Oxford and Cambridge compiled by Foster (1891) and Venn and Litt (1952), the paper is able to create a novel dataset on the names, degrees, places of origin, and life outcomes of all the 111,242 students and teachers at the universities of Oxford and Cambridge between 1600 and 1800. The students are then matched to the universe of all ∼470,000 titles that were published in the British isles and North America from the English Short Title Catalogue (ESTC). The paper then classifies the ESTC titles into different research fields using state-of-the-art natural language processing techniques that rely on recent advances in large language models (LLMs) (Vaswani et al., 2017; Bommasani et al., 2021). Next, the paper matches students to their teachers based on the college a fellow was teaching at. In seventeenth and eighteenth century Oxford and Cambridge, university teaching was mainly organized at the college level, where college-employed fellows taught, dined, and

[9] During the seventeenth and eighteenth century, the universities of Oxford and Cambridge were the only universities in England. There was some competition from dissenting academies that offered a higher education for dissenting students. Dissenting academies were first founded after the Act of Uniformity of 1662 that banned dissenters from attending the universities. Yet, the demand for a higher education of dissenters only really picked up, after the Toleration Act of 1689 that opened a path for dissenters to enter priesthood (Smith, 1954). Still even then, the numbers of students educated at dissenting academies remained small in comparison to the universities (see Queen Mary Centre for Religion and Literature in English, 2023). Furthermore, competition from the Scottish universities before their reforms in the early 1700s appears insignificant (see Gascoigne, 1990, p. 249).

lived together with their students. Hence, teacher treatment occurred at the college-level, not at the university-level.[10]

To estimate the strength of teacher-directed scientific change, the paper defines a teacher's and student's direction of research, v, as a vector of the researcher's strength of research, b, across the dimensions of n research fields, $v = (b_1/n, b_2/n, \ldots b_m/n)$. The paper assumes that the Scientific Revolution took place in the subset of the research fields of *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.*[11] Then, for all fields of the Scientific Revolution, it estimates the effect of teachers' strength of research on students' strength of research in the same field. The average teacher-coefficient across all fields then captures the strength of teacher-directed scientific change. This setup allows for the inclusion of college-, time-, topic-, and student-fixed effects. Student-fixed effects absorb all non-topic-specific student heterogeneity, making this setup ideal for estimating the strength of teacher-directed scientific change.

Estimating a causal effect of teachers on students' research faces the major challenge of dealing with students' self-selection into different colleges. While a student's choice of college was usually based on non-teacher related factors, such as regional-ties between a student's place of origin and a college, their father's choice of college, a college's religious leaning, or the number of scholarships offered by a college, we still cannot rule out that some students self-selected into colleges based on their teacher's research interests. This would create a positive association between teacher and student interests that would be solely due to sorting. Hence, the paper applies a twofold strategy to infer the causal effect of teachers on students: 1) it uses an instrumental variable design that exploits the strong-ties between individual colleges and English regions to predict a student's choice of college based on their place of origin. With this, the paper addresses both the self-selection of students and teachers into colleges. 2) it uses a quasi-natural experiment based on the politically forced expulsion of teachers and the

[10]Since all students went through the same arts degree, teacher assignment also did not depend on students' choice of degrees or courses.

[11]Appendix table 35 lists all other research fields within the text data used by this paper. The paper conducts a wide range of robustness tests to show that the empirical results are robust to using other plausible definitions of the fields of the Scientific Revolution.

forced appointment of teachers by parliament following the English Civil War. At the same time, region specific factors are absorbed by college fixed effects.

The first identification strategy is based on the historically strong ties between English colleges and English regions. Historically, colleges had often been founded with the stipulation of granting scholarships to a certain number of boys from the benefactor's home region. Furthermore, parents might have preferred to send their sons to colleges where they had some local connections, making the entry to university life easier. Lastly, there seems to have been a strong preference for cultural homogeneity (different regions still had very distinct accents in the seventeenth century). Based on this pattern, the paper uses an instrumental variable strategy, where a student's home region is used to predict the college he would attend and, following from this, the teachers he would face at the college.[12] This identification strategy removes all kinds of agency from students, only using variation from their home place which students would not have been able to influence themselves.

The second causal identification strategy exploits quasi-random variation from the forced appointment of new fellows at the University of Oxford following the end of the English Civil War. During the First English Civil War (1642-1646), the University of Oxford had sided with the king. After the king's defeat in 1646, victorious parliament set out to clear the teaching body of the university from any Royal influence. They sent a group of visitors to expel all fellows who would not submit to parliament. In the end, they expelled about half of all fellows. In a next step, the visitors needed to appoint new fellows that were not part of the old Royal and Laudian university tradition. They were either selected from outside the university (mainly the University of Cambridge) or from students at the University of Oxford that were then conferred to fellowships at different colleges. While it was not random who the visitors appointed, the paper argues that it was quasi-random which colleges the new fellows were sent to. The paper then uses the change in the direction of research of teachers at a college in a difference-in-difference design. The paper carefully discusses the selection process of new fellows and shows that the distribution of the newly appointed and scientifically interested fellows was unrelated to the prior distribution of scientifically interested fellows at the colleges.

[12] Throughout the seventeenth and eighteenth century women were excluded from attending university.

The paper finds a strong effect of teachers' direction of research on students' direction of research. Using a baseline model with topic- and student- fixed effects, shows that increasing teachers' direction of research for the field of the Scientific Revolution by 100% led to an increase in students' direction of research by 3% at the University of Oxford and 1% at the University of Cambridge. We can interpret the increase in student's direction of research as an increase of an average student's share of lifetime publishing in an average field of the Scientific Revolution by 3% and 1%. Given that these are estimates for students' lifetime publishing outcomes, these effect sizes are highly relevant. Taking further into account that university graduates accounted for 33% of all published works in Britain, shows that this is also a relevant effect for the trajectory of British intellectual life in general.

Additionally, it is important to realize that a 100% increase in teachers' publication share in the Scientific Revolution would only be a modest increase in teachers' total publication share in the Scientific Revolution at university, since the average share of having a teacher in a given field of the Scientific Revolution was only 5% and the average publication share of teachers in the fields of the Scientific Revolution was only 0.06%. Hence, a purely counterfactual increase of teachers' share of publications in the Scientific Revolution by one standard deviation (amounting to a 5 percentage point increase in teachers' publication share in the Scientific Revolution) would lead to a 13.44% increase in students' publication share in the Scientific Revolution at Oxford and a 5% increase at Cambridge.[13] Such a counterfactual increase of teachers illustrates the missed potential of teacher-directed change for a faster adoption of the ideas of the Scientific Revolution. Had someone reformed the universities to promote the fields of the Scientific Revolution, the overall impact of teacher-directed change on the trajectory of the British Scientific Revolution would have been very sizeable.

Furthermore, we want to understand whether the teacher-effect was mitigated by opposition to the Scientific Revolution from traditionalists. This would have included teaching staff that was opposed to the new ideas of the Scientific Revolution as well as traditional beliefs students would have encountered among their peers or at home. To get a relative idea about the size of the teacher-effect for the fields of the Scientific Revolution in comparison to other

[13] An increase by one standard deviation would amount to a 647% increase at the mean.

traditional academic fields, the paper also estimates teacher-effects for the fields of *art, religion, the public sphere, and classical education.* It finds that the size of the teacher-effect in the Scientific Revolution is broadly comparable to that of religion, the dominating topic of intellectual life in the seventeenth century - one that was also the place of fierce debates between traditional Anglicanism and various manifestations of Puritanism and dissent.[14] The teacher-effect in the Scientific Revolution is also found to be larger than in art, the public sphere, or classical education. Overall, the paper finds no evidence of teacher-directed change being more stronger for fields with less opposition from traditionalists. Instead, it even appears that the teacher-directed change was more pronounced for heavily contested fields such as the Scientific Revolution or religion.

The paper also considers alternative mechanism to teachers' direction of research in the fields of the Scientific Revolution, namely teachers' innovativeness and teachers' distance to the research frontier. To quantify innovativeness the paper develops a new index based on both titles' novelty and titles' impact on their own field, as captured through textual distances, similar to Kelly et al. (2021). To quantify distance to the research frontier, the paper calculates textual distance to the *Philosophical Transactions*, the journal of the Royal Society and Britain's only scientific journal in the seventeenth and early eighteenth century. The exercise shows that teachers' direction of research is the strongest determinant of students' direction of research. Furthermore, teachers' direction of research is also a strong determinant of students' distance to the research frontier, further stressing the importance of teachers' direction as a primary channel for the transmissions of ideas.

Both, the IV-approach and quasi-natural experiment confirm the size of the previously found coefficients. The IV-approach uses students' home region to predict their choice of college, based on the historically strong ties between colleges and regions at the University of Oxford. It returns a teacher-effect where a 100% change in teachers' direction of research

[14] This simple comparison might do injustice to the complexities of seventeenth century religious discourse. Traditional Anglicanism was never one single intellectual tradition, as can be seen from various movements within traditional Anglicanism such as Arminianism or the moderate Latitudinarianism. Puritanism is also a term that only applies to pre Civil War Britain where reform within the Church of England still appeared desirable. Afterwards, various dissenting groups, such as Quakers, Baptists, Fifth Monarchists, Levellers, or Ranters were set up outside of the Church of England and went through various changes or disappeared during the long seventeenth century.

would lead to a 3.6% change in students' direction of research for the Scientific Revolution. This is very close to the baseline effect of 3% and strong evidence that we can interpret the teacher-effect causally. As a second identification strategy, the paper exploits the forced appointment of new fellows following Parliament's reformation of the university in 1647/48 in a difference-in-differences design. It shows that an increase in the newly appointed teachers' publication share in the fields of the Scientific Revolution of 100% led to a 13% change in students' publication share in the fields of the Scientific Revolution. Yet, this effect only holds for newly appointed fellows by parliament and not for similar teachers appointed by the colleges post 1648. Hence, comparing the effect size to the coefficient of all teachers is difficult. Yet, although the external validity of the difference-in-difference results is limited, the exercise adds to the overall plausibility of the existence of a causal teacher-student effect on students' direction of research.

Overall, we can conclude a) that teachers' direction of research had a strong and relevant effect on their students' direction of research, b) that a purely counterfactual increase of teachers by one standard deviation would have led to a significantly faster adoption of the ideas of the Scientific Revolution for the whole of British intellectual life, c) that the effect size of teacher-directed change for the fields of the Scientific Revolution is similar to that of religious topics, and d) that the channel of teachers' direction of research dominates both teachers' innovativeness and teachers' distance to the research frontier for predicting student's direction of research.

The paper primarily contributes to the literature on teacher-directed scientific change. Up to now there exists little quantitative evidence on teacher-directed scientific or technical change. This is surprising since teacher-effects on students' quality of research have been widely recognized. One major contribution to this literature is Waldinger (2010) who uses the dismissal of Jewish scientists from Nazi Germany as an exogenous shock for department quality. He shows that PhD supervisors have a causal effect on the quality of their PhD students' publications. Furthermore, Borowiecki (2022) documents that within classical music teachers had a strong impact on the style of their students across multiple generations. Furthermore, the role of the curriculum on students' ideological beliefs has also been studied intensively.

Cantoni et al. (2017) exploit the staggered adoption of a textbook reform in China, to estimate the impact of curriculum change on students' ideological beliefs. It shows that the reform was effective in changing students' attitudes, although the evidence on behavioural change is mixed. Likewise, Arold (2022) finds that curricular changes that included the teaching of more evolutionary theory in the US changed student' evolution beliefs in the long-run. find that Moreover, Ash, Chen and Naidu (2022) show future judges who took part in the Manne program law-and-economics imposed longer criminal sentences and ruled more often against regulatory agencies.

Acemoglu and Johnson (2023) further present evidence of the effect of curriculum changes on students' direction of technical change. They show that the theory of shareholder value taught at business schools in the USA and Denmark changed manager's attitudes towards rent-sharing and generally depressed labor's share of income in the USA and Denmark. This paper contributes to the literature on teacher-directed scientific change by exploring the role of university teachers in one of the largest changes in the direction of scientific research, the Scientific Revolution. Hence, the results of this paper highlight the potential importance of university teachers in catalyzing ideological shifts and paradigm change that can shape a society's direction of research in the long-run.

Furthermore, the paper speaks to a growing literature on the general development of university-based science. This literature illustrates how shocks to the institutional settings of university research can have a large impact on scientific and technical productivity. Thus, De la Croix et al. (2019) show that academic labour markets between 1000-1800 were efficient in allocating human capital across universities. Dittmar and Meisenzahl (2021) show that the institutional establishment of the modern research university in the German lands increased inventive activity. Ytsma (2022) finds that recent German legislation, which raised economic incentives for scientific publishing, increased research output without enhancing research quality. Lastly, Azoulay, Fons-Rosen and Zivin (2019) study the role of senior researchers in inhibiting the reception of new researcher's ideas in their field. They exploit exogenous variation from premature deaths of senior academics in the life sciences and show that the flow of publications from their collaborators significantly decreased afterwards. Based on this finding, they argue that senior academics can inhibit the adoption of new ideas by junior researchers. This paper contributes to this literature by investigating how teachers affected the direction of their students' research in the long-run. It suggests that accounting for teachers' direction of research during university hiring processes can be important for shaping the direction of research of the next generation of researchers.

The study further integrates questions raised in educational economics: There, the effect of teacher quality in post-secondary education has been of considerable interest. Borjas (2000), Ehrenberg and Zhang (2005), Bettinger and Long (2004, 2005), Hoffmann and Oreopoulos (2009), and Feld, Salamanca and Zölitz (2018, 2019) find mixed effects of the value-added effects for different university teacher quality. However, these studies only look at the performance of students within the existing curriculum — thus following the same question as in the literature about primary and secondary education. However, the paper argues that one of the main virtues of university education is igniting students' interest in topics beyond the current curriculum and possibly outside the prevailing mainstream topics. So far, this outcome has received little interest in educational studies.

Furthermore, this study also contributes to the historical debate on how much the English universities contributed to the birth and rise of English science. This debate does not only speak to our understanding of the origin of the English Scientific Revolution, but also to the interplay between forces of tradition and innovation in the production of new knowledge (Mokyr, 2016; Nunn, 2021). Overall, the importance of the English universities has been widely debated in the historical literature. The English universities are either regarded as "fast approaching the status of an intellectual wasteland" (Westfall, 1983, p. 190) or seen as tolerant institutions that were open to new ideas. Both sides of the argument agree that the scholastic curriculum of the English universities underwent little change and remained deeply traditional throughout the seventeenth century. However, while some historians have seen this as sufficient evidence that the universities were detached from the intellectual changes of the Scientific Revolution (Hill, 1965, 1968; Manuel, 1968; Westfall, 1983), others have argued that many teachers were active participants in the Scientific Revolution and that the actual practise of teaching often found ways to circumnavigate the spirit of the scholastic curriculum (Curtis, 1959; Shapiro, 1969; Jacob and Jacob, 1980; Gascoigne, 1985, 1990; Jacob, 1997; Feingold, 1997). Furthermore, colleges were places where teachers and students lived, prayed, and dined together. So, it is likely that after living together in close quarters for four or seven years, students would have gotten to know their teachers' view on contemporary scientific debates in one way or the other. However, the question remains whether knowing their teachers views was sufficient influence to also adopt them. This paper provides a quantitative answer to this debate: There was a strong teacher-student effect at English universities that can account for some parts of the growth in the English Scientific Revolution. However, the paper also shows that the very limited number of teachers working on the Scientific Revolution at universities present a missed chance for English science. Had this number been significantly increased, then the English Scientific Revolution could have advanced significantly faster.

2.2 Historical Background

This section provides an overview over the historical debate on the impact of English universities on the English Scientific Revolution. It further discusses the historical background of the quasi-natural experiment that exploits the forced appointment of new fellows by Parliament following the English Civil War. For a detailed discussion of student life at the universities of Oxford and Cambridge during the seventeenth century, please refer to appendix section A.1.

2.2.1 The Scientific Revolution and the Universities

The Scientific Revolution was one of the largest shifts in the direction of research in history. It is usually dated between the fifteenth century and the beginning of the eighteenth century and is often associated with the names of scientific innovators such as Copernicus, Kepler, Gallilei, Boyle, or Newton. Following the Scientific Revolution's early rise on the continent, especially in Italy, the debates of the Scientific Revolution entered English discourse with the beginning of the seventeenth century (Wootton, 2015).

There are several hypotheses on the origin of the Scientific Revolution. One strain of the literature stresses the role of European discoveries and increasing commercialization that fuelled the demand for technical and scientific innovations (Hessen, 1931) and connected the spheres of the skilled craftsmen with the learned savants of the age (Zilsel and Zilsel, 2003). Another strain of the literature stresses the role of Protestantism and Puritanism (Merton, 1938; Hill, 1964). Eisenstein (1980) argues that the printing press increased the rate of the exchange of ideas. In the same spirit, Dittmar (2019) quantitatively shows that the introduction of the printing press shocked the market of ideas and led to an increase in the study of scientific subjects. Furthermore, historians argued that universities were important for intergenerational transmission of innovative ideas (Gascoigne, 1990; Feingold, 1997).

This paper restricts itself to the English Scientific Revolution. There are several factors making England an ideal case study. First, the extent of records on students, teachers, and publications is to the best of the author's knowledge unmatched.[15] Second, England was a late-comer to the intellectual debates of the Scientific Revolution with hardly any progress before 1600, but became one its intellectual centres and home to the Newtonian synthesis of physics within less than a century. Using quantitiative data from Wikipedia, De Courson, Thouzeau and Baumard (2023) show that by 1700, England had become the European leader in scientific productivity. Lastly, throughout the early modern period, England only had two universities, Oxford and Cambridge, that were institutionally highly similar, thereby making it possible to estimate the effect of teachers within an homogenous institutional framework.

Furthermore, England and the English universities have stood at the centre of a historical debate on the importance of the universities for the Scientific Revolution. While it is clear that the English universities were not a sufficient cause for the Scientific Revolution — after all they had already existed for about 400 years before the Scientific Revolution — some authors still argue that they were at least a necessary cause for the English Scientific Revolution (Curtis, 1959; Shapiro, 1971; Frank, 1973; Gascoigne, 1990; Feingold, 1984, 1997). On the other hand, historians such as Manuel (1968), Hill (1965, 1968) or Westfall (1983) have doubted that the English universities were a good place to learn about the new ideas of the Scientific

[15] In contrast, of the University of Paris's matriculation records there have only survived the entries for the faculty of arts from 1520–1680, as well as further records for the faculties of law from 1660–1790 and for the faculties of medicine for 1670–1786 (Brockliss, 1978, p. 508). For the Netherlands, records survive for the University of Leyden (Smith and Comrie, 1932; Underwood, 1969). Yet, the use of latinized names in the matriculation list at Leyden makes the list poorly suited for matching it with authorship records. Furthermore, extant material for the German universities of the 17th century appears scarce.

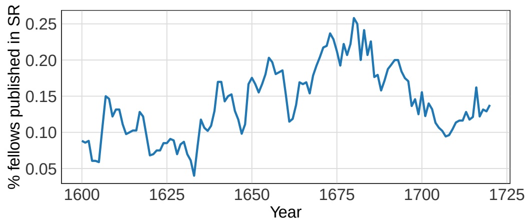
Revolution. They start with the observation that the official scholastic curriculum remained effectively unchanged since medieval times and argue that universities were passing on traditional perspectives on the natural world that were opposed to the world view of Scientific Revolution. Thus, Manuel calls restoration Cambridge an "intellectual desert" (Manuel, 1968, p. 133), Hill describes the universities as "backwaters so far as science was concerned" (Hill, 1968, p. 144), and Westfall sees Cambridge as "fast approaching the status of an intellectual wasteland" (Westfall, 1983, p. 190). Westfall even goes on to argue that "I am unable to perceive any scientific community in Cambridge. I am not even sure there was an intellectual community" (Westfall, 1980, p. 147).

In contrast, Gascoigne (1990), and Feingold (1984, 1997) start their argument by focussing on the interests of teachers at the universities. They concede that the curriculum at the universities was deeply traditional, but argue that this did not stop teachers from passing on new ideas, both inside and outside the classroom. With this, they make the case that universities were crucial for the transmission of research interests to the next generation. Feingold (1984) provides a broad range of case-studies of teachers who taught scientifically advanced material at university. Gascoigne (1990) further presents broad evidence that throughout Europe, most eminent scientists had been educated at university. He finds that 87% of all European scientists listed in the Dictionary of Scientific Biography born between 1551 and 1650 had received a university education.[16]

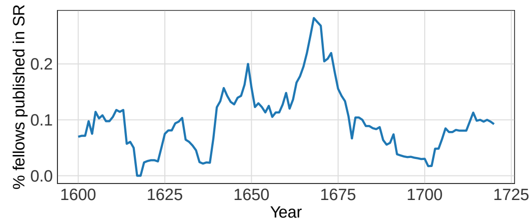
These stylized facts from Feingold (1984) and Gascoigne (1990) hold up when compared to the new dataset produced by this paper. Figure 1 presents the percentage of teachers at the universities of Oxford and Cambridge who had published at least once within fields of the Scientific Revolution.[17] We see that an average of 10–15% of all teachers had at least some interest in the fields of the Scientific Revolution. The number even reached 20% during the late restoration period of the 1670s. Note however, that this number would have significantly differed by individual colleges. Still, the aggregate statistics show that although fellows inter-

[16]This pattern remained stable over time. For the eighteenth century, Gascoigne (1995) finds that 71% out of 614 scientists were university educated.

[17]The paper defines the fields of the Scientific Revolution as: *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.*



(a) University of Oxford



(b) University of Cambridge

FIGURE 1: Percentage share of teachers at university who published at least once in the fields of the Scientific Revolution

Notes: The fields of the Scientific Revolution are defined as: astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.

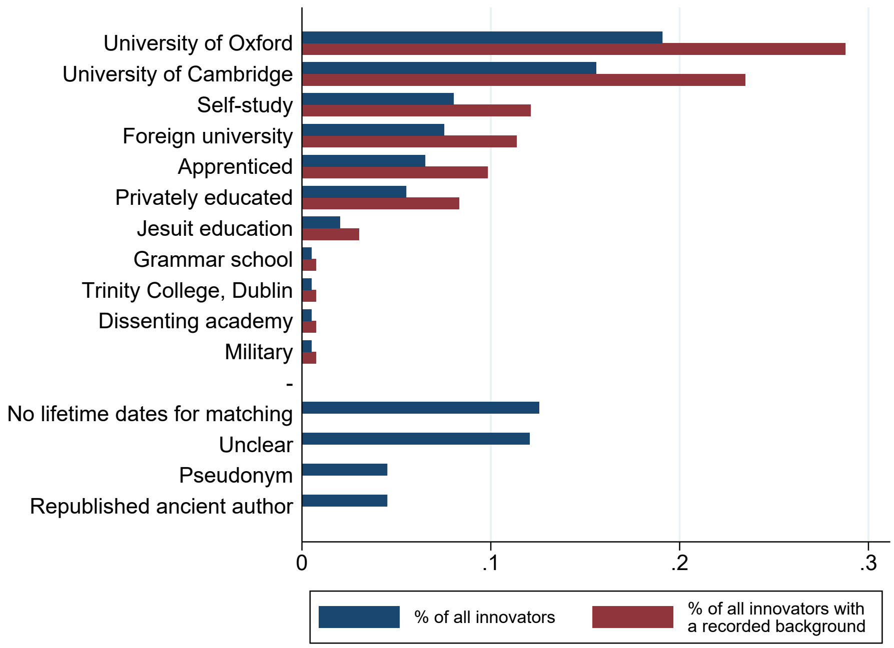


FIGURE 2: Educational background of the authors of the top 200 most innovative papers in astronomy, applied physics, and mathematics, 1620–1780

Notes: The figure presents the educational background of the 200 ESTC titles at the top 200 breakthrough index introduced by this paper (see data section 5.2 for the core-fields of the Scientific Revolution, astronomy, applied physics, and mathematics from 1600–1800. The educational background refers to the highest level of education received. E.g. an entry for "grammar school" means that the highest formal education received was at a grammar school.

ested in the Scientific Revolution were still in the minority, their number was high enough to expose a significant number of students to the ideas of the Scientific Revolution.

Furthermore, the paper presents evidence on the educational background of the 200 most innovative works published in England in the fields of *astronomy, applied phyics, and mathematics*, often seen as the core fields of the Scientific Revolution. The measure relies on the innovation index introduced by this paper (see section 2.3.4) and on a manual background search of the educational background of all authors who were not found to be matching to the university records. Figure 2 shows the results. Overall, we see that out of all authors with a known educational background, 49% had attended either the university of Oxford or Cambridge. This number is reasonably close to the percentage of 71% found by Gascoigne (1990) for the whole of Europe and using a different methodology. Together, these numbers show that the population of university graduates accounted for at least half of all publishing activity in the Scientific Revolution. Hence, the potential impact of universities on the Scientific Revolution appears large.

Yet, what these numbers cannot show is whether the high number of university graduates among top innovating scientists was due to their exposure to new ideas at university (as claimed by Gascoigne and Feingold) or if a university education did little more than to permit entry into the higher ranks of the scholarly community (as claimed by Hill and Westfall). Therefore, the paper will contribute to the historical debate by estimating teacher-effects in the Scientific Revolution based on micro-data and exploiting variation at the college-time level.

2.2.2 The Oxford visitations: A natural experiment

The history of the University of Oxford offers a unique shock where half of its fellows were expelled and new fellows appointed by force from outside. The paper uses this political shock as the basis for a natural experiment. This section gives a short overview over the history of the Oxford visitations.

During the English Civil War, the University of Oxford had backed the lost cause of Charles II. Thus, in 1648 victorious parliament chose to reform the Royalist institution and sent a board of visitors to the University of Oxford. The visitors expelled all fellows who would not submit to them and swear an oath to parliament. Overall, about half of all Oxford fellows were expelled. The visitors then intruded new fellows that were deemed to be free of Royalist sympathies. Because the visitors wanted to break the existing Royalist and Anglican tradition at colleges, new fellows were largely intruded from outside. Hence, the paper argues that the distribution of newly appointed scientifically interested fellows across colleges can be seen as an exogenous shock. This logic is based on the assumption that the visitors did not match the newly intruded fellows to colleges based on their research interest. This assumption appears plausible as the visitors, mostly political men who had never attended the university would have been in a poor position to judge pre-existing college traditions. Furthermore it was in their interest not to perpetuate college traditions, but to break with the old college traditions altogether.

Yet, it is important to consider who might have been able to influence the visitors' decisions. One might imagine that the colleges themselves might have tried to use their political capital to influence the appointment of new fellows. Yet, the political system had been turned upside down. The colleges still had hopes of a change of fortunes and until the very last petitioned to the king. If anything, this only helped to antagonize parliament further. Overall, it appears that communication between the existing heads of colleges (who still managed to hang on to their posts during the early visitation) and the visitors had completely broken down (Reinhart, 1984; Roy and Reinhart, 1997). The visitors often had to use military force to gain access to the colleges. Appendix section A.1.3 provides a detailed discussion of the political background of the Oxford visitation and outlines the process which led to the appointment of new fellows.

However, the visitors themselves being outsiders to academia appointed a committee for the examination of candidates for fellowships and scholarships. While they could not overrule the visitors, they could have leveraged significant influence on the appointment of new candidates for specific colleges. Appendix table 11 lists the names of these members of the committee, including their college affiliation during their studies, their former role at Oxford, and their position at Oxford after the visitations. The list provides strong evidence that the individuals chosen for the committee presented a clean break to existing college traditions.

In order to quantify the expelled and intruded fellows, we cannot simply rely on the number of new fellows who arrived between 1648 and 1652. Afterall, there were also some appointments made by the colleges themselves once the visitors had left. Instead, this paper draws on a list of fellows intruded by the order of the visitors. For this, the paper draws on a detailed compilation by Reinhart (1984, pp. 519–610). Reinhart's list in turn is a revision of a list compiled by Burrows (1881) that is based on the original visitor's register Reinhart (1984, p. 519). The paper manually matches the entries in the Reinhart list with the entries in the *Alumni Oxeniensis.*

Table 3: Overview of intruded fellows

	College	New fellows 1648–1652	Appointed by visitors	Appointed by visitors + from outside their own college
1	All Souls	39	39	39
2	Balliol	9	9	6
3	Brasenose	23	18	17
4	Christ church	52	15	15
5	Corpus Christi	22	19	17
6	Exeter	14	14	9
7	Jesus	16	16	13
8	John	27	14	14
9	Lincoln	10	9	8
10	Magdalen	40	31	26
11	Merton	21	18	16
12	New College	46	37	37
13	Oriel	11	8	8
14	Pembroke	8	8	5
15	Queens	10	6	5
16	Trinity	12	8	7
17	University College	20	17	14
18	Wadham	15	15	12
	Sum	395	301	286

Notes: The table shows the number of newly appointed fellows between 1648-1652 compared to the number fellows intruded by the visitors as well as the number of intruded fellows that were not appointed to the same college where they had studied before. The list is based on the doctoral thesis by Reinhart (1984) which presents revised numbers from Burrows (1881).

Table 3 presents an overview of the composition of all fellows appointed by the visitors. Altogether, ca. 50% of all former fellows at Oxford were expelled and ca. 80% of all newly intruded fellows were intruded from outside their new college. Altogether, one third of the intruded fellows were recruited from the University of Cambridge (Reinhart, 1984, p. 412). Cambridge had already been "reformed" in 1644 (Twigg, 1983), thus being a more reliable recruitment pool for fellows supporting Parliament. A further 5% came from other universities and another third came from Oxford colleges, but were intruded into another. Lastly, a fifth were intruded within the same college, usually from the lower ranks of the college (Reinhart, 1984, p. 411). The number of fellows who were intruded into their own college are excluded from the number of intruded fellows in the difference-in-approach as they might reflect some elements of a pre-existing college culture.

2.3 Data

2.3.1 Students at the English Universities

This paper presents a novel dataset on the students of the English universities of Oxford and Cambridge for the seventeenth and eighteenth century. The universities of Oxford and Cambridge were the only two universities in England during this timeframe. Overall, the dataset includes information on 144,748 students from the earliest times to the beginning of the nineteenth century. For the timeframe of 1600–1800 that is used for this paper, the empirical analysis can draw on 47,043 students at the University of Oxford, and 51,079 students at the University of Cambridge. The data is based on two detailed compilations of the matriculation and college registers of the the University of Oxford and Cambridge, the *Alumni Oxonienses* (Foster, 1891) and *Alumni Cantabrigienses* (Venn and Litt, 1952).

The individual micro-level information from the *Alumni Oxonienses* and *Alumni Cantabrigienses* is extracted using an automatic routine based on regular expression. To avoid OCR errors in the underlying data, the paper completely relies on manual transcripts. For the *Alumni Oxonienses 1500–1714*, the paper uses a double re-keyed transcript that was sponsered by *American Friends of the IHR* and made available through *British History Online*. For the *Alumni Oxonienses 1715–1886*, the paper uses a transcript from Wikidata (2022). Yet, by summer 2021 ca. 5% of the entries had not been fully transcribed. The author then transcribed these entries from the original. For the *Alumni Cantabrigienses*, the paper uses a full transcript made by *Ancestry.com* and published online by the *ACAD Cambridge Alumni Database* (see appendix section 9). Tables 13 and 16 provide a list of all variables automatically extracted from the text.[18]

Overall, Foster's *Alumni Oxonienses* and Venn and Litt's *Alumni Cantabrigienses* list a student's name, place of origin, status, time of matriculation and/or admission to college, all degrees, and the respective college a student was at for each degree,[19] as well as future careers within the Church, the Inn's of Court or the Royal College of Physicians. The *Alumni Oxonienses* and *Alumni Cantabrigienses* were compiled almost 50 years apart using slightly different methods. The individual publishing history, the individual methods used in compiling the original college registers, as well as the accuracy of these records are discussed in appendix section A.2.2.

In about 3/4 of all cases, the lists provided by Venn and Litt (1952) and Foster (1891) also include the address of a student's family. Omissions of a student's family address appear to have been more common in earlier periods. However, by the second quarter of the 17$^{\text{th}}$ century, recording the address of a student's family address seems to have been common practise at matriculation or admission processes. For about 1/3 of all addresses, the admission lists only give a student's county of origin, while we have detailed addresses for the rest, that provide locations at the village / town level.

Based on this data, students are matched to teachers based on the college they attended at the time of matriculation. This captures the teaching system at the universities of Oxford and Cambridge where teaching was mainly happening at the college-level.[20] Furthermore, it captures the close interaction between teachers and students outside the classroom while living in the same building.

[18] As the *Alumni Oxonienses* lack a list of the abbreviations used for status and degrees, a list of the complete and translated status titles has been produced as a side-product of this work (see appendix tables 19 and 20).

[19] In the case of a student not switching college, Foster only lists the college at matriculation time.

[20] There were a few university wide professorships offering classes to all students. However, their numbers were few and the main bulk of teaching was carried out the college-level. Since, classes by university professors were open to all students, this setup does not offer sufficient variation and is hence not further investigated by this paper. Furthermore, all students went through the same arts degree. Hence, teacher assignment also did not depend on students' choice of degrees or courses.

2.3.2 Publication titles, 1600–1800, and the direction of research

To capture the content of the British stock of knowledge of the seventeenth and eighteenth century, the paper uses the universe of 469,962 printed titles in England from the English Short Title Catalogue (ESTC) that were published between 1600 and 1800. Cleaning for duplicates leaves 285,985 titles (see appendix A.3.2). The ESTC was kindly shared by the British Library with the author. Seventeenth and eighteenth century publication titles offer comprehensive information on the published work, usually using the full space of the book cover and usually taking the form of short abstracts, that can be exploited using natural language processing. An average ESTC title for the subset of the fields of the Scientific Revolution consists of 48 words (see also appendix figure 7). Appendix A.3.1 lists a few examples and presents descriptive statistics on the titles.

The paper then uses the ESTC to construct a measure of teachers' and students' direction of research based on the subject fields teachers and students were publishing in. A researcher's number of publications in subject field i is denoted as b_i. A researcher's direction of research, v, is then defined as a vector of the researcher's strength of research, b/n, across the dimensions of m subject classes, $v = (b_1/n, b_2/n, \ldots b_m/n)$. For a more detailed definition, e.g. for the definition of the direction of research of all teachers, see section 2.4.1.

Furthermore, the paper investigates two other channels for the transmission of research interests from teachers to students, teacher innovativeness and teacher's distance to the frontier. Both measures have been identified in the literature as important factors that shape students' adoption of ideas (Waldinger, 2010; Biasi and Ma, 2022). Hence, they are treated as alternative hypotheses to students' exposure to teachers' direction of research.

However, seventeenth century titles create major challenges for the construction of these measures. While studies in the peer-effects literature using modern data can rely on citations and journal classifications to capture the research fields and innovativeness of publications (Waldinger, 2012; Iaria, Schwarz and Waldinger, 2018), this kind of data is not available for seventeenth century titles: First of all, during the seventeenth century, modern citation practises did not yet exist. Second, for the British ESTC data, classifications of individual titles are only available for about a third of all titles in the dataset. Therefore, the paper adopts an approach of using natural language processing with state-of-the-art transformer models to derive classifications of research fields, measures of innovativeness, and distance to the research frontier from the *content* of the ESTC titles. It is hoped that the new classification- and innovation-measures constructed by this paper will be of general use for the study of eighteenth century Britain.

2.3.3 Assigning subject classes

The paper uses a natural-language processing and machine-learning approach to assign subject classes to the universe of all ESTC titles based on state-of-the-art transformer models. For the training data, the paper relies on subject classes assigned by the British Library. They cover ~30% of the full ESTC dataset. These classes were assigned by the various curators of the dataset (right now, the British Library) and should be seen as high-quality assignments. The paper uses the information stored in these assignments to train a state-of-the-art large language model (LLM) to predict assignments for the rest of the dataset. Using large language models, the paper is able is use context-sensitive information and vector-space representations of the meaning of text as an input for the machine learning procedure. This way, obvious problems with seventeenth and eighteenth century text such as bias from changes in language or bias arising from the usage of different words for the same concepts are avoided. Furthermore, the approach allows for capturing similarities in the content of complex expositions and arguments.

Appendix section B.1.1 describes the actual pre-processing of the data, training process, and model evaluation in detail. The following is a short summary of the process:

1. Titles from other languages were translated into English to standardize the dataset. For this, the paper relied on the Google Translate API

2. The granular classification system of the British library were aggregated to 47 higher-order subject classes (see table 35)

3. A DistilBERT transformer model was trained on the classifications of ~30% of the ESTC dataset with pre-assigned subject classes

4. The pre-trained model is then used to predict subject classes the missing $\sim 70\%$ of the ESTC dataset

This process leads to a full classification of the universe of British publications between 1600 and 1800 into 47 higher order subject classes. The full list of 47 higher-order classes is listed in appendix table 35. Importantly, the paper uses 9 higher-order classes that capture the fields of the Scientific Revolution: *Almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.*[21]

2.3.4 Teacher innovativeness and proximity to the research frontier

The previous section has established a measure of students' and teachers' direction of research based on researchers' strength of research across multiple subject fields. The paper also investigates two alternative channels for the transmission of research interests from teachers to students, teacher innovativeness and teacher's proximity to the research frontier. Both measures have been identified in the literature as important factors that shape students' adoption of ideas (Waldinger, 2010; Biasi and Ma, 2022) and serve as alternative mechanisms for the transmission of ideas from teachers to students.

Both measures are based on mapping the text of the ESTC titles into text embeddings using a large language model (LLM). Then, the cosine distances between different vector representations of titles can be calculated to capture the distance between different titles. With this the paper creates two measures of teachers' research quality, first teachers' distance to the frontier and second, teachers' innovativeness:

Teachers' distance to the frontier: First, the paper defines the research frontier as all titles in the *Philosophical Transactions*, the journal of the Royal Society. During the seventeenth and early eighteenth century, the Royal Society was Britain's only scientific society, and would collect short papers on new findings at the frontier of contemporary science. Second, the paper calculates an ESTC title's average cosine similarity to the next forty years of the

[21] The paper conducts a wide range of robustness tests to show that the empirical results are robust to using other plausible definitions of the fields of the Scientific Revolution.

Philosophical Transactions as a measure of the research frontier. The calculation is carried out on a subject field by subject field basis.

Teachers' innovativeness: The paper uses the logic from Kelly et al. (2021) to calculate a measure of innovativeness based on the text of the titles. However, in contrast to Kelly et al. (2021), the paper uses text-embeddings from a large language model as an input for the calculation of title distances. This approach makes it possible to extract information on documents using complex and non-technical language as an input. Furthermore, in contrast to Kelly et al. (2021), this paper calculates the innovativeness index on a field-by-field basis. Intuitively, the paper defines an innovative publication as being a) novel and b) impactful. Being novel entails using new ideas and should therefore imply that a title has a high distance to the past of its field. Being impactful entails changing one's field and should therefore imply that a title has a high similarity to the future of its field. Following this logic, the paper calculates measures of 20 year *backward similarity*, 20 year *forward similarity*, and an index of *innovativeness* based on dividing *forward similarity* by *backward similarity.*

Appendix section A.3.6 describes the calculation of the two measures in further detail.

2.4 Empirical results

2.4.1 Framework

The empirical section is structured along three steps. First, this section sets out a framework to estimate the effect of teachers' direction of research on the lifetime direction of their students' research. Then, the next section presents baseline results for the teacher-effect. Finally, the paper presents two identification strategies to account for students' self-selection into colleges; first, an instrumental variable approach predicting a student's choice of college based on his place of birth and second, a natural experiment based on the parliamentary expulsion and intrusion of fellows at the University of Oxford.

First, we start by defining the measurement of the direction of research with respect to the Scientific Revolution: Assume that a single author publishes n books across publishing fields $\Phi = \{f_1, f_2, \ldots, f_m\}$. We further define the number of publications in a given field

j as b_j. Then the author's direction of research across all fields is given by the vector $v = (b_1/n, b_2/n, \ldots b_m/n)$. We can further define the average direction of research of a given number of multiple authors, μ as $p = 1/\mu \cdot (v_1 + v_2 + \cdots + v_m)$. With this we can define:

1. v: A student's direction of research

2. p: For all teachers at a college, their average research direction

To simplify the notation, we define the elements of these two vectors as:

1. v_j: A student's relative share of research in field j (b_1/n):

2. p_j: For all teachers at a college, their relative share of research in field j $((b_{1,1}/n + b_{1,2}/n + \cdots + b_{1,m})/\mu)$

By estimating the effect of p_j on v_j, we can estimate the effect of teacher's research interest in field j on student's research interest in field j. Analogously, by estimating the average effect of p_j on v_j for all $j \in v$, we can estimate the average effect of teachers' direction of research on student's direction of research across all fields of v. Using variation across all fields further means that we can estimate the model with student-fixed effects, thereby absorbing all unobserved student heterogeneity that is not field specific. The paper estimates the following model that uses variation across fields j and students i:

$$v_{jict} = \beta_1 p_{jict} + \boldsymbol{X'_{ct}} \beta_2 + \delta_i + \gamma_c + \zeta_j + \alpha_t + \varepsilon_{jict} \tag{1}$$

where the dependent variable, v_{jict}, captures student i's share of research in topic $v_j \in v$ at college c and matriculation cohort t. The treatment variable of interest, p_{jict} is the average teachers' share of research in topic v_j at college c at matriculation time t. The treatment happens at the college level, c, in time, t, where students are exposed to their college's teaching body. $\boldsymbol{X'_{ct}}$ is a vector of control variables for teacher characteristics. This includes the number of teachers at a college and the number of total teacher publications. To address overdispersion in count variables (number of publications, cohort size), we transform all count variables using the log-transformation. Likewise, all ratios all log-transformed to address overdispersion and to assure symmetry in the fixed-effects estimation (Gerdes, 2010).[22] The model further includes student-, topic-, college-, and time-fixed effects, δ_i, γ_c, ζ_j, and α_t. The model further allows to estimate the impact of all individual fields of the Scientific Revolution in determining teacher-directed change by interacting the teacher share, p_{jict}, by each field.

The model is based on the assumption of conditional exogeneity of teachers' direction of research at college c at time t, $\mathrm{E}(\varepsilon_{jict}|\beta_1 p_{jict}, \boldsymbol{X'_{it}}, \delta_i, \gamma_c, \zeta_j, \alpha_t) = 0$. This assumption is unlikely to hold as students interested in field j might have self-selected into a college where many teachers were working on field j. This issue is mitigated by only counting teachers and teacher fields at the time of a student's matriculation, thereby excluding variation coming from students that switched their colleges after some time at university. Thus, the analysis excludes all selection into colleges that was based on students' first-hands knowledge on the learning culture at other colleges. However, it is still possible that some students might have learned about teachers at different colleges even before coming to university and would have chosen their college accordingly. It is also possible that teachers selected into specific colleges. Hence, the paper exploits two identification strategies to establish a causal link for teacher-student effects. First, in an instrumental variable approach, it uses a student's place of origin as a predictor of future college affiliation. Second, it uses a natural experiment based on the parliamentary expulsion and intrusion of new fellows at the University of Oxford following the English Civil War. However, both strategies are restricted to a subset of the data, either due to the timing of the expulsion and forced appointments of fellows or data constraints on the information on students' home counties. Hence, both identification strategies present cumulative evidence on the presence of a causal teacher-student effect for the fields of the Scientific Revolution. The following section starts by presenting baseline results for the full sample and then continues by applying the two identification approaches to the baseline results.

[22]Because the logarithmic transformation is not defined at zero, we follow the conventional approach of adding a small number to the variables before applying the logarithmic transformation. In this case, other common methods to deal with overdispersions and zeros in the data are not applicable: Poisson or negative binomial estimators are not applicable to a continuos ratio as a dependent variable. Furthermore, the inverse hyperbolic sine transformation that is often used as an approximation for the logarithmic transformation significantly differs from the logarithmic transformation for small values such as ratios (Bellemare and Wichman, 2020; Aihounton and Henningsen, 2021).

2.4.2 How does teachers' direction of research affect students' direction of research?

This section presents the empirical evidence of teacher-directed scientific change at the English universities between 1620–1720. The section starts by providing a range of baseline results on the effect of teachers' direction of research on students' direction of research in the Scientific Revolution. It offers a simple decomposition of the teacher-effect by different research fields and compares the magnitude of the effect to other topics important to seventeenth century academia. Next, the section considers two alternative mechanisms, teachers' innovativeness and teachers' distance to the frontier. Lastly, the paper introduces two identification strategies that address possible bias from students' self-selection towards teachers interested in the same research fields. It first introduces an instrumental variable approach that exploits the historically strong ties between English regions and Oxford colleges by using a students' region of birth to predict their choice of college. Second, it introduces a difference-in-differences approach based on the expulsion and new appointment of fellows at the University of Oxford by parliament in 1647.

First, table 4 shows the main results of estimating the effect of teachers' direction of research for the fields of the Scientific Revolution on students' direction of research for the fields of the Scientific Revolution from equation 1. The fields of the Scientific Revolution are defined as *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.* The model estimates the average of field-specific teacher-effects on students' direction of research across all fields of the Scientific Revolution. It is based on the sample of all students that ever published.[23] Panel A shows the estimated coefficients for the University of Oxford and panel B shows the estimated coefficients for the University of Cambridge. Column (1) estimates the model from equation 1 with controls for student- and teacher-characteristics as well as college- and cohort-fixed effects. Column (2) adds topic-fixed effects. Column (3), further adds student-fixed effects. Overall, the size of coefficients decreases

[23]Since the paper's measure of the direction of research is not defined for students with zero publications, the model can only be estimated on publishing students. The number of students with at least one publication is $N = 1,276$ for the University of Oxford and $N = 1,359$ for the University of Cambridge.

Table 4: Effect of teachers' research fields on students' research fields

Panel A: University of Oxford			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	Mean topic	Mean topic	Mean topic
Log share of each topic in teacher publications	0.0662**	0.0285**	0.0297**
	(0.0201)	(0.00968)	(0.0112)
Teacher and college level controls	Yes	Yes	—
Student publication controls	Yes	Yes	—
Year fixed effects	Yes	Yes	—
College fixed effects	Yes	Yes	—
Topic fixed effects	No	Yes	Yes
Student fixed effects	No	No	Yes
Observations	11484	11484	11484
R-squared	0.02	0.04	0.17

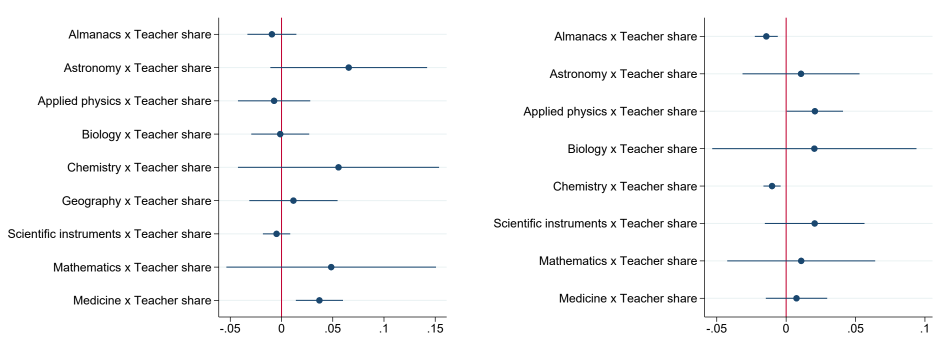
Panel B: University of Cambridge			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	Mean topic	Mean topic	Mean topic
Log share of each topic in teacher publications	0.0482**	0.0124***	0.00996***
	(0.0148)	(0.00359)	(0.000598)
Teacher and college level controls	Yes	Yes	—
Student publication controls	Yes	Yes	—
Year fixed effects	Yes	Yes	—
College fixed effects	Yes	Yes	—
Topic fixed effects	No	Yes	Yes
Student fixed effects	No	No	Yes
Observations	12231	12231	12231
R-squared	0.02	0.04	0.17

Notes: The table shows results from estimating equation 1. It estimates the effects of teachers' research fields on students' research fields for the 9 fields of the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. Column 1 estimates results for a baseline specification including teacher and student publication controls with college and college cohort effects. Column 2 adds topic fixed effects. Column 3 adds student fixed effects. Teacher controls include the log-transformed number of teacher publications, the log-transformed number of fellows at a college at a student's time of matriculation, and the log-transformed cohort size at a student's time of matriculation. Student controls include a student's log-transformed number of publications, and indicator variables taking the value of one if a student graduated with a B.A. or M.A, as well as a variable capturing the mean of all student publications that were predicted using machine learning. All count variables are transformed using the inverse hyperbolic sine transformation.. Standard errors are multi-way clustered at the student $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

with a higher number of fixed effects, suggesting that the model successfully captures positive sorting of teachers and students based on teacher-quality and student skills. Since student-fixed effects absorb all unobserved student heterogeneity, including students' general skills and previous education levels, column (3) is used as the preferred speciation for the discussion of results (yet sorting might also occur based on field-specific interests — see the next section for the IV approach and a quasi-natural experiment).

For the University of Oxford, in column (3), we find that increasing the share of teacher's research in one field of the Scientific Revolution by 100% leads to a 3% increase of the publication share in that field for the average student. The effect is sizeable given that it is estimated for the average student at a college including a high number of never-switchers (imagine e.g. a student who already decided to study theology before going to university or a student with a natural aversion to all mathematical subjects). Estimating the same model on the sub-sample of only students that published in the Scientific Revolution returns a significantly larger effect: Increasing the teacher publication share by 100% leads to a 16% increase in students' publication share (see appendix table 25). Yet, referring to the coefficients for the average student has one advantage: It also has the convenient interpretation of capturing the total change in the direction research of all graduates. For all Oxford graduates between 1620–1720, the lifetime publication share of works within the Scientific Revolution amounts to 4.53%. Increasing the Oxford teacher share in all the fields of the Scientific Revolution by 100% would have increased the graduate's publication share within the Scientific Revolution by 3% as well. Given that this shift affects the publishing output of students over their entire lifetime, the effect is clearly relevant.

Furthermore, when interpreting the coefficient we should also note that for the average student it was far more likely not to be exposed to a teacher publishing in any topic of the Scientific Revolution than to have such a teacher. Although 25% of all students had a teacher who published in at least one field of the Scientific Revolution, this also means that the number was much smaller for the individual fields of the Scientific Revolution: A student's average share of teacher-exposure to all nine topics of the Scientific Revolution was only 5.7% and the average publication share of teachers in the fields of the Scientific Revolution was only 0.06%. Therefore, a 100% increase of teachers' publication share in one topic would only raise the teachers' average publication share in the Scientific Revolution from 0.06% to 1.2%. Hence, the counterfactual of universities having at least one teacher publishing in any subject of the Scientific Revolution at every college would imply a much larger change in the teacher share than an increase by 100%. For example, a one standard deviation increase in the teachers' publication share in the Scientific Revolution by 5 percentage points would have increased the teacher-share by 647%. Such a change would have increased the overall student share in topics of the Scientific Revolution by 13.44% - a very sizeable effect for students' lifetime publishing outcomes. Given that university graduates accounted for at least 33% of all published titles in Britain (see appendix section A.3.3), this would also have been a significant shift in British intellectual life. Of course, in the light of seventeenth century intellectual life and seventeenth century academic politics, such a strong increase in teacher publishing in the Scientific Revolution is unlikely to have happened. However, the counterfactual illustrates the strength of the university teacher-channel. If someone had been in a position to change the full composition of the teaching body and to only appoint fellows working on a specific topic, this could have strongly impacted the direction of research and intellectual life among university graduates and British intellectual life. Given the context of the Oxford visitations in 1649 where Parliament evicted half of all Oxford fellows, such a counterfactual does not appear to be that unrealistic.



(a) University of Oxford

(b) University of Cambridge

Figure 3: Field-specific impact of teachers on students' research within the fields of the Scientific Revolution

Next, comparing the results for the University of Oxford (Panel A) to that of the University of Cambridge (Panel B), we can see that the teacher-effect for Oxford was stronger than for Cambridge. Looking at column (3), we can see that a 100% increase in the teacher-share in the Scientific Revolution led to a 1% increase in students' share of publications in the Scientific Revolution at the University of Cambridge, compared to a 3% increase at the University of Oxford. There are two possible explanations for this difference. First, the results would suggest that there was a university culture at Cambridge that was less conducive to the transmission of the ideas of the Scientific Revolution than at Oxford. For example, one could speculate that Parliament's radical reform of the University of Oxford might have contributed to a more open-minded teaching tradition. Furthermore, the the Cambridge Platonists, although an important group for the development of the new sciences, might have laid out a research program that was too theoretical to effectively inspire their students to pick up the new sciences. In contrast, the pragmatic and mechanical science of Boyle, Hooke, and Wilkins at the University of Oxford might have been more conducive to inspiring their students. Second, the difference in the strength of the teacher-effect might be due to a different composition of scientific fields taught at each university. To further understand the compositional effect of the teacher-student effect for the different fields of the Scientific Revolution, figure 3 interacts the coefficient from equation 1 by individual fields. The results show that teacher-effects at the University of Oxford were strongest in *astronomy, chemistry, mathematics, and medicine*, while at Cambridge the effect was strongest in *applied physics, biology, and scientific instruments.* Because, Medicine was the largest field in terms of publishing students and teachers, the absence of a strong teacher-effect in medicine at Cambridge might further explain its smaller coefficient for the teacher-effect across all fields (see also appendix table 25 that estimates the teacher-effect for different fields on the sub-sample of only students that published in the Scientific Revolution).

To further understand the importance of teacher-directed change in the Scientific Revolution, table 5 estimates equation 1 for other groups of British seventeenth century intellectual life, *art, religion, the public sphere, and classical education.* The group of art is composed of the fields of *poetry, music, and drama.* Religion is composed of *theology, dissenting theology, Catholic theology, Jewish theology, sermons, church administration, prophecies, and supernat-*

Table 5: Effect of teachers' research fields on students' research fields

Panel A: University of Oxford					
	Log share of each topic in student publications				
	(1)	(2)	(3)	(4)	(5)
	Scientific Revolution	Art	Religion	Public sphere	Classical education
Log share of each topic in teacher publications	0.0297**	0.0617	0.0158	-0.0111	0.00416
	(0.0112)	(0.0241)	(0.00919)	(0.0164)	(0.00859)
Topic fixed effects	Yes	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	11484	3828	10208	5104	8932
R-squared	0.17	0.44	0.37	0.32	0.19
Panel B: University of Cambridge					
	Log share of each topic in student publications				
	(1)	(2)	(3)	(4)	(5)
	Scientific Revolution	Art	Religion	Public sphere	Classical education
Log share of each topic in teacher publications	0.00996***	0.0353	0.0410**	0.00461	-0.0110
	(0.000596)	(0.0322)	(0.0137)	(0.00879)	(0.00818)
Topic fixed effects	No	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	12231	4077	10872	6795	10206
R-squared	0.17	0.47	0.39	0.33	0.18

Notes: The table shows results from estimating equation 1 on different groups of subject fields, *the Scientific Revolution*, *art*, *religion*, and *the public sphere*, and *classical education*. The fields of the Scientific Revolution are defined as *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*. The group of art is composed of the fields of *poetry, music, and drama*. Religion is composed of *theology, dissenting theology, Catholic theology, Jewish theology, sermons, church administration, prophecies, and supernatural occurrences*. The public sphere is composed of *administration, the law, reports of current events, and moral tales*, finally classical learning is composed of *philosophy, political philosophy, classical education (greek and roman), rhetorics, foreign languages, and pedagogical education*. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. The model includes cohort-, topic- and student-fixed effects. Standard errors are multi-way clustered at the college $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

ural occurrences. The public sphere is composed of *administration, the law, reports of current events, and moral tales*. Finally, classical learning is composed of *philosophy, political philosophy, classical education (Greek and Roman), rhetoric, foreign languages, and pedagogical education*. Table 5 reports the results. It shows that apart from the fields of the Scientific Revolution there only was a significant teacher-effect for the fields of religion. This strong teacher-effect in religion corresponds well to the overbearing role of religion on British society throughout the seventeenth century.

Hence, the fields of religion afford themselves as a good comparison group to understand the strength of the teacher-effect in the Scientific Revolution. It is clear that religion was important for students and that teachers could have strongly influenced a student's engagement with religion and theology. For the University of Oxford, we find that increasing the teachers' publication share in a field in religion by 100% increases students' publication share in that field by 1.6%, although we should note that the coefficient is insignificant. For Cambridge, we find a significant effect of 4.1%. These are coefficient sizes that are comparable to the ones found for the fields of the Scientific Revolution, 3% and 1%. Hence, the results confirm that the coefficients for the teacher-effect in the Scientific Revolution are comparable to the teacher-effect in religion, the most dominant topic of the seventeenth century.

We can also reflect on the fact that teacher-directed change only seems to have been present for fields that were discussed divisively at the time. The Scientific Revolution broke with many core-beliefs of the scholastic Aristotelianism that was taught at universities and challenged many beliefs about nature and humankind's place in nature. Likewise, the seventeenth century was the century of religious conflict and religious debates. In contrast, the fields of classical education would have been part of the old scholastic curriculum and would have been widely accepted in their current form. Likewise, the material taught at universities that related to the arts and the public sphere (thinking e.g. about rhetoric, or the study of historical dramata) was not contested, even though topics in art or the public sphere surely were the subject of politically divisive views. Hence, it appears that teacher-directed change might have been stronger for areas that were divisive and strongly contested.[24]

2.5 Identification

2.5.1 Instrumental variable approach: Predicting students' choice of college based on their parish of birth

This section introduces an instrumental variable approach that exploits the strong ties between colleges at the University of Oxford and English regions.[25] It uses college-enrolment shares per hundred (an old administrative unit) to predict a student's choice of college at the time of their

[24] In Kuhnian (1962) terms, we could say that teacher-directed change was more important for fields in its revolutionary phase and less important for normal science.

[25] With the exception of the interregnum from 1648–1659 where the matriculation records omit a student's place of origin. Hence, unfortunately this approach cannot be combined with the previous difference-in-differences strategy.

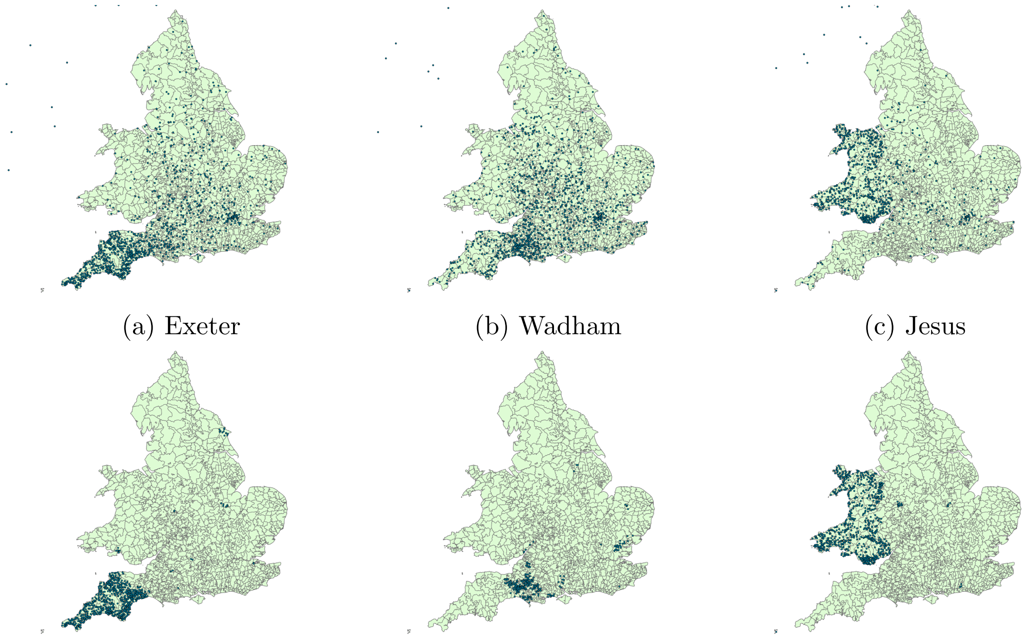
birth.[26] The instrumental variable then assigns each student the teacher publications from their predicted college. Thus, predicted exposure to teacher publications should be orthogonal to any student-factor determined after their birth, especially a student's interest in specific topics. Furthermore, the prediction is based on region specific college affiliations, thus it should also be orthogonal to any interests passed on within a family that are not universal to a region.

In order to predict a student's choice of college based on his place of origin, the paper first calculates college-shares for all English hundreds. It then imposes a a uniqueness condition that identifies hundreds with strong college-ties. Only hundreds with more than 2 students and hundreds with more than 20% of all students from the hundred enrolling at one specific college are considered to have had strong college ties. Thus, the analysis is conducted on a subsample of the whole student body based on two conditions 1) a student's place of origin is recorded and 2) their parish of origin had strong college-ties. Then in a next step, each hundred is assigned a predicted college based on the maximum college shares in that hundred. Figure 4 illustrates the process for three Oxford colleges, Exeter, Wadham, and Jesus College. The figure compares the actual spatial distribution of students' places of origin to the hundreds that are predicted as having strong-ties to that college.

Overall, for the sample of 1620–1720, 72% of all students have geo information at the hundred level. Out of these, 61% came from hundreds that were strongly aligned with an individual college. Table 32 and 33 present balancedness statistics for each subsample. Most of the missing observations of place of origin are due to a changed recording practice between 1648–1659. After the Parliamentarian reform of the university, the intruded-keeper of the records could not get access to the old student register and discontinued the recording of places of origin (Porter, 1997, p. 30) (see also the discussion of the college register in section A.2.2). Hence, the IV approach necessarily misses the teacher-effect during the interregnum.

Table 6 presents the results of the instrumental variable approach for the period 1620–1648 and 1660–1720 (given that the period 1648–1659 is missing). For the ease of comparison,

[26] Here the paper assumes that a student's place of origin as recorded in the university registers correspond to their place of birth. Surely, families could have moved in the meantime. However, the paper assumes that family locations were usually fixed in the seventeenth century. Furthermore location changes are unlikely to have to have been based on the college-affiliation of areas, thereby justifying this simplifying assumption.



(a) Exeter (b) Wadham (c) Jesus

(d) Exeter — predicted (e) Wadham — predicted (f) Jesus — predicted

FIGURE 4: Students' place of origin by colleges, actual and predicted distribution

column (1) presents the baseline results from equation 1 for the period of 1620–1720. Column (2) estimates the same model on the restricted sample of students with geo-information and coming from a parish with strong college-ties. As is shown by balancedness tables 32 and 33, the set of students with available geo-information and coming from a parish with with strong college ties is not representative for the wider dataset. Based on narrative evidence (Porter, 1997), it seems that hundreds with strong college ties are likely to have been older and richer and that students coming from these parishes are likely to have had a better prior education and better career prospects. Thus, column (2) finds a markedly stronger teacher-student student for the subsample of students with available geo-information and coming from a parish with strong college-ties. The next columns present the results for the instrumental variable approach. Column (3) present the reduced form results. Column (4) presents the the results from the instrumental variable approach. The IV-model predicts that a 100% change in teachers' publication share in the fields of the Scientific Revolution lead to a 3.6% increase in students' publication share in the fields of the Scientific Revolution. The estimate is of a very similar size to to the OLS results on the same sample of 4.2% in column (2). Thus, the

Table 6: Instrumental variable approach based on college-region ties for the University of Oxford

	Baseline	With geo info	Reduced form	IV
	(1)	(2)	(3)	(4)
	Mean top.	Mean top.	Mean top.	Mean top.
Log share of each topic of teacher publications	0.0297**	0.0424**		0.0358**
	(0.0112)	(0.0152)		(0.0121)
Log share of each topic of predicted teacher publications			0.00941*	
			(0.00478)	
Topic fixed effects	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes
Observations	11484	4743	4743	4743
R-squared	0.169	0.160	0.158	—
Centered R-squared				0.003
Kleibergen Paap F-statistic				32.82

Notes: The table shows results from estimating equation 1. It estimates the effects of teachers' research fields on students' research fields for the fields of the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within the fields of the Scientific Revolution of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in the fields of the Scientific Revolution out of all publications from student i. Column 1 estimates results for the baseline specification from table 4 for the sample of 1660–1720. Column 2 estimates the same specification for the sub-sample of all students with available geo-information and coming from parishes with strong college-ties. Column 3 presents first stage results for the instrument of predicted teacher publication shares based on a student's home parish. Column 4 presents the IV coefficents for the instrumental variable regression. Teacher controls includes the number of teacher publications. Student controls include dummies for whether a student graduated with a B.A. or M.A. Standard errors clustered at the college level in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

IV-approach indicates that bias arising from sorting affects seems to have been relatively small. This seems to fit the discussion in section A.1.1 that showed the new scientific topics were held in low esteem by public opinion. Hence, it is unlikely that parents would have actively chosen colleges on the basis of having teachers that were interested in the Scientific Revolution. The model has a Kleibergen Paap F-statistic of 32.82 indicating a moderately strong first stage.

The validity of the instrument is based on the exogeneity of the geographical college shares. Since the regional links of colleges dated back to the earliest times of the university, long before the emergence of the Scientific Revolution, the assumption appears plausible. Yet, we cannot rule out that some regions with links to colleges with a high share of teachers' publications in the Scientific Revolution were also on different growth-trends. Additionally, some historians have argued for a link between the Scientific Revolution and the emergent capitalism embedded in highly-skilled craftsmen (Zilsel and Zilsel, 2003). Hence, pre-trends in growth for regions associated with colleges with a high share of teachers in the Scientific Revolution would pose a violation to the exogeneity assumption of the instrument.

To account for this challenge to the exogeneity of the instrumental variable, the paper tests whether there was an association between city growth and the growth rate of the predicted teachers' publication share in the Scientific Revolution. Results are shown in appendix tables 30–31. Results are shown for Bairoch (1988) city growth for both the period of 1500–1600 and 1600–1700. Table 30 reports results for the city level and table 31 reports results for the county level. Throughout all specification, we do not find evidence of a significant effect of city growth rate on the growth rate of predicted teachers' publication share for a) all fields of the Scientific Revolution as well as b) all individual fields. Hence, it appears that local economic development as proxied through city growth did not affect trends in the instrumental variable.

2.5.2 Quasi-natural Experiment: Forced appointment of Oxford fellows during the Parliamentary visitations of Oxford

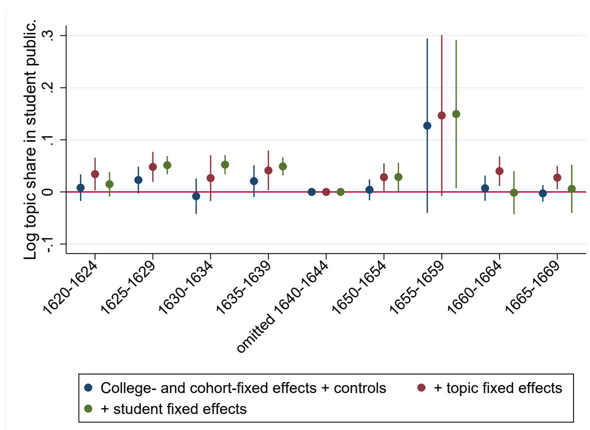


FIGURE 5: Difference in differences results for the change in intruded teachers publishing in the fields of the Scientific Revolution

Notes: The figure presents results from estimating equation 2 estimating the effect of the publication share in the Scientific Revolution from fellows appointed by Parliament on students' publication shares. The regression is estimated at the student × research field × year level. The graph shows the teacher-coefficients for three specification. A baseline model with college- and cohort-fixed effects as well as teacher- and student-control, a second specification with additional topic-fixed effect, and a third specification with student-fixed effects. The sample is limited to only publishing students. The treatment period are the two periods 1650-1654 and 1655-59. $N = 4,734$. *Standard errors are two-way clustered at the college and topic level. Confidence intervals are shown at the 90% level.*

This section introduces an identification approach that is based on the sudden and unexpected dismissal of teachers at the University of Oxford and the unexpected arrival of new teachers. This shock is based on the expulsion and forced appointment of fellows at the University of Oxford by the parliamentary visitors after the end of the English Civil war. The logic of the approach is outlined in section 2.2.2. The paper takes the forced appointment of fellows who published in the fields of the Scientific Revolution as an exogenous shock in a flexible difference-in-differences design:

$$v_{jict} = \sum_{\tau=1625-29}^{1655-1659} \beta_\tau \cdot \text{Appointed fellow field}_{jic} + \boldsymbol{X'_{ct}}\beta_2 + \delta_i + \gamma_c + \zeta_j + \alpha_t + \varepsilon_{jict} \tag{2}$$

where the dependent variable v_{jict} measures the share of student i's publications in research field j for all fields of the Scientific Revolution. The estimated coefficients β_τ capture the teacher publication shares from the forcibly appointed teachers. Technically, the paper uses only those fellows that were appointed by the visitors themselves and that came from outside their own college. Table 3 shows that this captures 76% of all newly appointed fellows during the period of 1648–1652. The rest of fellows were appointed by the reformed colleges themselves and hence potentially influenced by endogenous selection criteria of the colleges themselves. $\boldsymbol{X'_{ict}}\zeta$ captures teacher and student controls such as the number of student and teacher publications. It further imposes college- and cohort-fixed effect, γ_c and α_t, as well as topic- and student-fixed effects, ζ_j and δ_i.

Figure 5 presents the estimated coefficients for the flexible difference-in-differences model. The omitted period is 1640–1644, the last period not affected by the visitation shock. The treated period consists of the two treated period during the interregnum, 1650-54 and 1655-1659. After the interregnum, the new Royalist government ejected the fellows appointed by parliament and reinstituted many of those fellows that had been evicted by Parliament before. Hence in this setup, we can test for both pre-trends and post-trends as an indication of the plausibility of the parallel-trends assumption. The paper finds that both pre- and post-trends are flat. Additionally, it finds a slightly delayed treatment effect in 1655-1659: An increase in the publication share within the fields of the Scientific Revolution of the fellows appointed by parliament by 100% leads to a 15% increase in students' publication share in the Scientific Revolution. The effect is found to be significantly larger than the baseline coefficient of 3%.

However, the setup of the difference-in-difference design differs from the baseline along two dimension: First, the difference-in-differences model only returns the average treatment effects for fellows appointed by the Parliamentary visitors. After the initial appointments by the visitors, colleges were free to appoint fellows on there own which were often people closely connected to the newly appointed fellows and newly appointed heads of colleges. Thus, we would expect that the initial shock of the appointment of scientifically interested fellows would have led to further recruitment of scientifically interested fellows. Furthermore, the newly appointed fellows were younger than the fellows who had survived the visitation (Reinhart, 1984). This might have made them more relatable to their students, but might also speak to less teaching experience. Second, it is important to remember that difference-in-differences design is only estimated for the interregnum between 1650–1659. This was a period that was influenced by new Puritan ideas of education and science and might have been more conducive to the propagation of the Scientific Revolution than the rest of the period (Merton, 1938; Webster, 1977).

Hence, we should be careful in extrapolating this treatment effect to the full period and to all fellows. Yet, finding a strong and causal teacher-student effect based an exogenous shock to the distribution of scientifically interested fellows across colleges, even if only one 10 year-period, adds to the plausibility of a general causal teacher-student effect in the fields of the Scientific Revolution. Afterall, while this period was not representative among many dimensions (especially cultural ones), it is also not fundamentally different. The formal functioning of the university and the teaching curriculum remained virtually unchanged. Furthermore, the reformation of the universities by Parliament was mostly a political and religious endeavour. Basic attitudes to science would only have been affected indirectly. Hence, the paper argues that the results of the difference-in-differences approach should be seen as additional evidence that adds the plausibility of assuming the presence of teacher-directed change at the English universities for the whole period of the Scientific Revolution.

2.6 Mechanism

2.6.1 Basic mechanism and robustness checks

The paper further conducts a range of exploratory analyses to further investigate the mechanism between teacher-directed scientific change:

1. So far, the paper has tested the effect of teachers' direction of research in the Scientific Revolution on students' direction of research. In an exploratory analysis, the paper also tests whether exposure to scientifically interested teachers increased the general likelihood of publishing or the intensity of publishing (the number of students' publications). Such an effect would suggest that scientifically interested teachers might have been more effective in increasing students' general interest in research. However, table 28 shows that we cannot find evidence of such an effect. To the contrary, at Cambridge scientifically-interested teachers might even have led to a decrease in students' average number of publications.

2. We can distinguish between a field-specific teacher-effect in the fields in the Scientific Revolution and a non field specific effect of being exposed to any field of the Scientific Revolution. This mechanism would capture, e.g. a general culture within the new sciences, e.g. a quantitative and mathematical spirit as well as the focus on experiments. In appendix table 29, the paper further adds an explanatory variable that captures the share of teacher publications in any field of the Scientific Revolution. On its own, the coefficient is found to be positive and significant. However, in a horse race with the field specific teacher-effect from table 4 it is shown that the general culture channel only accounts for a small part of the previously found field-specific teacher-effect. Hence, the overall teacher-effect seems to be mainly driven by teachers passing on an interest in a specific research agenda within their own field.

The paper further conducts the following robustness checks:

1. The paper investigates if our results hold when restricting the fields of the Scientific Revolution to the "physical core" of *astronomy, applied physics, and mathematics* as-

sociated with the Newtonian Revolution. Table 26 presents the results. The coefficient is significant and positive for both universities. We can note the coefficient for Oxford is even larger for the *physical core* than in the baseline in table 4. This speaks to the importance of this physical core for the Scientific Revolution at Oxford.

2. One potential worry is that the teacher-effect captures other contemporary forces that might have changed students' future careers that then would have led to a stronger exposure to the fields of the Scientific Revolution. to test this hypothesis the paper tests whether teacher exposure to the fields of the Scientific Revolution could predict students' future degrees in medicine or law as well as students' future careers in the church, as a physician, or in law. It also tests whether it increases students' chances to become an M.P. or to be mentioned in the *Dictionary of National Biography.* The paper does not find that the teacher-effect has predictive power for any of these outcomes.

2.6.2 Alternative mechanisms: Teacher innovativeness and distance to research frontier

Next, the paper considers alternative channels to the direction of research through which teachers could have influenced their students. First, the paper considers teacher innovativeness. It is plausible that innovative teachers might have been able to create new research agendas and inspired their students to follow up on them (Waldinger, 2010). Innovative teachers might also have had a role model effect on their students (Akerlof and Kranton, 2002; Bettinger and Long, 2005). Second, the paper considers proximity to the research frontier. In line with the concept of an "education-innovation gap" (Biasi and Ma, 2022), we would expect that teachers who are publishing at the research-frontier of the Scientific Revolution would increase students' chances to both publish in the fields of the Scientific Revolution as well to publish at the frontier of the Scientific Revolution. To capture proximity to the research frontier we measure students' and teachers' textual distance to the *Philosophical Transactions*, the journal of the Royal Society and the only scientific journal in Britain for the period under consideration.

Teachers' average innovativeness in field j is measured as the field-specific average of the innovativeness index introduced in section 2.3.4. Intuitively, the innovativeness index captures how much an author's publication changed the field in the future, by dividing its forward similarity to all other titles in the future by the backward similarity to all the papers in the past. For calculating the index, this paper uses a twenty-year period of backward- and forward-comparison. The paper then adds teachers' average innovativeness as an additional regressor to the model from equation 1.[27] To capture teachers' proximity to the research frontier (Biasi and Ma, 2022), the paper constructs an NLP-based measure of the proximity of teachers' publications to the publications in the *Philosophical Transactions*. Students' *similarity* to the *Philosophical Transactions* is defined analogously.

Table 7 presents the results for these alternative channels of knowledge transmission on students' direction of research. The table compares four different channels: (1) the extensive margin of being exposed to at least one teacher who published at least once in a given field of the Scientific Revolution, (2) teachers' direction of research as estimated in table 4, (3) teachers innovativeness for the fields of the Scientific Revolution, and (4) teachers' proximity to the research frontier. Column (5) compares the explanatory power of all four mechanisms in a horse race. We see that individually all mechanisms, except for the extensive margin, have a significant effect on students' direction of research. The effect is largest for teachers' direction of research: For Oxford, increasing teachers' direction of research by 100% increases students' direction of research by 3%. In contrast, increasing the teachers' innovation index by 100% increases students' direction of research by 1%. Increasing teachers' proximity to the *Philosophical Transactions* by 100% increases students' direction of research by 1.5%. However, it is clear that all three mechanisms are related to each other. Hence, column 5 runs a horse race to test the relative importance of each channel for shaping students' direction of research. Although all four coefficients remain insignificant, it is noteworthy that both the extensive margin and teachers' proximity to the Philosophical Transactions are relatively precisely esti-

[27]Formally, the paper constructs a vector of teacher innovativeness across the dimensions of the fields of the Scientific Revolution. The vector of teacher-innovativeness, ι, is defined as an author's average innovativeness in field j, ι_j, across all fields, f: $v = (\iota_1, \iota_2, \ldots \iota_n)$. The vector of teacher innovativeness is then defined as the average of innovativeness in field j across all teachers, analogous to teachers' direction of research, p in section 2.4.1. The vector of similarity to the *Philosophical Transactions* is constructed analogously.

mated at zero. For Cambridge, the results look similar: Again, teachers' direction of research has the largest effect on students' direction of research. Teachers' innovativeness and teachers' proximity to the *Philosophical Transactions* are individually positive, but insignificant. In the horse race specification in column 5, we find again that both the extensive margin and teachers' proximity to the *Philosophical Transactions* is estimated relatively precisely at zero.

Hence, we can rule out that either the extensive margin or proximity to the research frontier are likely to be the main driver of the teacher-effect on students' direction of research. Furthermore, it appears likely that teachers' direction of research is the main mechanism in influencing students' direction of research, although the results indicate that teachers' innovativeness might play a smaller role as well.

Table 8 repeats the same setup for students' similarity to the *Philosophical Transactions* as a proxy for similarity to the research frontier. Crucially, we find that the only significant predictor is teachers' direction of research. Notably, teachers' similarity to the research frontier is individually insignificant and in column 5 precisely estimated at zero. Hence, teachers' direction of research not only seems to be a better predictor for students' direction of research than teachers' proximity to the research frontier, but teachers' direction of research also appears to be a better predictor of students' proximity to the research frontier than teachers' proximity to the research frontier. These findings underline the importance of teachers' direction of research in the transmission of knowledge and interest in the Scientific Revolution. The paper shows that teachers' intensity of research in a given subject seems to dominate teachers' innovativeness and teachers' proximity to the research frontier.

These results also yield a counterfactual policy implication for seventeenth century universities. If one would have wanted to direct future research towards the fields of the Scientific Revolution, it would have been important to appoint teachers whose direction of research was aligned with the Scientific Revolution. However, appointing innovative teachers or teachers at the frontier of research would only appear as a secondary concern.

Table 7: Effect of teachers' innovativeness on students' direction of research

Panel A: University of Oxford

	Share of each topic in student publications				
	(1)	(2)	(3)	(4)	(5)
	Mean top.	Mean top.	Mean top.	Mean top.	Mean top.
At least one teacher published in the topic	0.0496				-0.0890
	(0.0268)				(0.234)
Log share of each topic of teacher publications		0.0297**			0.0485
		(0.0112)			(0.0271)
Log teacher innovation index for each topic			0.0109*		0.0327
			(0.00551)		(0.0564)
Log teacher proximity to Philosophical Transactions for each topic				0.0151*	-0.0361
				(0.00749)	(0.0278)
Year fixed effects	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	11484	11484	11484	11484	11484
R-squared	0.17	0.17	0.17	0.17	0.17

Panel B: University of Cambridge

	Share of each topic in student publications				
	(1)	(2)	(3)	(4)	(5)
	Mean top.	Mean top.	Mean top.	Mean top.	Mean top.
At least one teacher published in the topic	0.0164				-0.281
	(0.0146)				(0.314)
Log share of each topic of teacher publications		0.00873***			0.00383
		(0.000797)			(0.0119)
Log teacher innovation index for each topic			0.00366		0.0741
			(0.00268)		(0.0724)
Log teacher proximity to Philosophical Transactions for each topic				0.00492	-0.0156
				(0.00401)	(0.0553)
Year fixed effects	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	13851	13851	13851	13851	13851
R-squared	0.17	0.17	0.17	0.17	0.17

Notes: The table shows results from estimating equation 1 while further adding a measure of teachers' average innovativeness. It estimates the effects of teachers' research fields on students' research fields for the 9 fields of the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. Likewise, teacher's average innovativeness in field j, ι_j is measured as the field-specific average of the innovativeness index introduced in section 2.3.4. The model includes student-, topic-, and cohort fixed effects. All count variables are transformed using the inverse hyperbolic sine transformation. Standard errors are multi-way clustered at the college $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 8: Effect of teachers' innovativeness on students' direction of research

Panel A: University of Oxford					
	Similarity to Philosophical Transactions of the Royal Society				
	(1)	(2)	(3)	(4)	(5)
	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans
At least one teacher published in the topic	0.0430				-0.0725
	(0.0249)				(0.220)
Log share of each topic of teacher publications		0.0258**			0.0428*
		(0.0109)			(0.0208)
Log teacher innovation index for each topic			0.00945*		0.0229
			(0.00507)		(0.0434)
Log teacher proximity to Philosophical Transactions for each topic				0.0131*	-0.0252
				(0.00696)	(0.0317)
Year fixed effects	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	11484	11484	11484	11484	11484
R-squared	0.20	0.20	0.20	0.20	0.20
Panel B: University of Cambridge					
	Similarity to Philosophical Transactions of the Royal Society				
	(1)	(2)	(3)	(4)	(5)
	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans	Sim. PhilTrans
At least one teacher published in the topic	0.0154				-0.279
	(0.00874)				(0.250)
Log share of each topic of teacher publications		0.00720***			0.000393
		(0.000405)			(0.00798)
Log teacher innovation index for each topic			0.00345***		0.0722
			(0.000976)		(0.0575)
Log teacher proximity to Philosophical Transactions for each topic				0.00468**	-0.0121
				(0.00152)	(0.0443)
Year fixed effects	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	13851	13851	13851	13851	13851
R-squared	0.19	0.19	0.19	0.19	0.19

Notes: The table shows results from estimating equation 1 while further adding measures for the extensive margin (being exposed to at least one teacher who published at least once in a given field of the Scientific Revolution), teachers' innovativeness, and teachers' proximity to the *Philosophical Transactions* as a proxy for proximity to the research frontier. It estimates the effects of teachers' research fields on students' research fields for the 9 fields of the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. Likewise, teacher's average innovativeness in field j, ι_j is measured as the field-specific average of the innovativeness index introduced in section 2.3.4. The model includes student-, topic-, and cohort fixed effects. All count variables are transformed using the inverse hyperbolic sine transformation. Standard errors are multi-way clustered at the college $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

2.7 Conclusion

Overall, the paper has shown concrete evidence of teacher-directed scientific change during the English Scientific Revolution. It has shown that teachers at the English universities of Oxford and Cambridge had a strong impact on the research direction of their students for the fields of the Scientific Revolution. These results contribute to our understanding of teacher-directed scientific change in general as well as to our understanding of the English Scientific Revolution.

By matching the universe of university students and teachers between 1600–1800 and all English printed titles between 1600–1800, the paper provides novel data on the research trajectory at English universities during the time of the Scientific Revolution. The paper operationalizes the text-data on titles by using a machine learning approach based on the subject classification of the British library that is available for a subset of the data. It further used a transformer-model based modification of the Kelly et al. (2021) approach to create a measure of the innovativeness of individual titles. By using data on a topic- and sub-student level, the paper is able to estimate the effect of teachers' direction of research on students' direction of research while applying topic- and student- fixed effects. Thus, the model absorbs all non-topic specific factors of student heterogeneity, such as talent or economic background.

Using this data, the paper has shown that teachers' direction of research is a strong determinant on students' direction of research for the fields of the Scientific Revolution. The results indicate that the teacher-effect is strong and relevant and can account for 6% of students' share of research within the Scientific Revolution at Oxford and 2% at Cambridge. Given that the outcome is based on students' lifetime publications, this is a highly relevant effect. The paper has further argued that even larger effects had been possible if each college had had a small number of teachers interested in the Scientific Revolution. Hence, the results of the paper highlight the potential impact of teacher-directed change on the direction of science and paradigm change (Kuhn, 1962).

In order to show that these results are causal, the paper introduced two distinct identification approaches. First, it has used an instrumental variable approach based on the strong ties between individual colleges and English regions. Based on this pattern, the paper has predicted a student's future college based on his place of origin and then predicted the teachers a student would face at college. Using the research direction of predicted teachers as an instrument, the paper has shown that both the OLS and IV coefficient have a similar size. Hence, the estimated effect does not seem to be driven by students' selection to teachers with similar interests. The paper has further used a difference-in-differences approach based on the eviction and forced appointments of new teachers by victorious Parliament following the English Civil War. The results also indicate the presence of a strong teacher-student effect.

These results contribute to our understanding of teacher-directed technical change. So far, evidence of teacher-directed scientific and technical change has been limited to the case of business schools (Acemoglu, He and Le Maire, 2022), composers in classical-music (Borowiecki, 2022), and PhD students in mathematics during the dismissal of Jewish scientists in Nazi Germany Waldinger (2010). This paper contributes the literature by presenting evidence of teacher-directed scientific change during one the largest shifts in the direction of science throughout history, the Scientific Revolution. Thus, it has presented evidence that the future research trajectory of students can be crucially determined by their exposure to teachers at university. Hence, changing the composition of teachers at university can have a long-lasting impact on society's research trajectory. This effect even holds for events of crucial paradigm change, such as the Scientific Revolution.

The paper has further contributed to the historical literature on the role of the English universities for the Scientific Revolution that has been severely contested. While some scholars have argued that the universities were an "intellectual desert" (Manuel, 1968, p. 133) or an "intellectual wasteland" (Westfall, 1983, p. 190), others have argued that universities were important places for the transmission of new ideas from teachers to students (Gascoigne, 1990; Feingold, 1984, 1997). This paper provides a clear quantitative answer by showing that teachers at the English universities were able to pass on their research interests in the Scientific Revolution. Thus, it seems that universities were an important place for the early intellectual formation of many English scientists of the seventeenth century.

Lastly, the paper begs the question of how much of the western take-off in science can be explained by comparing different institutional designs of learning environments. For example, China's education system was built around a centralized civil service exam that every future civil servant needed to pass. Hence, the civil service exam might have created incentives for complying with tradition and against adopting novel ideas (Needham, 1964; Lin, 1995; Ma, 2021). Huff (2003) also argues that Islamic madrasas were important centres of learning, but were exclusively centred on religion. Furthermore, early Islamic advances in science often originated in small and short-lived circles of learning that never managed to achieve a full institutionalization (Huff, 2003) (the same can be said about early Italian academies). In contrast, the English university system always aimed at providing a broad education across many fields and fostered the exchange between fellows and students through living together in a closed college environment. This paper shows that teacher-directed change in the Scientific Revolution had a significant effect on the lifetime direction of research of the graduates of the English universities. One can speculate that the effects of teacher-directed scientific change at other important European universities of the seventeenth century, such as Leyden, Padua, or Paris would have been of a similar size. Hopefully, future research can shed more quantitative evidence on the European scale of teacher-directed change in the Scientific Revolution. Similarly, it seems that future comparative research could shed further light on the global importance of European universities for the Scientific Revolution and the rise of the west.

Appendices

A Appendix for Paper 1

A.1 History of the seventeenth and eighteenth century English university

A.1.1 Students

In the seventeenth century, most of a student's learning and social life at the English universities of Oxford and Cambridge was centred around the individual colleges. This was before the emergence of social clubs that would bring students into contact with their peers from other colleges. In contrast, the social life of students in the seventeenth century was more strictly regulated than in the centuries to come and it was centred at a student's own college (Brockliss, 2016). Furthermore, while originally lectures were held through chairs at the university, this declined throughout the fifteenth and sixteenth century. Instead, since the sixteenth century, colleges themselves increasingly took up the duty of teaching their undergraduates, establishing college lectureships and college tutorial systems (Feingold, 1990, p. 8). Hence, educational experiences at the universities of Oxford and Cambridge would have differed according to the presence of different fellows at different colleges. Furthermore, fellowships were only held for an average of about 10 years, leading to constant change in the teaching body. Hence, this setting creates valuable variation at the college level over time. In order to illustrate the working of this college channel, this section will give a short portrayal of students' and faculties' life at the English universities of the seventeenth century.

In the seventeenth century, a student's decision to go to university could be based on different motivations. Many boys still came to Oxford for its traditional role as a training ground for the clergy.[28] "William Trumbull instructed his son to concentrate on Greek, Latin, and the 'liberal arts' and to 'learn to make a verse, a theme and an oration'." (Porter, 1997,

[28] Note that during the seventeenth and eighteenth century, girls were excluded from attending university. Catholic students were excluded as well - these often attended the English college at Douai. Furthermore, non-Anglicans were excluded as well. Further note that before the English Civil War, Puritans were usually seen as reformer within the Anglican Church, not outside the Anglican Church. Hence, before the English Civil War, Puritans were not excluded, although some Puritan students might have been deterred by the Laudian administration.

p. 27, citing from Berks, RO Trumbull Add. MS 46, letter 24 August 1622), a list of the humanistic skills valued by higher society in the seventeenth century. William Trumbull's list does not include mathematics, nor does it even touch the areas of the "new sciences". Such views would have been representative among student's parents. Indeed, the historical evidence illustrates that parents did not have an interest in choosing colleges with a strong reputation in mathematics or the "new sciences". To the opposite, Hill (1965, p. 55) provides examples of how some parents disapproved of their students being exposed to the mathematical "black art" (Osborne, 1689, p. 5) or the "art diabolical" (Ward and Wilkins, 1654, p. 58).[29] Even parents with less strong opinions feared that "the new sciences" would "either distract them [their sons] from more important studies or adversely affect their cultivation of good breeding" (Feingold, 1997, p. 428). Feingold (1997, ibid.) further shows how opinions of the sciences being non-becoming for higher status were mixed with practical considerations. Thus, we can read how in 1688, Edmund Verney's father vividly warned his sons against the perils of studying chemistry:

> "I am gladd, you didd not goe through with a course of chymistry. That sort of learning I do not approve of for you; it is only usefull unto physicians and it impoverisheth often those that study it, and brings constantly a trayne of beggars along with it." (Verney, 1899, p. 405)

Instead key aspects for seventeenth century parents choosing a college for their son would have been personal contacts and the regional focus of a college, as well as its religious leaning (Brockliss, 2016, p. 232).

Once a student had enrolled at a college, he would be fitted into the ranks of the student body. At Oxford, there were foundationers, whose education was sponsored through college scholarships, and non-foundationers paying for their own education (Brockliss, 2016, p. 226).[30] The foundationers themselves were split into different groups. At the top were the fellow

[29] Seeing mathematics as a part of the dark arts had a long European history (see e.g. Taylor 1957, p. 90.)

[30] The system at Cambridge, split between sizars at the bottom, pensioners, and fellow commoners at the top was, except for naming conventions, almost identical to its sister university. Hence, for brevity's sake the following discussion will illustrate basic features of 17th century university life by the example of the University of Oxford.

commoners, paying the highest entrance fee and often being of noble descent. Below them came the commoners who also paid the full tuition. They were followed by battelers, not being supplied with the "commons" at dinner, but also paying lower fees. At the bottom were the pauperi, performing additional duties for the college in return for even lower fees, and often taking up the role of servitors to the upper student ranks or faculty (Brockliss, 2016, p. 227). The different status translated into different accommodation, gowns, and quality of food (ibid.).

These differences in status also translated themselves into the daily college life. Gentleman commoners dined at the fellow's table at the end of the hall, while ordinary commoners and battelers dined at separate tables. Servitors and the pauperi would wait for the upper ranks to finish, while the servitors would assist their masters. Only then would they dine on the leftovers from the upper ranks (Brockliss, 2016, p. 229).

However, the formal ritualization of social ranks does not imply that the fellows did not socially interact with the lower ranks. Fellows in their capacity as tutors shared their bedchamber with students and in case a pauperi performed servatory duties to a faculty member, we might even suspect a closer exchange between servitor and master than with other students — one example is Robert Hooke serving for the extra-collegial Robert Boyle lodging in Oxford and later becoming his laboratory assistant. Furthermore, all ranks studied together and had a strong college identity throughout the ranks (Brockliss, 2016, p. 233).

Within seventeenth century society, a student was not necessarily expected to have taken a degree at university. Nonetheless, we can see from the student data that 52% of all students took a bachelor's degree, while 33% passed on to a master's degree. Minimal residency for a B.A. were four years and further three years for an M.A. Beginning his studies, a student pursuing a B.A. would have spent his first year studying grammar and rhetoric in order to get his Latin to an academic level (Clark, 1887, p. 225 f.; Brockliss, 2016, p. 236). After this, he would have succeeded with ancient logic and ethics, the main pillar of his bachelor's degree, and would have started to study Greek and geometry in his third year (Brockliss, 2016, p. 236). Only after having completed a bachelor's degree would students have started to study (ancient) natural philosophy, metaphysics, astronomy, and mathematics (Frank, 1973,

p. 201; Brockliss, 2016, p. 236). In Oxford, the award of a bachelor's degree depended on the completion of a set of disputations, a public exercise of a scholasticly formalized debate of a given topic in Latin (see also Thompson, 1959, p. 26), and a final oral examination.[31] The completion of a master's degree depended on the requisite years of study and completion of the formal disputations (Allen, 1949; Brockliss, 2016, p. 236).[32] For the late sixteenth and early seventeenth century there survives evidence on students that were refused their degrees at examination (Clark, 1887, p. 227 f.), proving that examinations were a strict requirement and not only a formal exercise.

This stands in clear contrast to the eighteenth century, where examination standards declined at the English universities. To some extent this decline might have already started during the seventeenth century. Indicators for this were e.g. Cambridge abandoning required residence for a bachelor's student's final Lent term in 1681 (Westfall, 1980 p. 138; Wistanley, 1935, p. 42). However, most of the changes in examination seem to have started during the "first two or three decades of the eighteenth century" (Wistanley, 1935, p. 48). Similarly, Frank (1973, p. 206) draws on additional evidence from questions discussed in the disputations and students' letters describing their experience during their disputations. This material leads him to conclude that "disputations maintained a good portion of their intellectual rigour until well into the 1720s and 1730s" (ibid.). Afterwards, the universities seem to have to have put less and less weight to an examination mode that was increasingly seen as outdated (Wistanley, 1935, p. 48–60). Around the 1800s this decline in the standard of the arts degrees led to institutional change at both, Oxford and Cambridge. Notably, in 1807 the current-day practice of awarding automatic master's degrees three years after the completion of a B.A. was established in Oxford (Brockliss, 2016, p. 237 f.), a practise that survives up to today and might be well known to many readers. Yet, this was a reform of nineteenth century Oxbridge, standing in clear contrast to the seventeenth century, where the M.A. was both a taught and

[31] These examinations usually took the form of scholastic "quaestiones", consisting of the statement of a problem, the presentation of objections, the logical treatment of each objection, and a final synthesis. For Oxford, there exist written records of the contents of these questiones for 1576 and 1622 compiled by (Clark, 1887, p. 169–217). Many of these "quaestiones' came directly from the treatises of Aristotle (ibid. p. 170) and illustrate the monopoly of scholastic teaching at the university.

[32] In Cambridge, the requirements for passing a the bachelor and master's of arts degree were similar (Wistanley, 1935, pp. 41–46).

examined degree that fulfilled an important role in introducing students to advanced materials of study, such as natural philosophy (ibid.).[33]

A.1.2 Faculty

On the other side of a college's body was the faculty consisting of the college's fellows and senior administrators, with the college's head or warden at the very top. A fellowship in the seventeenth and eighteenth century was situated somewhere between a modern Ph.D. and a faculty position. They were given to to advanced students, either having passed their master's degree or being senior master's students (Brockliss, 2016, p. 226 f., 281). A fellowship included an annual stipend and brought teaching obligation with it. It was usually dependent on both, a college examination and the particular conditions of the specific fellowship, sometimes linking the fellowship to a student's county or town of birth. As part of the seventeenth century world of patronage, the influence of a candidate's patron could be decisive as well (Brockliss, 2016, p. 230). After being awarded a fellowship, the award was open-ended, although the compulsory celibacy for a fellowship was often sufficient motivation to seek employment elsewhere (usually securing a parish as a priest). In case a fellow secured himself the position of e.g. a professorship, chaplain, or warden, etc., the fellowship still continued. For a detailed description of fellowships see Brockliss (2016, p. 281 f.).

The teaching demanded of fellows was either given through lectures at their college or through tutorial duties. The tutorial system at Oxford evolved parallel to the development of college-specific lectures. A tutor was supposed to oversee his student's academic development and to give private lessons. However, he was also a strong personal anchor in a student's life who would share his chamber with his tutor. However, during the seventeenth century tutors started to instruct multiple students at once (Feingold, 1990, p. 8), therefore leading to a decline in the strength of the tutorship channel over time. See Brockliss (2016, pp. 251–254) for a detailed discussion of the tutorial system at Oxford. All in all, seventeenth century colleges seemed to have offered students close contact to teachers and their views, either through

[33] One might note that at least in Cambridge, the residency requirements were less strict for master's degrees than for bachelor's degrees (Wistanley, 1935, p. 62). However, the biographical material studied for this essays gives no indication that perpetuated absence was a common practice during the seventeenth century.

interaction after college lectures, through a student's tutor, through conversation at dinner or through other informal meetings. Lastly, a short case study of Christopher Wren will serve to illustrate this channel. Christopher Wren enrolled at Wadham College in 1650, completed his B.A. already in 1651, his M.A. in 1653 — a speed that was unusual for this time — and was elected as a fellow of Wadham College in the same year. He was later elected as a member of the Royal Society in 1660 and would become president of the Royal Society from 1680 to 1682. Studying Christopher Wren, Downes (2012) argues that his engagement with the general arts curriculum that was based on a traditional scholastic curriculum did little to bring Wren into contact with the "new sciences". However, Downes (2012) explicitly recognizes the importance of informal acquaintance with the fellows for his learning of the "new sciences" that Wren could get at Wadham College – e.g. at dinner, where Wren, as a fellow-commoner (the upper-ranks of the student body paying highest fees), could dine at the fellows' table. Faculty members in return seem to have recognized their promising student. We do not know which form of indirect contact prevailed in the end, yet, we find that already in 1650, the year of Wren's enrolment, word from Wadham College hard reached Samuel Hartlib who noted Wren's "fine inventions and contrivances ... Hee is but 18 years of age and highly commended by Dr. Wilkins. [and] Mr. Wallis" (Hartlib, 1650, as quoted by Frank 1973, p. 202). Both John Wilkins, John Wallis, and Christopher Wren would be among the founding members of the Royal Society a decade later.

A.1.3 The political background of the Oxford visitation and the appointment of new fellows

When civil war broke out in 1642, the Laudian university sided with the king. It further started to finance the king's cause (Roy and Reinhart, 1997, pp. 695, 714). In September 1642, the city of Oxford was shortly seized by parliamentary troops after which most students left the university for their homes or joined the war parties (Roy and Reinhart, 1997, p. 698). At the end of October 1642, the city fell back in Royalist hands and soon after the town of Oxford became the king's headquarters. Finally, as the king's campaign dismantled, the city was besieged by parliamentary troops throughout May and June 1646 until it finally surrendered to Fairfax.

With the king's cause lost, parliament was keen on extending its rule to the Royalist university. Not only did parliament see Oxford as a dangerous stronghold of Royalist sentiment, but Oxford and Cambridge were also the training grounds for the next generation of clergy and thus would have to be cleansed of all Laudian and suspectedly Arminian influences. In 1647 parliament sent out an array of visitators to the university of Oxford (appendix table 10 presents a list of the original visitor including both, their former role at Oxford and their political role for parliament). The list illustrates that the visitors were intentionally chosen as "outsiders" of the existing college tradition. Thus, the body of the visitors was dominated by parliamentary commissioners and preachers. The former Oxonians on the committee were mainly ejected heads of the halls. The only head of a former college was Nathaniel Brent, former warden at Merton, who in 1646 had resumed his role of warden at Merton college. However, it appears that Nathaniel Brent was fully excluded from the process of appointing new fellows. In February 1651 he officially sent a protest note to the visitors complaining that they had "claimed to rule Merton College as they pleased, and, without consulting the warden, they admitted fellows, masters, and bachelors of arts" (Lee, 1886, p. 263). It seems that the appointment process was indeed swift and happened without regard for pre-existing college traditions.

During 1647, the parliamentary visitors proved successful in replacing half of all college heads with senior academics from outside the university that were known to be loyal to parliament.[34] However, until the spring of 1648, Oxford dons were generally successful in their resistance to the visitors. They based their resistance on grounds of conscience, their oaths to the king, and legal arguments that the king being was the only one with authority over the university (Reinhart, 1984, p. 322–346). This strategy played out successfully during a time

[34] These new appointments reflected the circumstances a "fluid" political situation, where Presbyterians and Independents opposed each other in parliament (Shapiro, 1969, p. 81). Thus, appointments during this time did not follow a general strategy, nor a general Independent or Presbyterian leaning (ibid.). This uncertain climate was exacerbated by the fact that new appointments were sometimes made urgent by the death of old college heads and a subsequent election of a new college head by the existing fellows — elections that parliament had to undo as timely as possible.

of internal frictions within parliament and the uncertain position of the king within the new order (Roy and Reinhart, 1997, p. 727).

During 1647, parliament, although victorious, was still in negotiation with the king. Yet, the position of the university changed drastically with the beginning of 1648: With the Vote of No Addresses on 17 January 1648, parliament broke off its negotiations with Charles I. Soon after, in spring 1648, Royalists rose again and ignited the Second English Civil War. At this point, loyalty to the king had become synonymous with treason (Reinhart, 1984, p. 378).

Thus, in 1648 parliament finally enforced its rule on the University of Oxford through drawing on the military thread of its garrison at Oxford. Parliament ultimately decided to order all Oxford fellows before the visitors and asked them to swear an oath on the new commonwealth. Absence or evasive answers were taken as non-submission and non-submitting fellows were removed (Roy and Reinhart, 1997, p. 729).[35] Roy and Reinhart (1997, p. 731) show that 190 fellows out of 379 were effectively expelled, 43 were expelled but nonetheless managed to remain, and 146 submitted to the oath and remained. Thus, the personal break was not absolute, but severe.

At the same time, the parliamentary commission was overseeing the appointment of new fellows. Because the purge of old fellows had been a hasty reaction to the political events leading to the Second English Civil war, preparations for the replacement of expelled fellows were not in place. In order to maintain the functioning of the university and to leave no doubt that expelled fellows had no chance of regaining their old positions, the visitors had to act fast. The decision which new fellows to accept was taken by a committee established by the visitors in July 1648. The main aim of the visitors was to establish their authority, promote a Calvinist leaning within the fellowship, and to establish this reform in a very short time frame (Reinhart, 1984, pp. 406 f., 413). Hence, the focus was mainly political, and the speed of political events did not leave visitors enough time to choose new fellows that would be acceptable to the traditions and sentiment of individual colleges - a selection criterion that would have been unlikely either way, given their intention to disrupt these very college tradition. Hence, the

[35] Curiously, there remained a significant number of non-submitters who were expelled, but not effectively removed — the reasons for this are not straightforward, especially as it is difficult to categorize all the individual elaborate reasons given for non-submittance (Roy and Reinhart, 1997, p. 729).

paper argues that the intrusion of fellows constituted an exogenous shock to the distribution of fellows across colleges.

A.2 Student and teacher data

A.2.1 Sources

TABLE 9: Overview over Data Sources

Data	Unit	Source
Ancient counties	Boundaries based on historic counties standard	Shapefile provided by the Historic County Borders Project http://www.county-borders.co.uk
Hundreds 1831	Hundred boundaries	Satchell, Shaw-Taylor and Wrigley (2017)
Transcript of the *Alumni Oxonienses 1500–1714* (Foster, 1891)	Students	British History Online, https://www.british-history.ac.uk/alumni-oxon/1500-1714, accessed 5 April, 2020
Transcript of the *Alumni Oxonienses 1715–1886* (Foster, 1891)	Students	Wikidata, https://www.wikidata.org/wiki/Q19036877, accessed 20 August, 2022
Transcript of the *Alumni Cantabrigienses* (Venn and Litt, 1952)	Students	ACAD - A Cambridge Alumni Database, https://venn.lib.cam.ac.uk/, accessed 11 November, 2020.
Titles of printed works	Titles	English Short Title Catalogue (ESTC) kindly shared with the author by the British Library
List of the fellows of the Royal Society	Fellows	Raymond and Beverly Sackler Archive Resource Project (see Nixon, 1999), kindly shared with the author by the Royal Society

A.2.2 Critical discussion of the Alumni Oxonienses and Alumni Cantabrigienses

Out of the *Alumni Oxonienses* (Foster, 1891) and the *Alumni Cantabrigienses* (Venn and Litt, 1952), the *Alumni Oxonienses* was the first compilation of the two to be published in 1891. The editor of the *Alumni Oxonienses*, Joseph Foster, extended his work beyond the matriculation registers by further drawing on the university archives to compile all the degrees awarded at Oxford and tried to incorporate a wide array of biographical information on each student to get additional information about a student's life after graduating. Foster was in a good position to do so: He had already spent years on the collection of material on members of the Inns of Court, knights and members of parliament (Foster, 1891, pp. i ff.).[36] After the completion of the *Alumni Oxonienses* by Joseph Foster, mathematician John Venn (who is also gave his name to Venn diagrams) started to compile a similar list for Cambridge. However, as the matriculation lists for Cambridge were less complete than the Oxford ones, Venn additionally resorted to the admission lists of each college (Venn and Litt, 1952, pp. i ff.). In general, college admission lists have the advantage that they capture the actual date of enrollment at a college as opposed to the date of the official matriculation that was sometimes postponed by one or two years after enrolment. Furthermore, admission lists had a less unified structure than the matriculation list. For example, some colleges only include a student's county of origin for his place of origin while others record the actual birth-place (Venn and Litt, 1952, pp. viii. ff.). Additionally, not all colleges started recording a student's place of origin at the same time. Furthermore, some colleges started to keep their admission lists later than others (mainly around the turn of the sixteenth century) necessitating Venn to still rely on the matriculation register for some cases.

Furthermore, Foster (1891) and Venn and Litt (1952) include information on students' outcomes including students acquiring a priesthood and an incumbents' position, being mentioned in the *Dictionary of National Biography*, joining the Inn's of Court or being a member of the Royal College of Physicians. For compiling this information, Foster consulted the *Index*

[36] Foster himself concludes that "In these absolutely unique collections, I possess the materials for illustrating and annotating the Oxford Matriculation Register to an extent and with an accuracy that no one else, not even the authorities of the University themselves, can hope to rival" (Foster, 1891, p. iii)

Ecclesiasticus, Cotton's *Fasti Ecclesiae Hibernicae*, Foster's *Judges and Barristers*, Foster's *Inns of Court Reg.*, Foster's Gray's Inn Register, Foster's *Dictionary of M. P.'s* as well as the *Munk's Roll* from the College of Royal Physicians. It further lists membership in the Royal Society. In compiling these outcomes, Venn closely followed the methodology of Foster. However, Venn's method for compiling a list of Anglican incumbents differed significantly from Foster's. While Foster drew on the Institution Books at the public Record Office, Venn relied on the more complete County Histories including compilations of the Episcopal registers of local dioceses (Venn and Litt, 1952, p. xiii). Furthermore, we should keep in mind that Venn had the privilege of working a few decades after Foster, thus being able to draw on updated and extended volumes of e.g. the *Dictionary of National Biography.* In the same manner, the lists also report membership in the Royal Society. However, here again, Venn seem to have had access to more recent scholarship on the sometimes obscure fellows of the Royal Society. Given the importance of Royal Society members as an outcome variable, this paper repeats Foster's and Venn's task and matches students to the list of Royal Society members produced by the Beverly Sackler Archive Resource Project (see Nixon (1999)) and kindly shared with me by the Royal Society being the most up to date historical scholarship on the Royal Society.

Comparing the summary statistics between Oxford and Cambridge in tables 13 and 16, shows that most variables show little difference between both universities (e.g. comparing 53% with a bachelor's degree at Oxford to 55% with a Bachelor's degree at Cambridge or 35% with a master's degree at Oxford to 38% with a bachelor's degree at Cambridge), a result that would be expected for these highly similar sister-universities. This speaks both for the accuracy of the *Alumni Oxonienses* and *Alumni Cantabrigienses* as well as the quality of this study's automatic extraction of information from the texts. The accuracy of the works of Foster (1891) and Venn and Litt (1952) have been further recognized by the historical literature. Thus, for the *Alumni Oxonienses*, Porter (1997, p. 40 f., 45) argues that the matriculation register is more consistent than the censuses of 1605, 1611, 1612, 1622, 1634, 1642, 1661, 1667, and the 1690s, while also containing more information on the student body.

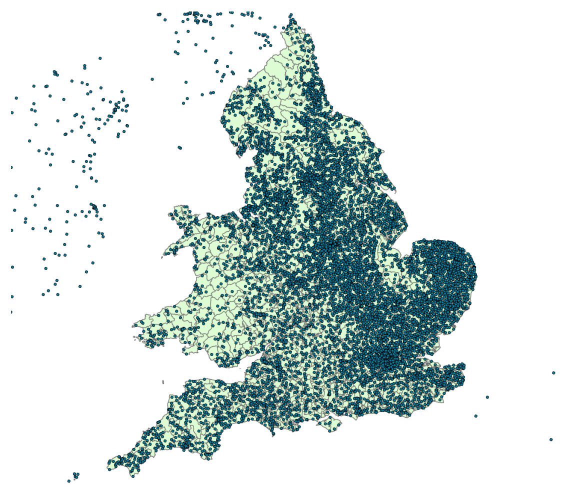
However, these records are necessarily only as good as the original matriculation registers or admission registers of the universities. Recording practises did vary over time and political shocks also affected the recording practice: For Oxford, before 1622, a student's name, status, age, and county were usually recorded, then after 1622 his father's name and place of residence would also be included (Porter, 1997, p. 30). However, we lack information on student's age, father's name and place and county of residence for the interregnum years 1648-1660, as the intruded keeper of the records was not given the old recordings by his predecessor, forcing him to start anew with all categories (ibid.). Thus, the completeness of data for Cambridge where Venn and Litt could additionally rely on the admissions list seems to be superior when it comes to students' place of origin and further personal controls.

Furthermore, data before 1580, the time of the formal establishment of the matriculation registers (Stone, 1974, p. 12), seems to be unsystematic and irregularly recorded. Furthermore, matriculation dates did not always correspond to the actual date of enrolment at a college, with the matriculation being a formal act that was only irregularly enforced (Porter, 1997, p. 31 f.). Porter (ibid.) further suggests that some students not taking a degree could have avoided matriculation altogether and that there even was a number of students taking a B.A. who had not matriculated (ibid., Stone, p. 13). Some of the latter, however, are included in the *Alumni Oxonienses 1500-1714*, although without a matriculation date. Degrees and degree dates were regularly recorded, however. Again, with respect to matriculation dates, Venn and Litt's information for Cambridge that additionally gives the date of admission to a college seem to be more reliable.

There are additionally, a number of degrees not associated with a specific college or hall. While in the early times before 1620 and especially 1580, this would often have been due to irregular book-keeping, there are a couple of other reasons for later times where the quality of book-keeping had increased substantially: Some degrees were conferred by Royal Charter as a reward and were not the product of actual studies at Oxford. A high number of these titles fall in the time of the civil war, when scholars were compensated for lost time in their studies when serving in the king's army. Furthermore, the university was always ready to award degrees to figures of political eminence, or respectively their family or protégé (see e.g. Roy and Reinhart, 1997, p. 727).

Figure 6: Families' geo-locations

(a) Geo-location of origin for Oxford students



(b) Geo-location of origin for Cambridge students

A.2.3 The Oxford visitation: Material on visitors

Table 10: Background of Parliamentary Visitors Sent to Oxford

Name	Former role at Oxford	Political Role
Original proposal of visitors		
Ministers		
Edward Corbett	Parliamentary preachers	
Long Harry Wilkinson	Parliamentary preachers	
Edward Reynolds	Parliamentary preachers	
Robert Harris	Parliamentary preachers	
Francis Cheyneel	Parliamentary preachers	
John Wilkinson Sr.	Ejected by Charles II. as Head of Magdalen Hall	
Christopher Rogers	Ejected by Charles II. as Head of New Inn Hall	
John Wilkinson Jr.	Master of Magdalen Hall	
Civilians		
Nathanial Brent	Warden of Merton and Judge Marshall for Parliament	
John Mills	Advocate of the New Model Army	
William Prynne		
Country gentlemen		
Sir William Cobbe		Parl. comm. for Buckinghamshire and Oxfordshire
William Cope		Parl. comm. for Oxfordshire
George Greenwood		Parl. comm. for Oxfordshire
John Heylin		Parl. comm. for Westminster
Thomas Kingt		Parl. comm. for Oxfordshire
John Packer		Parl. comm. for Berkshire
William Prynne		Parl. comm. for Flintshire
John Pulston		Parl. comm. for Flintshire
William Typping		Parl. comm. for Oxfordshire
Additions through lobbying of the House of Lords		
Gabriel Beck		Parl. comm. for Oxfordshire
John Cartwright		Parl. comm. for Northamptonshire and Oxfordshire
William Draper		Parl. comm. for Oxfordshire
Samuel Dunch		Parl. comm. for Berkshire

Notes: The information on the parliamentary visitors is taken from Reinhart (1984, p. 308 f.). Abbreviations: Parl. Comm.: Parliamentary commissioner

Table 11: Background of the Committee for the Examination of Candidates for Fellowships and Scholarships Set up 5 July 1648

Name	University education	Former role at Oxford	New role at Oxford
Intruded heads of colleges			
Joshua Hoyle	Magdalen Hall, Oxford; Trinity College, Dublin (BA 1610, MA 1618, BD 1625)	—	Master of University College since 1648 and Professor Divinity since 1648
Edmund Stanton	Matr. at Wadham (9 June 1615), transferred to Corpus Christi (adm. 4 October 1615, BA 1620, MA 1623)	—	President of Corpus Christi since 1648
Daniel Greenwood	Lincoln College (matr. 1624, BA 1626, MA 1629, BD 1640)	—	Principal of Brasenose College since 1648
John Wilkins	Matr. at New Inn Hall, transferred to Magdalen Hall (BA 1631, MA 1634)	—	Warden of Wadham College since 1648
Preachers sent by parliament			
Mr. Langley	Matr. Magdalen College (1627), transferred to Pembroke College (BA 1632, MA 1635)	—	One of the seven Preachers of 1646; Master of Pembroke since 1647
Henry Cornish	New Inn Hall (matr. 1631, BA 1634, MA 1636-7)	—	One of the seven Preachers of 1646; Canon of Christ Church since 1648
John Palmer	Queen's College (matr. 1628, BA 1628, BM 1630)		Warden of All Souls since 1648
Proctors			
Robert Crosse	Lincoln College (matr. 1622, BA 1625, MA 1628, BD 1637)	Fellow of Lincoln College (1627–1642), but left the university in 1642, joined the assembly of divines at Westminster	Regius professor of Divinity 1648
Ralph Button	Exeter College (matr. 1631, BA 1633), transferred to Merton College (1640)	Fellow of Merton College (1633–1642), but left the university in 1642 and went to Gresham	Canon of Christ Church 1648, junior proctor since 1648
Remaining loyal fellows			
Robert Hancocke	Exeter College (matr. 1640)	Fellow of Exeter College (1648–1657)	Delegate of the visitors
Thankfull Owen	Exeter College (matr. 1636, BA 1639-40), transferred to Lincoln College in 1642 (MA 1646)	Fellow of Lincoln College (since 1642)	Delegate of the visitors
Edward Copley	Exeter College (matr. 1631, BA 1632), transferred to Merton College (MA 1639-40)	Fellow of Merton College (since 1633)	Delegate of the visitors
Anthony Clifford	Gloucester Hall (matr. 1634, BA 1637, MA 1640)	Fellow of Exeter College (1641–1662)	Delegate of the visitors since 1647

Notes: The information on the committee is taken from (Burrows, 1881, p. 141) and (Reinhart, 1984, p. 407). Full names, degrees, and biographical information have been supplemented by drawing on the *Dictionary of National Biography* and Foster's *Alumni Oxenienses*. Degrees refer to the period before 1648 and exclude any degrees awarded by the visitors themselves.

TABLE 12: Overview of Intruded and Reinstituted "Royal Society" Fellows, 1647–50 and 1660

Name	College before visitation	Start	End	College during interregnum	Start	End	College after restoration	Start	End
Intruded Fellows									
Morley; George (1597 - 1684)				Wadham College; Oxford	1648	1659			
Wallis; John (1616 - 1703)	Queen's College; Cambridge	1644	1645	Exeter College; Oxford	1649	1660	Exeter College; Oxford	1660	1703
Pope; Walter (c 1627 - 1714)				Wadham College; Oxford	1651	1662			
Wood; Robert (? 1621 - 1685)				Lincoln College, Oxford	1650	1659			
Petty; Sir; William (1623 - 1687)				Brasenose College; Oxford	1648	1652			
Pett; Sir; Peter (? 1630 - 1699)				All Souls; Oxford	1649	1650			
Harley; Thomas (- c 1685)				All Souls; Oxford	1648	1659			
Croke; Sir; George (- 1680)				All Souls; Oxford	1648	1659			
Submitted to Visitors									
Bathurst; Ralph (1620 - 1704)	Christ Church; Oxford	1640	-	Christ Church; Oxford	-	1660	Trinity Oxford (President)	1660	1704
Stayed at Oxford after Visitations									
Willis; Thomas (1621 - 1675)	Christ Church; Oxford		B.Med. 1646	pratised at Oxford; kept close connections to Christ Church	1648	1660	Christ Church; Oxford (Sedleyan Professor)	1660	1675
Expelled by Vistors and Reinstituted Fellows									
Morley; George (1597 - 1684)	Christ Church; Oxford	1622	1648				Christ Church; Oxford	1660	1660
Birkenhead; John (1616 - 1679)	All Souls; Oxford	1639	1648				All Souls; Oxford	1660	1661
Dolben; John (1625 - 1686)	Christ Church; Oxford	1647	1648				Christ Church; Oxford	1660	1660
Expelled by Visitors and not Reinstituted in 1660									
Clerke; Henry (c 1622 - 1687)	Magdalen; Oxford	1642	1648						
Newly Instituted in 1660									
Mayow; John (1640 - 1679)							All Souls; Oxford	1660	1678

The fellows are compiled drawing on the *Raymond and Beverly Sackler Archive Resource Project* and Reinhart (1984).
Fellowship dates are coded consistently with the dataset with starting dates are only measured after a fellow's M.A.

A.2.4 Summary statistics for the Alumni Oxonienses and Alumni Cantabrigienses

Table 13: Descriptive Statistics of Oxford students and faculty, 1580–1720

	Mean	Std.Dev.	Sum	Obs
Studies				
Matriculated	0.9015	0.2979	42411	47043
Bachelor's degree	0.5310	0.4990	24982	47043
Master's degree	0.3505	0.4771	16489	47043
Status				
Fellow	0.0250	0.1561	1175	47043
Scholar	0.0058	0.0757	271	47043
arm.	0.1300	0.3363	4823	37107
baronet	0.0019	0.0431	69	37107
cler.	0.0867	0.2814	3216	37107
comitis.	0.0005	0.0220	18	37107
doctoris	0.0074	0.0856	274	37107
episcopi	0.0002	0.0127	6	37107
eq. aur.	0.0058	0.0761	216	37107
equitis	0.0115	0.1065	426	37107
gent.	0.2960	0.4565	10982	37107
militis fil.	0.0061	0.0776	225	37107
militis	0.0072	0.0847	268	37107
p.p.	0.0451	0.2076	1674	37107
paup.	0.0143	0.1188	531	37107
pleb.	0.3659	0.4817	13578	37107
serv.	0.0216	0.1453	801	37107
Career				
Royal Society	0.0042	0.0649	199	47043
Entry in the D.N.B.	0.0193	0.1377	909	47043
Inn's of Court	0.1503	0.3573	7069	47043
College of Physicians	0.0041	0.0641	194	47043
Priest	0.3609	0.5903	16976	47043
Observations	47043			

TABLE 14: Publication statistics for publishing Oxford students and faculty, 1620–1720

	Mean	Std.Dev.	Min	Max	Obs
Students					
Share of each topic in student publications	0.0298	0.1408	0	1	39556
No. student publications	7.1959	14.3591	1	259	39556
Share ML predicted in student publications	0.4271	0.3747	0	1	39556
Student graduates with B.A.	0.6936	0.4610	0	1	39556
Student graduates with M.A.	0.5901	0.4918	0	1	39556
Teachers					
Log share of each topic in teacher publications	0.0256	0.1013	0	1	39556
No. teacher publications at college	21.9248	27.3898	0	176	39556
No. teachers at college	12.6356	9.6136	0	51	39556
Cohort size at college	25.7516	19.3221	1	157	39556
Observations	39556				

TABLE 15: Publication statistics for the fields of the Scientific Revolution for publishing Oxford students and faculty, 1620–1720

	Mean	Std.Dev.	Min	Max	Obs
Students					
Share of each topic in student publications	0.0066	0.0698	0	1	11484
No. student publications	7.1959	14.3595	1	259	11484
Share ML predicted in student publications	0.4271	0.3747	0	1	11484
Student graduates with B.A.	0.6936	0.4610	0	1	11484
Student graduates with M.A.	0.5901	0.4918	0	1	11484
Teachers					
Log share of each topic in teacher publications	0.0079	0.0508	0	1	11484
Teacher innovation index	0.0604	0.2387	0	1	11484
No. teacher publications at college	21.9248	27.3907	0	176	11484
No. teachers at college	12.6356	9.6139	0	51	11484
Cohort size at college	25.7516	19.3227	1	157	11484
Observations	11484				

Table 16: Descriptive Statistics of Cambridge students, 1580–1740

	Mean	Std.Dev.	Sum	Obs
Studies				
Admissioned	0.6994	0.4585	35723	51079
Matriculated	0.2987	0.4577	15257	51079
Bachelor's degree	0.5543	0.4970	28314	51079
Master's degree	0.3761	0.4844	19210	51079
Status				
Fellow	0.1032	0.3042	5272	51079
Fellow Commoner	0.0995	0.2994	4743	47645
Pensioner	0.4774	0.4995	22746	47645
Sizar	0.4230	0.4940	20156	47645
Career				
Royal Society	0.0044	0.0662	225	51079
Entry in the D.N.B.	0.0377	0.1905	1926	51079
Priest	0.2297	0.4206	11731	51079
Deacon	0.2116	0.4084	10806	51079
Inn's of Court	0.0994	0.2992	5076	51079
Geo-Info				
Families' county recorded in list	0.7534	0.4310	20780	27582
Precise information on family's address	1.0000	0.0000	27582	27582
GIS coding of precise info on families' address	0.9354	0.2459	25799	27582
Latitude	52.5677	1.0917	1356298	25801
Longitude	-0.8070	1.4457	-20820	25801
Information of county, from list and from GIS combined	0.9547	0.2079	26333	27582
Observations	51079			

Table 17: Publication statistics for publishing Cambridge students and faculty, 1620–1720

	Mean	Std.Dev.	Min	Max	Obs
Students					
Share of each topic in student publications	0.0301	0.1430	0	1	43488
No. student publications	6.8278	13.5667	1	194	43488
Share ML predicted in student publications	0.4221	0.3871	0	1	43488
Student graduates with B.A.	0.7528	0.4314	0	1	43488
Student graduates with M.A.	0.6115	0.4874	0	1	43488
Teachers					
Share of each topic in teacher publications	0.0284	0.1024	0	1	43488
No. teacher publications at college	37.3105	39.1814	0	165	43488
No. teachers at college	30.2156	20.5885	0	79	43488
Cohort size at college	29.0589	18.9601	1	88	43488
Observations	43488				

Table 18: Publication statistics for the fields of the Scientific Revolution for publishing Cambridge students and faculty, 1620–1720

	Mean	Std.Dev.	Min	Max	Obs
Students					
Share of each topic in student publications	0.0059	0.0649	0	1	12231
No. student publications	6.8278	13.5671	1	194	12231
Share ML predicted in student publications	0.4221	0.3871	0	1	12231
Student graduates with B.A.	0.7528	0.4314	0	1	12231
Student graduates with M.A.	0.6115	0.4874	0	1	12231
Teachers					
Share of each topic in teacher publications	0.0051	0.0336	0	1	12231
Teacher innovation index	0.0803	0.2730	0	1	12231
No. teacher publications at college	37.3105	39.1826	0	165	12231
No. teachers at college	30.2156	20.5891	0	79	12231
Cohort size at college	29.0589	18.9607	1	88	12231
Observations	12231				

A.2.5 Status Abbreviations and Degree Titles

Table 19: Overview of Status Abbreviations — As Translated by the Author

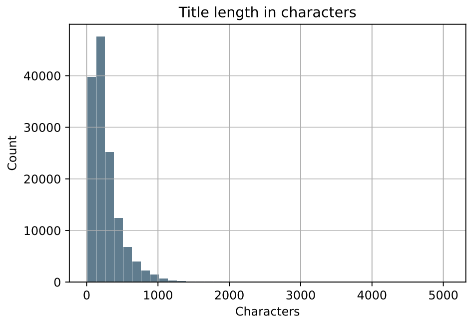
Classification in Project	Abbreviation in Original	Full Title	Translation
Commoner	pauper	Pauper	Poor
	p.p.	Pauper puer	Poor boy
	serv.	Servus	Servitor (as additional duty performed at the college)
	pleb.	Plebeii	Commoner
Academic	doctoris	Doctoris	Doctor title
Clergy	cler.	clerici	Clerical
	episcopi.	Episcopi	Bishop
Nobility	gent.	Gentilis	Gentleman (lower nobility)
	militis	Militis	Military (from *miles*)
	arm.	Armiger	Esquire (literally *arms-bearer*, but for the register strictly limited to esquire — see Hehir (1968, p.14))
	eq.	equitis	Knight (from *eques*)
	eq. aur.	Eques auratus	Knight Bachelor (literally *golden knight*)
	baronet	Baronet	Baronet
	comitis	Comitis	Earl
Further extensions	fil.	filius	Son of
	nat. min.	natu minimum	The youngest
	nat. max.	natu maximum	The oldest

Table 20: Coding Overview for Degree Titles

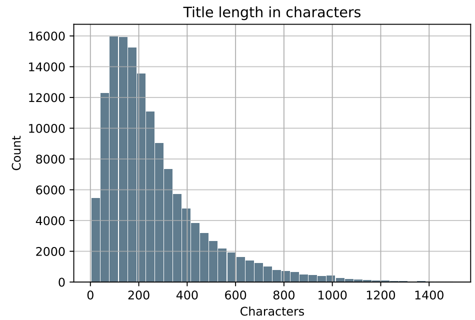
General Classification in Project	Sub-classification in Project	Abbreviation in Original	Full Degree Name
Bachelor's Degree		B.A.	Bachelor of Arts
	Clerical Degree	B.D.	Bachelor of Divinity
	Medical Degree	B.M.	Bachelor of Medicine
	Medical Degree	B.Med.	Bachelor of Medicine
	Law Degree	B.C.L.	Bachelor of Civil Law
	Law Degree	LL.B	Bachelor of Law
Master's Degree		M.A.	Master of Arts
Doctoral Degree	Clerical Degree	D.D.	Doctor of Divinity
	Law Degree	D.C.L.	Doctor of Civil Law
	Law Degree	L.L.D.	Doctor of Law
	Medical Degree	M.D.	Doctor of Medicine
	Medical Degree	D.Med.	Doctor of Medicine

A.3 Text data

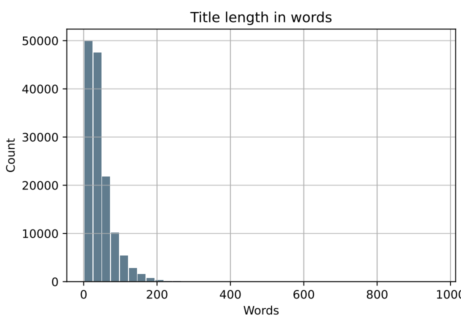
A.3.1 ESTC titles



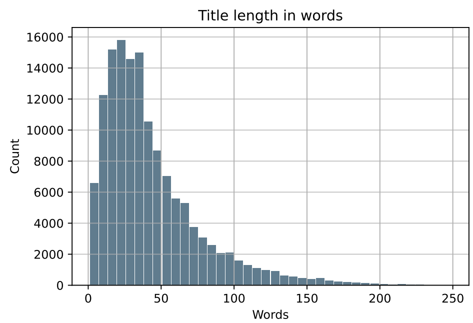
(a) Length in characters



(b) Length in characters (less than 1500)



(c) Length in words



(d) Length in words (less than 250)

Figure 7: Histogram for ESTC text length

The following lists a few examples illustrating the amount of information available from seventeenth and eighteenth century titles. These examples of titles are not meant to be representative in content, but to illustrate the varying degree of information found in seventeenth and eighteenth century titles, a format that is usually unknown to the modern reader. Figure 7 shows histogram plots for title length in either character or word counts.[37]

> Dioptrica nova. A treatise of dioptricks, in two parts. Wherein the various effects and appearances of spherick glasses, both convex and concave, single and combined, in telescopes and microscopes, together with their usefulness in many concerns of humane life, are explained.

or

[37] The statistics apply to the translated titles that are cleaned for near duplicates

Moor's arithmetick. In tvvo books. The first treating of the vulgar arithmetick in all its parts, with several new inventions to ease the memory, by Nepairs rods, logarithms, decimals, &c. fitted for the use of all persons. The second of arithmetick in species or algebra, whereby all difficult questions receive their analytical laws and resolutions, made very plain and easie for the use of scholars and the more curious. To which are added two treatises: 1. A new contemplation geometrical upon the oval figure called the ellipsis. 2. The two first books of Mydorgius his conical sections analized by that reverend divine Mr. W. Oughtred, Englished and completed with cuts. By Jonas Moore, Professor of the Mathematicks. (Jonas Moore, 1660)

or

Arithmetick made easie for the use and benefit of trades-men. Wherein the Nature and Use of Fractions, both Vulgar and Decimal, are Taught by a New and Exact Method. Also The Mensuration of Solids and Superficies. The twelfth edition, corrected and amended. By J. Ayres, late Writing-Master in St. Paul's Church-Yard, London. To which is added, A short and easy method; after which Shop-Keepers may State, Post, and Balance their Books of accompts. By Charles Snell, Writing-Master, and Accomptant, in Foster-Lane, London. (John Ayres, 1714)

or

The complete wall-tree pruner; or Principles of Pruning and Training all sorts of Wall Fruit Trees, and Espaliers, In the most Improved Degree of Perfection and Fruitfulness; Systematically Explained by a New Scientific Plan, never before attempted. Comprehending The Completest Practical Directions for performing all the different Operations of Pruning and Training all Sorts of Wall Trees and Espaliers, in the most successful Manner, according to their different Modes of Bearing, and in their several Stages of Growth, from the earliest State of Training to their utmost Maturity, and latest Duration, whereby to have them always Prosperous, Beautiful, and abundantly Fruitful. Consisting of Common Wall Trees, Half Standard Wall Trees, High Standard Wall Trees, Espalier Trees, &c. comprehensively explaining the respective Orders of Training, different Modes of Bearing, several Sorts of Bearers, various Kinds of Branches and Shoots, Fruit Buds, Fruit Spurs, and all other Parts of the Trees in their different Ways and Habits of Growth, describing accordingly the peculiar and most effectual Methods of Pruning, both for occasional and general Practice. With full Explanations of the whole Process and true Principles of First Pruning and Training, General Pruning, Summer Pruning, and Winter Pruning. The Whole being Systematically displayed, according to an eligible New Plan, is peculiarly calculated to render all the different Operations of Pruning easily comprehended, and successfully practised, that every one may prune his Wall Trees, &c. with the utmost Facility, and Certainty of having them in the highest State of Perfection, and Bearing; the Fruit large, fair, and of superior Quality. Also, A Complete Register of all the different Species and respective Varieties of the best Fruits, with their Times of ripening, &c. By John Abercrombie, (oxford Street (319.) London.) Author of Every Man His Own Gardener, The British Fruit Gardener, and other Works no Gardening. (John Abercrombie, 1783)

or

Osteographia elephantina: or, a full and exact description of all the bones of an elephant, which died near Dundee, April the 27th. 1706. with their several dimensions. To which are premis'd, 1. An Historical Account of the Natural Endowments, and several wonderful Performances of Elephants; with the manner of Taking and Taming them. 2. A short Anatomical Account of their Parts. And added, 1. An exact Account of the Weight of all the Bones of this Elephant. 2. The Method us'd in preparing and Mounting the Skeleton. 3. Four large Copper Plates, wherein are represented the Figures of the Stuff'd Skin, and prepared Skeleton, as they now stand in the Publick Hall of Rarities at Dundee; with the separated Bones in several Views and other Parts of this Elephant.

A.3.2 Cleaning the ESTC titles

The raw data poses several challenges:

1. Publication titles are written in different languages (especially in Latin)
2. There is a significant number of near duplicates with varying title length
3. Sometimes, editions and publishers are included in the title itself

To deal with foreign languages, this paper adopts an approach where all titles are first translated to the same language to be comparable. It first identifies foreign languages using Facebook's *fasttext* package. It then uses the Google Translator API for translating titles. This returns high-quality translations that should be practically indistinguishable from titles of works that were already translated back in the past (see next paragraph on near duplicates).

The significant number of near duplicates seems to stem from several versions of the book that have been entered into the database. However, some entries seem to have only included parts of the title, possibly from different editions with different covers, so that the titles were not spotted as duplicates. A further challenges arises from different editions with slight changes in the title, e.g. from translations or different editions:

> "A panegyric on our late sovereign lady Mary Queen of England, Scotland, France, and Ireland, of glorious and immortal memory. Who died at Kensington, on the 28th. of December, 1694. By James Abbadie, D.D. minister of the Savoy" (Abbadie, Jacques, 1654-1727)

and

> "Panegyric of Mary Queen of England, Scotland, France, & Ireland, of glorious & immortal memory. Decedie in Kensington on December 28, 1694. By J. Abbadie D. en T. Minister of Savoy" (Abbadie, Jacques, 1654-1727)

automatically translated from:

"Panegyrique de Marie reine d'Angleterre, d'Ecosse, de France , & d'irlande, de glorieuse & immortelle memoire. Decedie à Kensington le 28. Decembre 1694. Par J. Abbadie D. en T. Ministre de la Savoye" (Abbadie, Jacques, 1654-1727)

Here, the first title is a contemporary translation from the original French work - taking a small liberties with the original work (adding the late sovereign). Hence, translations give rise to very similar, but slightly different titles. Furthermore, the automatic translation came to a very similar, but slightly different translation.

Thus, an algorithm spotting near duplicates should be able to correctly identify duplicates where the text of both titles almost literally overlaps, however with one of the titles having an attachment of additional text. It should also be able to ignore small differences in the texts arising from translations or different editions. Furthermore, it should not capture semantically similar titles, but titles that have a high word-by-word similarity.[38] As a solution to this task, the paper uses Jaccard distances on word-vector representations of titles.[39] Jaccard distance is the complement to Jaccard similarity measuring the size of the intersection of two sets divided by the size of their unions, $J(A,B) = \frac{A \cap B}{A \cup B}$. Jaccard distances are calculated for the matrices of each author's word-vector representation of their titles. In the case that an author name does not exist, the paper uses either the corporation name or general title classifier if known. For all titles without any information on origin, titles are grouped by the first 10 letters of their titles. The Jaccard distances are calculated for pre-cleaned titles (already removing parts of the title-string that do not belong to the title, e.g. information on the publisher). All titles below a threshold distance of 0.5 are identified as near duplicates. Then for each list of similar titles, the algorithm only keeps the title that was published first. Altogether, the algorithm removes 183,978 near duplicates, reducing the number of distinct titles to 285,985.

Finally, titles are cleaned by removing information that is not related to its content using regular expressions. This includes e.g. the name of the publisher or editor, information on

[38]We would expect e.g. authors to publish multiple works on similar topics. These should still be listed as distinct titles.

[39]Another possible candidate for measuring near duplicates are Euclidean distances between titles. However after practical experimentation with different titles, Jaccard distances seem to outperform Euclidean distance measures with respect to minimizing false positive duplicates.

the number of volumes, or the number of the current edition. It also removes information on months and weekdays, as well as information on attached copper-plates.

A.3.3 Matching students and fellows to publishing records

This section describes matching titles from the ESTC catalogue to the catalogue of university students. Matching between the entries of the ESTC catalogue and the student and fellow entries from the *Alumni Oxenienses* (Foster, 1891) and the *Alumni Cantabrigienses* (Venn and Litt, 1952) faces a number of challenges. First, seventeenth and early eighteenth century spelling practices were not yet standardized. Second, years of death are only given for a small subset of students within the *Alumni Oxenienses* and *Alumni Cantabrigienses*. Furthermore, contemporary information on years of deaths are often inaccurate within a small range (explained in detail below). Furthermore, a year of death was not given, the paper has to use years of birth instead. Additionally, years of death are often less precisly recorded than years of death. Finally, whenever years of birth were not included in the *Alumni Oxenienses* and *Alumni Cantabrigienses*, years of birth had to be estimated from the year of matriculation creating a further source of inaccuracy. To address these challenges, the paper uses a combination of phonetic matching and matching on a range of $[+1, -1]$ year of death, whenever years of death are given. Whenever years of death are not known, the paper matches on a range of $[+3, -3]$ year of birth. The section continues by first addressing challenges in spelling and date accuracy in detail. It then describes the matching strategy and presents statistics for matching rates.

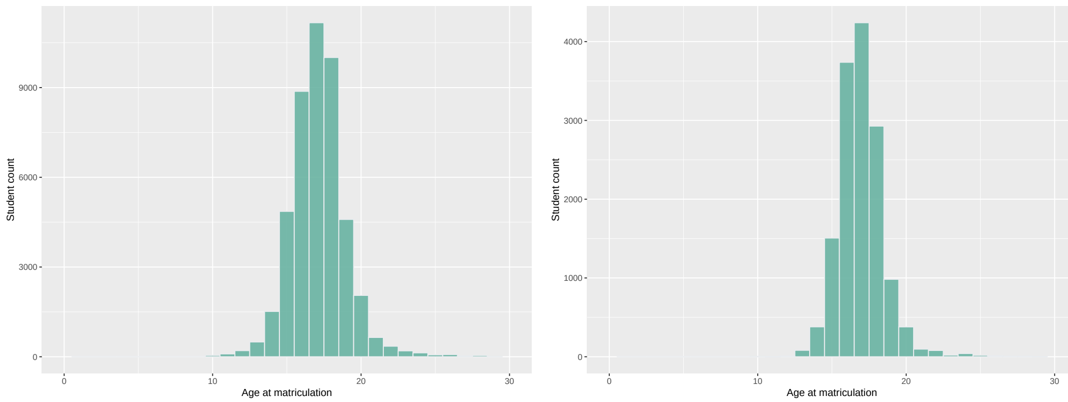
First, seventeenth century century spellings of names were not yet standardized and it is common to find contemporary sources referring to the same person with different spellings. Sometimes, people even changed the spelling of their own name over time. For example, Edmond Halley used the spelling of "Edmond" and "Edmund" interchangeably in both his letters and publications (Hughes and Green, 2007). Hence, the paper adopts a phonetic matching procedure that reduces the spelling of names to their phonetic sounds. It uses the New York State Identification and Intelligence System (NYSIIS) phonetic code known to combine high accuracy with a low number of false positives (Snae, 2007). It also seems to successfully capture some basic Latinizations of names. For example, it matches "Silius Titus" in the ESTC catalogue with "Silas Titus" from the ESTC catalogue.[40]

Second, any matching of seventeenth and eighteenth century biographical information must take account of the inaccuracy of lifetime dates during this age. In principle, years of death are more reliable than years of birth for seventeenth and eighteenth century records. For example, Cummins (2017) shows that for the European high nobility, years of death did not show significant patterns of age heaping. However, 10–20% of recorded birth years showed patterns of age heaping in the seventeenth century. The number is likely to be higher for university students from common backgrounds. Yet, even the accuracy of historical death years, especially for the non-nobility, should not be taken for granted. A further issue are conversions between the Gregorian and Julian calender. Besides the general difference between the Gregorian and Julian calender of a few days, the English Julian calender started the new year on the 25th of March, thus creating a difference of about 1/4 of a year. For lifetime entries in the ESTC it is impossible to know whether lifetime dates are taken at Julian face value or converted to the Gregorian calender (even in the case of the Oxford Dictionary of National Biography this is not always clear). Hence, any successful matching of seventeenth and eighteenth century records needs to allow for a certain degree of fuzziness in the recording of dates.

Given this background on the accuracy of historical dates, years of death within a range of $[+1, -1]$ years are used for matching. However, the university registers only contain years of death for about 15% of all students making it necessary to match on birth years for the rest of the sample For ca. 40% of all students, the age of matriculation is recorded. From this we can calculate the year of birth. For the rest of students, the age at matriculation is not known. Yet, it is possible to predict the year of birth based on the year of matriculation (or award of B.A./M.A.) and students' median age at matriculation.

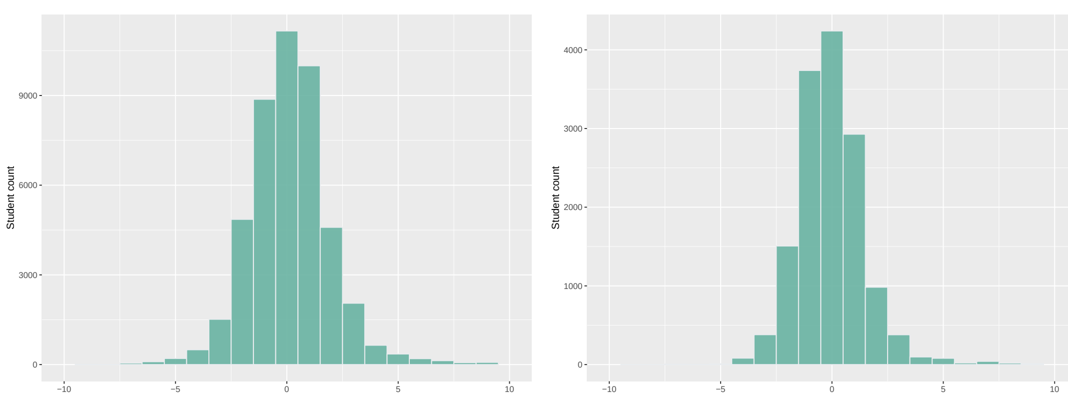
Figure 8 shows the age distribution of students at the time of matriculation. The median age at matriculation was 17, with the 10th and 90th percentiles between 15 and 19. Hence, based

[40] Manually comparing the entry for "Silius Titus" in the *Oxford Dictionary of National Biography* provides the same year of matriculation and name of College as the Oxford register. Hence, it appears that the Oxford entry "Titus, Silas, s. Silas, of Bushey, Herts, gent. Christ Church, matric. 16 March, 1637-8, aged 15" is identical to "Titus, Silius, 1623?-1704", the author of *Killing no Murder*.



(a) University of Oxford (b) University of Cambridge

FIGURE 8: Distribution of students' age at matriculation (1620–1720)



(a) University of Oxford (b) University of Cambridge

FIGURE 9: Distribution of prediction error between predicted and actual age at matriculation for students with recorded age mat matriculation (1620–1720)

on the assumption that the non-recorded age at matriculation followed a similar distribution, a student's year of birth can be extrapolated based on a student's year of matriculation minus medium age 17. For students without information on their year of matriculation, the year of the award of either their bachelor's or master's degree is used with the additional knowledge that based on the university's statutes, a bachelor's degree took four and a master's degree two years. Figure 9 shows that calculating the differences between known years of birth and extrapolated age from students' year of matriculation, bachelor's degree, and master's degree is normally centred around 0. Hence, at least for students with information on their age at matriculation, extrapolating years of birth appears unbiased. Furthermore, it can be seen that the distribution of extrapolated minus actual years of death's 5 percentile lies at -3 and its 5th percentile at 3, an inaccuracy that should be accounted for when matching. Hence, if years of death are not known the paper matches on birth intervals of $[+3, -3]$.

TABLE 21: List of different ranges of matching accuracy

Match on	Matched titles	Unique matches	Dropped duplicate matches	Percentage duplicates out of all matches
Cambridge				
Step 1: Year of death	29,526	27,663	1,863	6.3%
Step 2: Year of birth	16,138	9,773	6365	39.4%
Overall:	54,677	46,927	7,720	14.1%
Oxford				
Step 1: Year of death	35,514	33,307	2,207	6.2%
Step 2: Year of birth	25,034	14,144	10,890	30.66%
Overall:	65,548	47,451	13,097	20,0%
Both universities				
Overall matches	120,225	94,378	20,817	17.32%

Overall, 204,700 entries from the ESTC with information on the author's name and lifetime dates are matched against 144,748 students with information on either year of birth, death or the year of their matriculation or further degrees.[41] This yields an overall of 120,225 title

[41]It should be noted that not all names on authorship from the ESTC might be meaningful. Sometimes first names are not fully included. Furthermore, pseudynoms (e.g. "Philosophus" or "Paddy Strongcock") might further obscure authorships.

matches. However, a last issue arises from duplicate matches: Being only able to match on names and lifetime dates, can lead to the presence of duplicate entries for common entries. Table 21 shows the number of total and unique matches as well duplicate matches for students from Oxford and Cambridge. As would be expected, matching on the greater range of $[+3, -3]$ for years of birth than $[+1, -1]$ for years of death creates more duplicate matches. Overall, 17.32% of all matches are duplicate matches that are dropped from the matching sample.[42] This yields an overall number of 94,378 unique title matches for 3808 students from Oxford and 3464 students from Cambridge.[43] Thus, at least 33% of all ESTC titles from 1600 to 1800 that were published under some personal name (as opposed to institutional publications, e.g. from parliament or other institutional bodies) were written by a university graduate.

A.3.4 Classification – Machine Learning

Transformer models are foundation models (Vaswani et al., 2017; Bommasani et al., 2021) trained on very large corpora of text that cover a large part of human knowledge, e.g. including Wikipedia and Google Books. Using pre-trained foundation models offers a natural representation of the meaning embedded in words and sentences. In contrast to word-embedding models that translate the meaning of individual words into a multi-dimensional vector representation, transformer models use a self-attention mechanism to capture the meaning of words based on their context in a textual environment. As in word-embedding models, each input is assigned as an embedding that is stored in a 512×768 dimensional matrix. However, in contrast to word-embedding models, the inputs are longer periods of text that can be translated into text-specific embeddings. Transformer based models have set the standard for the current state of natural language models and, as e.g. in the case of GPT-3 and GPT-4, often approach near-human capabilities of text processing.

Before training a transformer model on the ESTC titles, the data on the titles had to be-processed in order to make them comparable. In a first step, the text data had to be made comparable across different languages. For this, the language of all titles were identified

[42] Given that the ESRC does not contain additional information on authorship, there is little room for exploiting additional information to decrease the rate of duplicate matches.

[43] Note that these numbers do refer to raw ESTC titles and not the ones cleaned from duplicates.

using the fasttext library (see Bojanowski et al., 2017) and non-English titles translated using the Google Translate API. Appendix figure 33 shows the composition of all titles in foreign languages. It can be seen that Latin titles prevailed, with French coming into more common use during the second half of the eighteenth century. In a second step, the vary granular subject classes assigned by the British Library (with about 50,000 different classes)[44] had to be turned into higher-order classes. For this, each of the $\sim 50,000$ classes were hand-assigned to 47 higher-order classes. The list of the 47 higher-order classes was designed to capture scientific fields such as mathematics, astronomy, applied physics, biology, or chemistry. Appendix table 35 lists all topic names and provides a short description of each topic.

Next, the higher-order classifications were used to train a transformer model that was then used to predict classes for the full dataset. The paper uses a DistilBERT transformer model that provides a good compromise between accuracy and model size. The model uses a standard set of hyperparameters with a learning rate of 0.005, 3 epochs, and an effective batch size of 32.[45] For testing the model, it is first trained on 60,000 observations of titles with higher-order classes. It is then used to predict a training dataset with 47,650 observations with known subject classes. The predicted classes are then compared to the true classes. Overall, the model has a Matthews correlation index of 0.66. Furthermore, table 36 shows that the model is successful in predicting all kinds of classes, even those that are based on context-sensitive distinctions such such as *Sermons*, *Catholic*, or *Sects* as contrasted to *Religion* or *Moral tales*. Figure 30 presents the confusion matrix for the DistilBERT model. Larger spillovers mostly occur within related fields such as *Administrative* and *Legal* or *Stories* and *Supernatural*, but not between distinct fields such as *Astronomy* and *Chemistry*. Given the successful evaluation of the training dataset, the full DistilBERT model is then trained on all 75,856 titles with manually assigned higher-order subject classes.

[44]The number refers to all titles before cleaning for duplicates.

[45]To save GPU memory, the model uses a batch size of 8 and 3 gradient accumulation steps.

Table 22: Text classification based on ESTC subjects

Category	Description
Scientific Revolution	
Alchemy	Occult studies, purification of materials
Astrology	The study of the heavens in relation to signs, omens, and prophecies
Astronomy	The physics of the heavens
Almanacs	All almanacs and calendars
Applied physics	Mechanical philosophy that is not part of astronomy, e.g. optics, heat, and mechanical forces.
Biology	Natural histories including the study of plants and animals
Chemistry	Systematic study of the elements, minerals, metals, etc.
Geography	Geography, Cartography, Geology
Scientific Instruments	All scientific instruments (including nautrical instruments)
Mathematics	All mathematical treatments
Medicine	Medical studies, incl. anatomy, and surgery
Political economy	Political economcy, society wide study of improving agriculture, manufactures, or trade, does not include administrative reasonings on the economy, e.g. famines or other scarcities[46]
Higher education	
Philosophy	Philosophical treatises (excludes political philosophy)
Political Philosophy	All philosophical treatises on political institutions
Classical Education	Latin, Greek, ancient mythology, drama and poetry
Logic and rhetoric	Logic and rhetoric as classical categories of education
University matters	University administration and politics
Languages	Foreign languages as well as English (excluding Latin and Greek learning, see classical education)
Business, trade, and innovation	

[46] A note of warning: By placing a focus on the study of the economy independent of the administrative proceedings of the state, this category might be ill-suited to fully capture early mercantilist ideas as well as some early physiocratic ideas.

Technical instructions in trades	Technical instructions, improvements in trades manufactures
Technical instructions in agriculture	Technical instructions in agriculture
Encyclopedias and dictionaries	Systematic collections of knowledge on a given topic, usually with lists and explanations of terms or concepts
Navigation	Publications on navigation, incl. finding latitude and longitude at sea and nautical instruments
Business	Business endeavours, communication, and advertising
Printing and book trades	Anything related to printing and publishing
Public sphere	
Stories and public discourse	Descriptions and tales of any kind of notable event or personal experience, pamphlets, periodicals, and discussion of politics
Moral tales	Moral advise often linked to stories with a moral core
Biographies	Biographical description of the life of noteworthy individuals
Drama	Drama, excluding classical drama (see classical education) as well as prosaic fiction
Poetry	Poetry and songs
Music	Music and music theory
Supernatural	All descriptions of magical events, wonders, and ghosts (both held to be authentic as well as with sceptical attitude)
History	State history
Curiosities and wonders	Strange, phenomena, and sightings
Antiquities and archaeology	Antique collections, archaeological findings
Amusements	Games, food, and festivities
Societies	All kind material (statutes, transactions) on all societies except for economic societies,
Economic societies	All kind material (statutes, transactions) on economic societies
Religion	
Religion	All religious topics
Religion – Sermons	Sermons (often relating other topics to religious themes)
Religion – Catholicism	All works on Catholicism

Religion – Judaism	All works on Judaism
Religion – Dissenters	All works on dissenters (Quakers, Baptists, Methodists etc.)
Prophecies	
Public administration	
Administrative	Administration and politics, proceedings of the House of Commons and local administrative bodies
Legal	Legal questions
Military	Management of the military and navy, military strategy and practises
State affairs	Diplomacy, Royal privileges, Treaties, and Peace negotiations
Wars	Reports on military campaigns, battles, and wars
Colonial exploration	Overseas expeditions, including description of natives, and descriptions of the slave trade

Subject classes are constructed as classifiers for the more than 50,000 subject classes from the ESTC subject index classification.

A.3.5 Classification – Evaluative statistics

Table 23: Classification Report – DistilBERT

Subject class	Precision	Recall	F1-score	Support
Administrative	0.8	0.8	0.7	8726
Alchemy	0.1	0.1	0.1	28
Almanacs	0.7	0.7	0.7	284
Amusements	0.6	0.6	0.6	377
Antiquities	0.4	0.4	0.4	87
Applied physics	0.6	0.6	0.6	183
Architecture	0.6	0.6	0.6	97
Art	0.7	0.7	0.7	213
Astrology	0.5	0.5	0.5	220
Astronomy	0.5	0.5	0.6	181
Biography	0.3	0.3	0.4	132
Biology	0.7	0.7	0.7	312
Chemistry	0.6	0.6	0.6	99
Church administration	0.5	0.5	0.5	934
Classical education	0.6	0.6	0.6	755
Curiosities and wonders	0.3	0.3	0.4	80
Drama	0.8	0.8	0.8	2422
Economic societies	0.0	0.0	0.0	15
Economics	0.4	0.4	0.5	48
Education	0.6	0.6	0.6	357
Encyclopedias and dictionaries	0.5	0.5	0.5	212
Exploration	0.6	0.6	0.6	508
Foreign languages	0.7	0.7	0.8	467
Geography	0.6	0.6	0.6	141
Geology	0.1	0.1	0.2	22
History	0.3	0.3	0.4	167
Legal	0.5	0.5	0.6	1932
Mathematics	0.8	0.8	0.8	351
Medicine	0.9	0.9	0.8	2127
Mercantile	0.4	0.4	0.4	1190

Military	0.5	0.5	0.6	327
Military Wars	0.6	0.6	0.6	701
Moral tales	0.3	0.3	0.4	692
Music	0.6	0.6	0.6	251
Navigation	0.6	0.6	0.7	192
Philosophy	0.5	0.5	0.5	316
Poetry	0.8	0.8	0.7	4042
Political philosophy	0.3	0.3	0.4	198
Printing and book trades	0.8	0.8	0.8	800
Prophecies	0.6	0.6	0.6	171
Religious	0.7	0.7	0.7	7390
Religious Catholicism	0.3	0.3	0.4	297
Religious Judaism	0.6	0.6	0.6	116
Religious Sects	0.5	0.5	0.5	1827
Religious Sermons	0.8	0.8	0.8	2788
Scientific instruments	0.7	0.7	0.6	85
Societies	0.6	0.6	0.6	130
State affairs	0.4	0.4	0.5	392
Stories	0.5	0.5	0.5	3222
Supernatural	0.6	0.6	0.6	148
Technical instructions Agriculture	0.7	0.7	0.7	276
Technical instructions Trades	0.5	0.5	0.5	358
Travel descriptions	0.0	0.0	0.0	23
University learning	0.5	0.5	0.6	184
University matters	0.3	0.3	0.3	57
Macro Avg	0.5	0.5	0.5	47650
Weighted Avg	0.7	0.7	0.7	47650
Accuracy: 0.7				

Notes: Precision measures the ratio of true positives over true and false positives. Recall measures the ratio of all true positives over all true positives and false negatives. The F1-score is a weighted harmonic mean between precision and recall. Higher values indicate better performance. Support is the number of observations of classes in the test dataset. Accuracy is the overall number of correct predictions over all predictions.

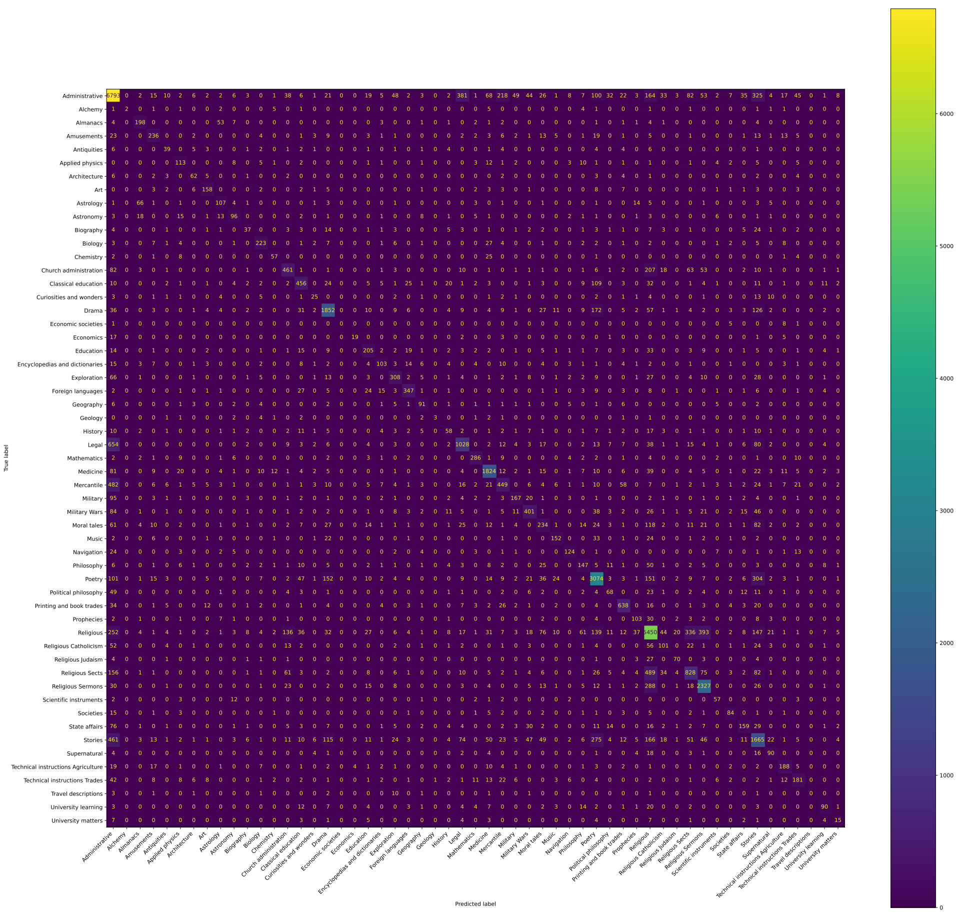


FIGURE 10: Confusion matrix – DistilBERT classification

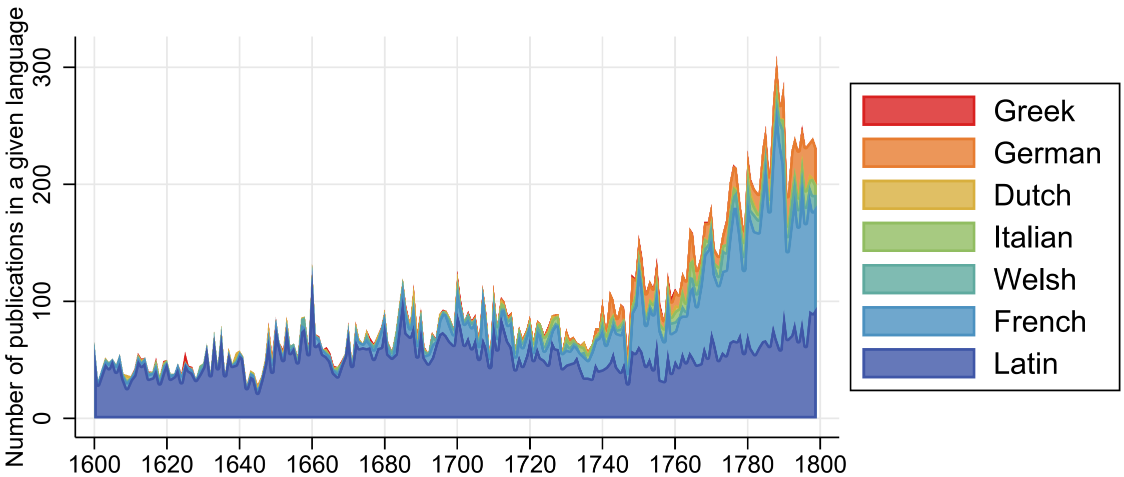


FIGURE 11: ESTC titles published in foreign languages over time

A.3.6 Calculation of teachers' direction to the research frontier and teachers' innovativeness

First, the paper introduces a new approach of calculating a researcher's innovativeness based on the logic from Kelly et al. (2021). They introduce an intuitive approach of calculating innovativeness based on natural language processing. It is based on the logic that a innovative publications are more similar to the future of its field than to the past of its field. Hence, one can get a measure of paper's innovativeness by dividing its forward similarity (similarity to future titles in the field) over its backward similarity (similarity to past titles in the field):

$$\text{Innovativness}_i = \frac{\text{Forward similarity}_i}{\text{Backward similarity}_i} \tag{3}$$

Hence, it captures the logic that an innovative publications needs both to be novel and to have an impact on the future of the field. The index captures novelty through the inverse backwards similarity and impact on the future of a field through forward similarity.

Kelly et al. (2021) implement this logic in a tf-idf bag-of-words approach. It transforms both the text of the document and all the text of the corpus into a large vectors of words. With these, it calculates the frequency of a word in a document compared to its frequency in the whole corpus. Based on this, it calculates similarities between documents based on the overlap of words that are infrequent in the whole corpus, hence words that individually characterize the individual title.

However, this approach is more suited to highly technical text with many specific technical terms, such as the patents analysed by Kelly et al. (2021).[47] Yet, the scientific literature of the seventeenth century uses a more complex language that poses a significant challenge to bag-of-word approaches. Hence, this paper pioneers a new way of applying the basic logic

[47] The literature on scientific and technical innovation usually defines innovativity as how much a publication changed its field. For example, Funk and Owen-Smith (2017); Park, Leahey and Funk (2023) and Wu, Wang and Evans (2019) measure disruptive publications using citation counts. Funk and Owen-Smith (2017) define disruptive inventions as publications that replace the corpus of citations they cite. Wu, Wang and Evans (2019) compare whether future works are more likely to cite the cited works in an article or the article itself. However, the context of the seventeenth and eighteenth century poses the challenge that citations were not yet a common practise within seventeenth and eighteenth century academia. Therefore, the paper adopts a language-based innovation index. Instead of counting citation links, this approach calculates the similarity between the content between titles.

from Kelly et al. (2021) to more complex corpora of text: It applies a a BERT transformer model to the text to create context-sensitive text-embeddings and then calculates the textual similarity based on the text-embeddings.[48] This approach offers a powerful approach that is able to capture similarities in the meaning of documents in contrast to similarities in word-frequencies. Appendix section B.1.2 illustrates the advantages of transformer models over bag-of-word or word-embedding models by comparing the performance of different language models for an exemplary set of titles.[49]

Technically, the index is calculated by taking the mean of a title's, i, cosine similarity (cos) to all other titles in its field within a shifting time-frame. We define backward similarity as a title's mean cosine similarity to all titles within a twenty year time interval into the past, T_p.

$$BS_i = \frac{1}{N} \sum_{j \in T_p}^{N} cos(i, j) \tag{4}$$

Analogously, forward similarity is defined as a title's mean cosine similarity to all titles with a twenty year time interval into the future, T_f

$$FS_i = \frac{1}{N} \sum_{j \in T_f}^{N} cos(i, j) \tag{5}$$

Title i's innovativeness is then defined as the ratio of its forward similarity (FS) over its backward similarity (BS):

$$I_i = \frac{FS_i}{BS_i} \tag{6}$$

Following Kelly et al. (2021) we can interpret this innovation index as a language-based alternative to a citation index. To the best of the author's knowledge, it is the first paper within the innovation literature that uses transformer distances to calculate a publication's innovativeness.

[48] The paper uses the ll-MiniLM-L6-v2 model that was pretrained on over 1 billion sentence pairs and optimzed as as a sentence and short paragraph encoder.

[49] Within the context of the ESTC, we should note that Bert uses word piece tokenization that breaks individual words into multiple tokens. This has the advantage that unknown words are broken down into pieces. For most unknown words a representation exists at least for some of its sub-parts reconstructing its original as close as possible. This feature is especially valuable for dealing with different spellings in the seventeenth century.

In a next step, the paper creates a measure for a title's proximity to the research frontier. The paper introduces proximity to the *Philosophical Transactions*, the journal of the Royal Society, as a proxy for proximity to the research frontier of the Scientific Revolution. Since its foundation in 1665, the *Philosophical Transactions* was the only scientific journal in Britain during the seventeenth and early eighteenth century. It was founded to publish new findings at the frontier of the Scientific Revolution. Articles that were submitted to the *Philosophical Transactions* had to pass an early editorial review process that practically ensured that articles were scientifically relevant and of a sufficiently high quality (Andrade, 1965; Csiszar, 2016). The paper collects all 10,730 titles from the journal's articles and uses them as a proxy for the research frontier of the Scientific Revolution.

Calculating the proximity to the *Philosophical Transaction* rests on two tasks. First, classifying the Philosophical Transactions into the same subject fields as for the ESTC and second, calculating the ESTC titles' proximity to the current research frontier in a given field. The paper solves the first task of classifying the titles from the *Philosophical Transactions* by using the DistilBERT classification model that was pre-trained on the ESTC subject classes in section 3.3.1. The model was also trained on scientific texts from the same time period and therefore perfectly applies to the classification task for the *Philosophical Transactions*. Furthermore, this approach has the advantage of applying the same classification system to both datasets. Next, the paper calculates forward facing cosine similarities of ESTC title i to all titles in the *Philosophical Transactions* from the next 40 years in the same field, T_f :

$$\text{Dist. frontier}_i = \frac{1}{N} \sum_{j \in T_f}^{N} cos(i, j) \tag{7}$$

Using proximity to the next forty years is supposed to capture proximity to the concepts that will be important in the future, i.e. the frontier. The index mainly differs from the innovation index by a) using proximity to a select group of titles that are seen as high-quality and b) not requiring a title to be novel. In comparison, the innovation index requires a title to be (one of) the first in its field to introduce a new concepts and to have a large impact, while the proximity to the *Philosophical Transactions* index only captures a title's use of "cutting-edge" concepts from the research frontier.

A.3.7 Comparison of different natural language models for processing distances

In order to illustrate the differences between different ways of measuring sentence similarities, e.g. bag-of-words methods, word-embeddings, sentence embeddings, and the BERT model, we can take a look at a stylized example of titles. We compare Isaac Newton's famous work *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* to a work that is known to have been an important influence for Newton, Christian Huygen's *Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection* and a later work on optics that was likely inspired by Newton's work, David Gregory's *Elements of catoptrics and dioptrics.* We further compare Newton's Optics to a set of unrelated titles that mentions similar words such as "light" or "reflexions", but in an unrelated context. Table 37 shows the comparative statistics. A good measure of sentence similarity should be able to a) identify titles of similar content that are described with different words and b) distinguish related from unrelated titles using the same words, but in a different context.

Comparing Newton's *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* and Huygen's *Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection* is relatively straightforward. Both titles essentially describe the same set of phenomena that are explained, although described slightly differently. However, the challenge set by David Gregory's *Elements of catoptrics and dioptrics* in comparison to Newton's *Opticks* is significant as both works do not have an overlapping technical vocabulary. In order to identify the similarity between both works we need the additional information that catoptrics deals with the phenomeon of reflacted light and that dioptrics is the branch of optics studying refraction. Hence, the similarity exists between the meaning of the words, and not the technical vocabularly itself. Looking at the unrelated placebo titles, we see that titles such as *The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints* or *A true and impartial account of the dark and hellish power of witchcraft* use the same technical vocabulary of light and colour, but in a different context. Thus, distinguishing

Newton's *Optics* from these placebo titles not only involves comparing the meaning of words (e.g. "dark" and "colour" might be similar), but understanding the context of its use.

Table 37 compares a tf-idf bag-of-words approach, word-embeddings in spacy, sentence embeddings in Google's Universal Sentence Encoder, and a BERT transformer model.[50] It shows that the bag-of-words tf-idf method succesfully identifies a high similarity between Newton's and Huygen's works, but shows a similarity of 0 between Newton's and Gregory's works on optics. Comparing Newton's work to a group of unrelated placebo titles, it picks up on the use of "light" and "reflexions" in a completely different context, although the similarity scores are still relatively low. In general, we see that the main shortcoming of bag-of-word methods is its inability to account for the similar meaning of different words, leading to a significant loss of information in comparing scientific articles.

These shortcomings of bag-of-words methods might lead us to prefer similarity measures based on word embeddings. Column (2) presents the average of the similarity of word-vectors using spacy. This method is able to successfully capture the similarity between Newton's, Huygens's, and Gregory's work. However, the vector representation of words also recognizes a similar meaning in the unrelated controls that also use phrases of light - although in a religious, or figurative meaning. The method still gives a higher similarity score to the true works on optics. However, the difference in similarity scores is less than we might prefer. Thus, the results on word-embedings highlight the need for a method that can account for different meanings based on context. This leads to transformer models based on deep neural networks that can compute context-aware representations (Vaswani et al., 2017). Column (3) shows the results for Google's Universal Sentence Encoder (Cer et al., 2018) that uses sentence embeddings from a pre-trained transformer model and column (4) shows results for the BERT transformer model (Devlin et al., 2018). The results for the USE are disappointing. It gives a lesser similarity score to Gregory's work than to *The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints.* However, the BERT model successfully identifies the true

[50] Before running the similarity measures for Tf-idf and spacy, titles are broken down into only nouns, adjectives, and adverbs – terms that are most likely to capture the relevant topic of the words.This avoids an overweighting of usual stop-words such as "that" or "and" or of verbs with versatile meanings. Nouns, adjectives, and adverbs are identified using spacy. Both USE and BERT use context-information from the whole sentence and thus require the complete use of complete use of the text-structure.

works of optics and gives a significantly lower similarity score to the unrelated placebos. Thus, it is able to distinguish between the context of physical treatments of light and colours and the context of religious and figurative use of light and colours. These results indicate that using transformer models can lead to more comprehensive and accurate similarity measures between book titles than tf-idf bag-of-word models or word-embedding models. However, it still shows the presence of false positives within a lower probability limit. Hence, this paper will combine the transformer models for measuring novelty with a prior categorization of topics. Similarity measures are then only calculated for documents within each topic.

Table 24: Comparing title similarities with different NLP methods

Similarity between:	Tf-idf	Spacy	USE	BERT
Newton's famous work on optics:				
"Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light"[1)]				
and				
Prior works on optics:				
"Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection & Refraction"[2)]	0.24	0.67	0.38	0.64
Later works on optics:				
"Dr. Gregory's Elements of catoptrics and dioptrics. To which is added, I. A method for finding the foci of all Specula as well as Lens's universally. As also for Magnifying or Lessening a given Object by a given Speculum or Lens in any assign'd Proportion, &c. A particular account of microscopes and telescopes, from Mr. Huygens. With an introduction shewing the Discoveries made by Catoptrics and Dioptrics."[3)]	0	0.55	0.21	0.41
Unrelated placebo titles:				
"The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints"	0.08	0.46	0.28	0.23
"A true and impartial account of the dark and hellish power of witchcraft"	0	0.47	0.22	0.18
"A new torch to the Latine tongue: so enlightned, that besides the easie understanding of all classical authours, there is also laid open a ready way to write and speak Latine well and elegantly"	0	0.48	0.18	0.12
"Political reflections upon the finances and commerce of France; shewing the causes which formerly obstructed the advancement of her trade"	0.11	0.41	0.19	0.20

1): Isaac Newton, 1704, 2): Christiaan Huygens, 1690, 3): David Gregory, 1715.

List of natural language processing models used: Tf-idf: term frequency-inverse document frequency implemented with Python's sklearn. Spacy: Word-embeddings implemented in spacy with similarity calculated as average cosine similarity accross words. USE: Universal Sentence Encoder, a sentence embedder based on a transformer model (Cer et al., 2018). The paper uses the TF2-v5 model from Tensorflow. BERT: Bidirectional Encoder Representations from Transformers, a state-of the art transformer model (Devlin et al., 2018). The paper uses the ll-MiniLM-L6-v2 model that was pretrained on over 1 billion sentence pairs and optimzed as as a sentence and short paragraph encoder. The text of the titles is presented in the original spelling. For the presentation of this stylized example the "unrelated controls" titles have been shortened but remain otherwise unchanged.

A.3.8 Trends in scientific fields and innovativity

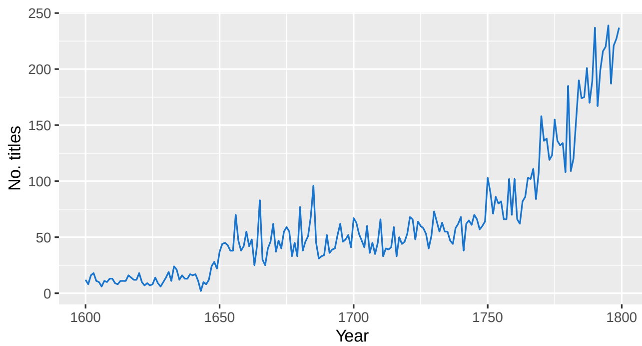


Figure 12: Total number of British publications in the fields of the Scientific Revolution

The figure plots the total number of yearly publications in the fields of the Scientific Revolution in the ESTC. Publications in the fields of the Scientific Revolution are defined as publications within the fields of astronomy, almanacs, applied physics, mathematics, chemistry, biology, and medicine.

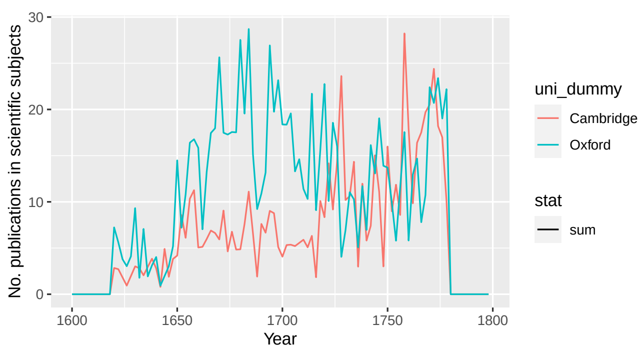
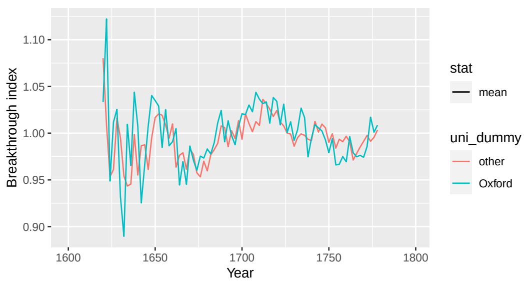
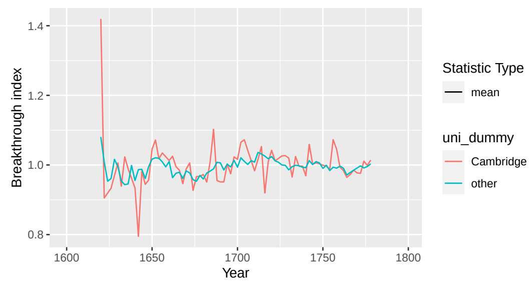


Figure 13: Comparison of total number of publications in scientific fields by graduates of either Oxford or Cambridge

The figure compares the total number of publication in scientific fields from authors with an educational background from either Oxford, or Cambridge. Scientific publication are defined as publications within the fields of astronomy, almanacs, applied physics, mathematics, chemistry, biology, and medicine.The line shows average values for 5 year intervals.



(a) University of Oxford



(b) University of Cambridge

FIGURE 14: Comparison of average breakthrough index by authors' educational background

The figure compares the of average breakthrough index (see equation 4, 5, and 6) between scientific publications from authors with an educational background from either Oxford, Cambridge, or other backgrounds. Scientific publication are defined as publications within the fields of astronomy, almanacs, applied physics, mathematics, chemistry, biology, and medicine. The line shows average values for 5 year intervals. It should be noted that the matching procedure between ESTC titles and university students is not perfect. Hence, some titles written by unmatched authors' with a university background might enter the cateogry "other".

A.4 Empirical results

Table 25: Teacher-effect for the fields of the Scientific Revolution estimated on the subsample of only students that published in the Scientific Revolution

Panel A: University of Oxford			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	All topics	Without medicine	Core topics
Log share of each topic in teacher publications	0.162**	0.101	0.140
	(0.0614)	(0.180)	(0.158)
Topic fixed effects	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes
Observations	1287	648	342
R-squared	0.30	0.07	0.18
Panel B: University of Cambridge			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	All topics	Without medicine	Core topics
Log share of each topic in teacher publications	0.0807***	0.166*	0.334**
	(0.0190)	(0.0889)	(0.116)
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes
Observations	1233	603	423
R-squared	0.28	0.12	0.26

Notes: The table shows results from estimating equation 1 while limiting the sample only to students who published in any of the topics of the Scientific Revolution. The table then successively uses different definitions of the fields of the Scientific Revolution. In column 2 it uses the standard definition of this paper that includes the fields of astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. Next, in column 2 it uses the same definition, but excludes medicine. Lastly in column 3, it uses the "core of the Scientific Revolution" consisting of astronomy, applied physics, and mathematics. It then estimates the effects of teachers' research fields on students' research fields. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. The model includes student-, topic-, and cohort fixed effects. All count variables are transformed using the inverse hyperbolic sine transformation. Standard errors are multi-way clustered at the college $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 26: Teacher-effect for the fields of the Scientific Revolution for the full sample when using different definitions of the fields of the Scientific Revolution

Panel A: University of Oxford			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	All topics	Without medicine	Core topics
Log share of each topic in teacher publications	0.0297**	0.0197	0.0565
	(0.0112)	(0.0194)	(0.0454)
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Topic fixed effects	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes
Observations	11484	10208	3828
R-squared	0.17	0.17	0.37

Panel B: University of Cambridge			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	All topics	Without medicine	Core topics
Log share of each topic in teacher publications	0.00996***	0.0124***	0.00612
	(0.000598)	(0.00197)	(0.0151)
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Student fixed effects	Yes	Yes	Yes
Observations	12231	10872	4077
R-squared	0.17	0.19	0.46

Notes: The table shows results from estimating equation 1. The table successively uses different definitions of the fields of the Scientific Revolution. In column 2 it uses the standard definition of this paper that includes the fields of astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. Next, in column 2 it uses the same definition, but excludes medicine. Lastly in column 3, it uses the "core of the Scientific Revolution" consisting of astronomy, applied physics, and mathematics. It then estimates the effects of teachers' research fields on students' research fields. The strength of teachers' research fields within each of these fields is calculated as the share of all teachers' publications within field τ of all publications within all fields at college c at time t. The strength of students' research fields is calculated as the share of student i's publications in field τ out of all publications from student i. The model includes student-, topic-, and cohort fixed effects. All count variables are transformed using the inverse hyperbolic sine transformation. Standard errors are multi-way clustered at the college $\times$ topic level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 27: Effect of teachers' research in the Scientific Revolution on lifetime career outcomes

Panel B: University of Oxford	University degrees		Career in the church			Other careers			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Medicine	Law	Rector	Vicar	Prebendary	Physician	Law	M.P.	D.N.B.
Teachers' publication share in the Scientific Revolution	0.00266	0.00200	0.00834	-0.00221	0.000896	0.00137	-0.00322	-0.000330	-0.000394
	(0.00221)	(0.00286)	(0.00578)	(0.00600)	(0.000657)	(0.000792)	(0.00789)	(0.00130)	(0.00135)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	28396	28396	28396	28396	28396	28396	28396	28396	28396
R-squared	0.01	0.04	0.02	0.02	0.00	0.01	0.03	0.01	0.01
Mean dep. var.	0.016	0.024	0.204	0.143	0.005	0.005	0.151	0.020	0.015
Panel B: University of Cambridge	University degrees		Career in the church			Other careers			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Medicine	Law	Rector	Vicar	Prebendary	Physician	Law	M.P.	D.N.B.
Teachers' publication share in the Scientific Revolution	-0.00218	-0.00168	0.000128	0.00200	0.00200	0.00146	-0.00797	0.00139	-0.00131
	(0.00226)	(0.00188)	(0.00586)	(0.00601)	(0.00601)	(0.00174)	(0.0104)	(0.00210)	(0.00207)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	27228	27228	27228	27228	27228	27228	27228	27228	27228
R-squared	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01
Mean dep. var.	0.020	0.011	0.214	0.161	0.161	0.022	0.139	0.025	0.035

Notes: The table estimates the effects of teachers' publication shares in the Scientific Revolution on students' choice of advanced degrees, career choices, and lifetime outcomes based on information in Foster (1891) and Venn and Litt (1952). The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. Column 1-2 present results for the dependent variable of students taking an advanced degree in either medicine (B.Med., M.D., D.Med.) or law (B.C.L., LL.B, D.C.L., L.L.D.). Column 3-5 present results for the dependent variable of students choosing a career as either a physician, clergyman or at one of the inns in London. Finally column 6-7 capture whether a student became a member of parliament (M.P.) or got an entry in the Dictionary of National Biography (D.N.B.). Teacher controls includes the number of teacher publications. Student controls include dummies for whether a student graduated with a B.A. or M.A. Standard errors clustered at the college level in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 28: Direction of teachers' research on students' general publication outcomes

Panel A: University of Oxford			
	Student lifetime publishing		
	(1)	(2)	(3)
	Ever published	Log number publi	Innovativeness
Log share of teachers' publications in the Scientific Revolution	0.00138	0.0230	-0.000812
	(0.00226)	(0.0609)	(0.00182)
Teacher publications and college level controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Observations	28396	1273	1268
R-squared	0.01	0.11	0.09
Mean dep. var.	0.04	1.58	1.00
Panel B: University of Cambridge			
	Student publication outcomes across all fields		
	(1)	(2)	(3)
	Ever published	Log number publi	Innovativeness
Log share of teachers' publications in the Scientific Revolution	-0.00231	-0.138***	-0.00212
	(0.00230)	(0.0443)	(0.00224)
Teacher and college level controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Observations	27228	1358	1349
R-squared	0.01	0.10	0.09
Mean dep. var.	0.05	1.52	1.00

Notes: The table shows results from estimating equation 1 on the college × cohort level. It estimates the effects of the average of teachers' research fields in the Scientific Revolution on the average of students' research fields in the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The model applies college- and cohort-fixed effects. Teacher controls include the log-transformed number of teacher publications, the log-transformed number of fellows at a college at a student's time of matriculation, and the log-transformed cohort size at a student's time of matriculation. Column 1 estimates the effect of teachers' average publication share in the Scientific Revolution on whether a student ever published. Column 2 estimates the effect of teachers' average publication share in the Scientific Revolution on a student's log-transformed number of publication. Column 2 estimates the effect of teachers' average publication share in the Scientific Revolution on a student's average innovativeness. Standard errors are clustered at the college level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 29: Field-specific teacher-effect in the Scientific Revolution vs. general teacher-effect for all the fields of the Scientific Revolution

Panel A: University of Oxford			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	Mean top.	Mean top.	Mean top.
Log share of each topic in teacher publications	0.0285**		0.0298**
	(0.00975)		(0.0105)
Log share of average of teacher publications in the Scientific Revolution		0.00557	-0.00448
		(0.0115)	(0.00873)
Teacher and college level controls	Yes	Yes	Yes
Student publication controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Observations	11484	11484	11484
R-squared	0.04	0.04	0.04
Panel B: University of Cambridge			
	Log share of each topic in student publications		
	(1)	(2)	(3)
	Mean top.	Mean top.	Mean top.
Log share of each topic of teacher publications	0.0124***		0.0108**
	(0.00359)		(0.00461)
Log share of average of teacher publications in the Scientific Revolution		0.00903	0.00474
		(0.00863)	(0.00820)
Teacher and college level controls	Yes	Yes	Yes
Student publication controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
College fixed effects	Yes	Yes	Yes
Observations	12231	12231	12231
R-squared	0.04	0.04	0.04

Notes: The table shows results from estimating equation 1 on the college $\times$ cohort level. The table compares the average of the field-specific teachers' share of publications for each field of the Scientific Revolution with the general teachers' share of publications in any field of the Scientific Revolution. Thus, the share of publications in any field of the Scientific Revolution captures the general culture within the new sciences where being exposed to any field of the Scientific Revolution would increase students' chances of publishing in any field of the Scientific Revolution. The fields of the Scientific Revolution are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The model applies college-, cohort-, and topic-fixed effects. Since the general teacher-effect is not varying across topics, student-fixed effects are excluded. Teacher controls include the log-transformed number of teacher publications, the log-transformed number of fellows at a college at a student's time of matriculation, and the log-transformed cohort size at a student's time of matriculation. Standard errors are clustered at the college level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 30: The effect of city growth on growth-trends in the instrumental variable, city level

	Growth rate of teachers' publication shares for the fields of the Scientific Revolution									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	All	Almanacs	Astronomy	Applied physics	Biology	Chemistry	Geography	Instruments	Mathematics	Medicine
City growth rate 1500-1600	-0.0644	0.0493	-0.0215	-0.108	-0.0455	-0.217	-0.0233	-0.0496	-0.0382	-0.124
	(0.0926)	(0.0828)	(0.0572)	(0.123)	(0.0664)	(0.132)	(0.0858)	(0.0538)	(0.0546)	(0.112)
Observations	78	78	78	78	78	78	78	78	78	78
R-squared	0.00	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.00	0.01

	Growth rate of teachers' publication shares for the fields of the Scientific Revolution									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	All	Almanacs	Astronomy	Applied physics	Biology	Chemistry	Geography	Instruments	Mathematics	Medicine
City growth rate 1600-1700	-0.0343	0.106	0.0550	-0.0572	0.0936	0.155	0.0153	0.0343	0.0976	-0.0224
	(0.127)	(0.0902)	(0.0919)	(0.147)	(0.119)	(0.137)	(0.116)	(0.111)	(0.118)	(0.129)
Observations	78	78	78	78	78	78	78	78	78	78
R-squared	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.00

Notes: The table shows results from regressing the growth rate of predicted teachers' publication shares on city growth, 1500-1600 and 1600-1700. For the calculation of regionally predicted teacher publication shares, see section 2.5.1. The unit of analysis is the Bairoch (1988) city level. City growth is defined the arcsinh approximation of the city growth rate, $arcsinh(x_t) - arcsinh(x_{t-1})$, similar to a log-approximation. Robust standard errors in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 31: The effect of city growth on growth-trends in the instrumental variable, county level

	Growth rate of teachers' publication shares for the fields of the Scientific Revolution									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	All	Almanacs	Astronomy	Applied physics	Biology	Chemistry	Geography	Instruments	Mathematics	Medicine
City growth rate 1500-1600	-0.130	0.0146	0.0535	0.0548	0.0253	-0.0188	0.0299	0.0119	0.0177	-0.214*
	(0.106)	(0.0153)	(0.0386)	(0.0486)	(0.0662)	(0.0536)	(0.0628)	(0.0343)	(0.0246)	(0.113)
Observations	32	32	32	32	32	32	32	32	32	32
R-squared	0.04	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.11

	Growth rate of teachers' publication shares for the fields of the Scientific Revolution									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	All	Almanacs	Astronomy	Applied physics	Biology	Chemistry	Geography	Instruments	Mathematics	Medicine
City growth rate 1600-1700	0.00903	0.0436	-0.152	-0.128	0.0177	-0.0921	-0.0791	0.0866	0.0557	0.0499
	(0.0900)	(0.0665)	(0.0937)	(0.0844)	(0.129)	(0.0820)	(0.143)	(0.0743)	(0.0849)	(0.0895)
Observations	32	32	32	32	32	32	32	32	32	32
R-squared	0.00	0.01	0.07	0.05	0.00	0.02	0.02	0.02	0.01	0.01

Notes: The table shows results from regressing the growth rate of predicted teachers' publication shares on city growth, 1500-1600 and 1600-1700. For the calculation of regionally predicted teacher publication shares, see section 2.5.1. The unit of analysis is the county level. City growth is defined the arcsinh approximation of the city growth rate, $arcsinh(x_t) - arcsinh(x_{t-1})$, similar to a log-approximation. Robust standard errors in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 32: Balancedness for geo information, 1620–1720

Variable	(1) Students without geo info	(2) Students with geo info	(3) Difference
Student graduates with B.A.	0.505	0.543	0.037***
	(0.500)	(0.498)	(0.007)
Student graduates with M.A.	0.309	0.322	0.013**
	(0.462)	(0.467)	(0.006)
Cohort size	29.914	25.423	-4.491***
	(24.413)	(16.168)	(0.249)
Number of student's publications	0.357	0.310	-0.047
	(3.968)	(3.135)	(0.045)
Share of fields of the Scientific Revolution in a student's publications	0.007	0.006	-0.001
	(0.025)	(0.023)	(0.001)
Sum students' publications in the fields of the Scientific Revolution	0.013	0.018	0.006
	(0.238)	(0.430)	(0.005)
Number fellows	15.036	11.229	-3.807***
	(10.961)	(9.070)	(0.127)
Teacher publications	21.303	21.139	-0.164
	(26.768)	(29.197)	(0.377)
Share of fields of the Scientific Revolution in teacher's publications	0.009	0.007	-0.002***
	(0.019)	(0.017)	(0.000)
Sum teachers' publications in the fields of the Scientific Revolution	0.483	0.420	-0.063***
	(0.966)	(1.057)	(0.014)
Observations	7,964	20,434	28,398

Notes:

Table 33: Balancedness for geo information and predicted colleges, 1620–1720

Variable	(1) Students without geo info	(2) Students with geo predictions	(3) Difference
Student graduates with B.A.	0.514	0.554	0.040***
	(0.500)	(0.497)	(0.006)
Student graduates with M.A.	0.320	0.318	-0.002
	(0.466)	(0.466)	(0.006)
Cohort size	27.032	26.247	-0.784***
	(21.014)	(16.016)	(0.226)
Number of student's publications	0.354	0.285	-0.068*
	(3.495)	(3.252)	(0.040)
Share of fields of the Scientific Revolution in a student's publications	0.007	0.006	-0.001
	(0.024)	(0.023)	(0.001)
Sum students' publications in the fields of the Scientific Revolution	0.020	0.013	-0.006
	(0.424)	(0.333)	(0.005)
Number fellows	13.240	11.122	-2.118***
	(10.209)	(9.103)	(0.116)
Teacher publications	21.741	20.493	-1.248***
	(28.486)	(28.585)	(0.341)
Share of fields of the Scientific Revolution in teacher's publications	0.008	0.006	-0.002***
	(0.018)	(0.016)	(0.000)
Sum teachers' publications in the fields of the Scientific Revolution	0.492	0.370	-0.122***
	(1.064)	(0.988)	(0.012)
Observations	15,748	12,650	28,398

Notes:

3 Did a feedback mechanism between propositional and prescriptive knowledge create modern growth?

Abstract

This paper tests Joel Mokyr's (2002) hypothesis that for the first time in history,ia feedback loop between propositional and prescriptive knowledge started to appear in the eighteenth century and led to a new regime of self-sustained modern growth. The paper applies new natural language processing measures of knowledge spillovers between scientific and technical fields to the universe of the titles of all British publications between 1600 and 1800. Based on these knowledge spillovers, the paper estimates the strength of a feedback loop between propositional and prescriptive knowledge over time. It finds that a positive feedback loop started to emerge during the second-half of the eighteenth century. These finding stand in support of the theory of Mokyr (2002) and shed new light on the mechanism of knowledge spillovers between science and technology.[51]

Keywords: Feedback Loop Processes, Knowledge Spillovers, Innovation, Economic Growth, Natural Language Processing

JEL Classification: O33, O31, O14, O47, O49, N13, N33

[51]I also want to thank Joel Mokyr for his invaluable input that has made this project possible. I would like to thank my supervisors Prof. Max-Stephan Schulze and Dr. Jeremiah Dittmar at LSE for their ever-present guidance and support. Further thanks go to seminar participants at the LSE graduate economic history seminar. I would further like to thank the British Library for kindly sharing their data from the English Short Title Catalogue as well as Alessandro Nuvolari and Valentina Tartari for kindly sharing their data on English patents.

3.1 Introduction

Was the Industrial Revolution caused by advances in new knowledge connected to the Scientific Revolution? One important contribution to this question is Mokyr's theory of a feedback mechanism between different types of knowledge (Mokyr, 2002, 2005). Mokyr distinguishes between propositional knowledge, knowledge about the world, and prescriptive knowledge, knowledge how to change the world (Mokyr, 2002). While propositional and prescriptive knowledge had increased in waves throughout much of human history, it was only since the Industrial Revolution that both types of knowledge started to increase permanently. Mokyr (2002) argues that a key explanation for this permanent increase in knowledge is a feedback mechanism between propositional and prescriptive knowledge. Through a large enlightenment literature on useful knowledge, propositional knowledge was mapped into the layer of prescriptive knowledge. Furthermore, collecting experiences with useful knowledge provided the right kind of questions and empirical data to advance propositional knowledge as well. The strength and importance of the mapping from propositional knowledge (especially science) to prescriptive knowledge have been controversy discussed in the literature (Musson and Robinson, 1969; Mathias, 1972; Hall, 1974; Jacob, 1997, 2014; Ó Gráda, 2016; Kelly and Ó Gráda, 2022). Yet, little has been done to investigate the existence of such a feedback mechanism quantitatively.

However, recent advances in natural language processing (NLP) and the digitization of historical publications have made this task technically feasible. First, information on the titles of national library holdings have become digitally available. Second, advances in natural language processing (NLP), especially the arrival of foundational models and the transformer architecture (Bommasani et al., 2021), have made it possible to generate context-sensitive content distances between written works.

Based on these technical advances, this paper introduces an NLP based measure for spillovers between fields of propositional and prescriptive knowledge. It then tests for the presence of a feedback loop mechanism within the universe of titles of British publications from the English Short Title Catalogue (ESTC), 1600-1800. By estimating whether a spillover from field A to field B made it more like for another spillover from field B to field A to occur, we get a direct estimate of the strength of a feedback loop between field A and field B. The paper applies this method to spillovers between fields from propositional and prescriptive knowledge. The fields of propositional knowledge used for this paper consist of *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine*. The fields of prescriptive knowledge consist of *techniques in trades, techniques in agriculture, and navigational techniques.* Hence, this setting allows a direct test of the first part of Mokyr's (2002) feedback loop hypothesis, namely the claim that a feedback loop between propositional and prescriptive knowledge started to arise within the eighteenth century. Second, it also tests Mokyr's (2002) claim that the feedback loop mechanism led to a modern growth regime. For this, the paper tests whether knowledge spillovers affected patenting as well.

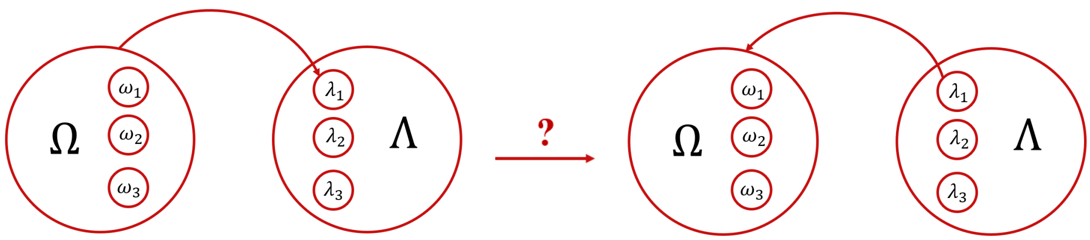
The paper finds evidence of a structural break in the development of feedback loop processes throughout the seventeenth and eighteenth century. Across different fields it finds that the coefficient for the feedback loop process was still negative at the beginning of the eighteenth century. Hence, titles receiving knowledge from other fields were less likely to create knowledge spillovers on their own. We can interpret this as evidence that scientific and technical fields were still immature, incorporating e.g. early scientific models that still included many errors and simplifications, and that might have practical applications worse rather than better. Yet, throughout the seventeenth century, estimates of the feedback loop coefficient approach zero. Titles that received spillovers from other fields were as likely as other titles to cause spillovers on their own. Additionally, for the end of the eighteenth century, we find evidence of a positive feedback loop for a few number of fields. However, the analysis reveals that there is substantial heterogeneity across fields. Furthermore, the paper also finds a single case of a negative feedback mechanism at the end of the eighteenth century.

Overall, this is evidence of the beginning of a structural break in the knowledge economy of Britain in the seventeenth and eighteenth century. On average, feedback loop processes became stronger over time, despite substantial heterogeneity across fields. Yet, the evidence found by this paper rather points towards the beginning of a structural break rather than a mature knowledge economy with a strong feedback mechanism between propositional and prescriptive knowledge. The findings are compatible with Mokyr's (2002) description of a gradually increasing feedback loop process in Britain's knowledge economy as well as established evidence in economic history that has stressed that early growth in the eighteenth century was still slow and limited to a few sectors. The paper further finds that titles in *techniques in trades* that received knowledge spillovers from *applied physics* were also more likely to be patented - showing that feedback loop-driven growth in prescriptive knowledge increased innovative activities in the real economy.

One of the paper's main contributions is the creation of a new framework to estimate the strength of a feedback loop between different fields based on recent methods in natural language processing. The following sketches out the intuition of this paper's framework for estimating feedback loops. Basically, the paper introduces a framework where feedback loops are composed out of mutual knowledge spillovers. First, the paper develops a NLP-based measure of capturing knowledge spillovers. Then, knowledge spillovers are combined to estimate a) direct feedback loops between two fields and b) knowledge spillovers that lead to growth in the receiving field, thereby giving rise to an indirect feedback loop. The following five paragraphs explain the basic framework of this approach.

The paper introduces three new measures of knowledge spillovers between and within different fields: a) a measure of how much one title shifted another field, b) a measure of how much one title shifted its own field, and c) how much a title was shifted itself by another field. All three measures are based on the simple intuition that we can capture how much title i from field A shifted field B, by comparing title i's similarity to the past of field B to the future of field B. The extent of how much title i's similarity to the future of field B is larger than its similarity to the past captures the strength of knowledge spillovers created by title i. In order to calculate similarity between titles, the paper uses a large language BERT model to map all titles into an embedding space that represents titles' context-sensitive meaning within a 512×768 multidimensional space. Then, it calculates cosine distances between titles. To capture similarity to all titles within the future and past of a field, the paper averages across all cosine distances between title i and every title $j \in B$. By levering the time dimension in title similarity, the measure evokes a notion of Granger causality. The approach is similar in spirit to the innovation measure introduced by Kelly et al. (2021).

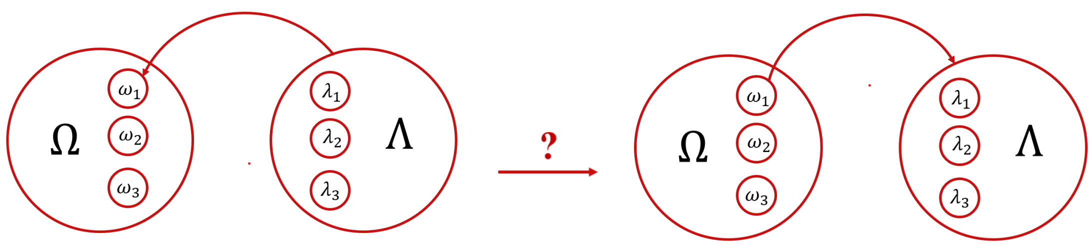
Having a measure of knowledge spillovers then enables us to estimate the strength of the feedback mechanism between a field from propositional knowledge, Ω, and prescriptive knowledge, Λ. The mechanism of this direct feedback loop is illustrated in figure 15–16. Essentially, we can test whether a title i in field A that received a knowledge spillover from field B (figure 15a) is also more likely to create a knowledge spillover into field B (figure 15b).



(a) t_1 : Knowledge spillover from Ω to λ_1

(b) t_2 : Knowledge spillover from λ_1 to Ω

FIGURE 15: Illustration of the left hand-side of direct feedback mechanism between Λ and Ω

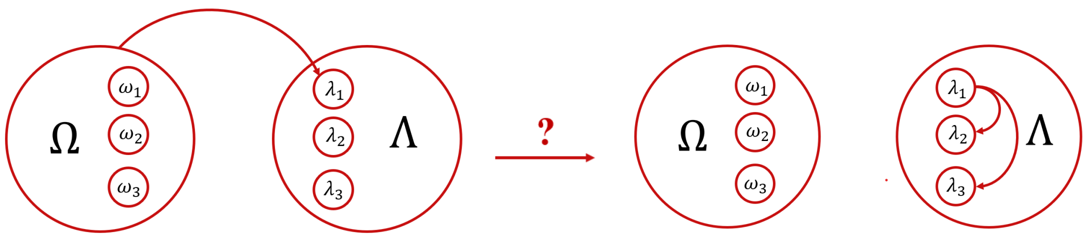


(a) t_1 : Knowledge spillover from Λ to ω_1

(b) t_2 : Knowledge spillover from ω_1 to Λ

FIGURE 16: Illustration of the right hand-side of direct feedback mechanism between Λ and Ω

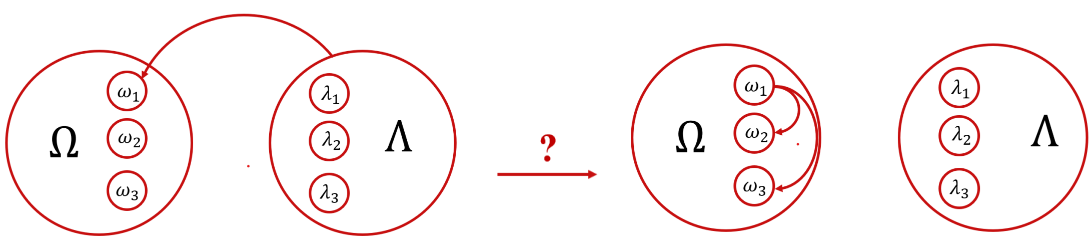
We can estimate this feedback mechanism from two sides. First, there is one process that starts in Ω, affects title i in field Λ, and creates a spillover back into Ω (figure 15). Then, there also is a process that starts in Λ, affects title i in Ω, and creates a spillover back into Λ (figure 16). Having these two measures allows us to capture the responsiveness of titles at the receiving side of knowledge spillovers. Hence, the left-hand-side mechanism (15) shows the responsiveness of titles in Λ to create spillovers conditional on receiving spillovers. The right-hand-side mechanism (16) shows the responsiveness of titles in Ω. Intuitively this captures the epistemic gain that is created by incorporating ideas from the other field. For example, this would be the epistemic gain of implementing a prediction from physical theory for the practical purpose of building a waterwheel. Let us assume the prediction from physical theory would be about the optimum number of blades on a water wheel. Then, the epistemic gain is the practitioner's ability to confirm or reject the theory, thereby changing knowledge about the theory in physics.



(a) t_1 : Knowledge spillover from Ω_1 to λ_1

(b) t_2 : Knowledge spillover from λ_1 to λ_2 and λ_3

FIGURE 17: Lasting knowledge spillovers



(a) t_1 : Knowledge spillover from Ω to ω_1

(b) t_2 : Knowledge spillover from ω_1 to ω_2 and ω_1

FIGURE 18: Lasting knowledge spillovers

Lastly, the paper also introduces a framework that estimates whether titles affected by spillovers from another field are more likely to shift their own field. Intuitively, this captures whether titles receiving knowledge spillovers are more innovative than other titles (see Kelly et al., 2021, for a similar intuition on measuring innovativeness). The mechanism is illustrated in figure 17-18. It can also be estimated from two sides, with the initial spillover either originating in field Ω or Λ. We can interpret the estimated coefficient from this framework as capturing the multiplier effect of initial knowledge spillovers. Essentially, an initial knowledge spillover can give rise to a chain-reaction of further knowledge spillovers within the receiving field, thereby increasing the total stock of knowledge in that field. Such an increase in the stock of knowledge in a field as a response to initial knowledge spillovers can give rise to an indirect feedback loop.

Intuitively, an indirect feedback loop captures the effect of spillovers from field A to field B causing B to grow in consequence and then causing random spillovers in return. In contrast, a direct feedback loop captures spillovers from field A to a specific title i in field B that creates a direct spillover back to field A. Yet, the contribution of indirect feedback loops to the overall production function of knowledge crucially depends on how many of the new ideas created within field B (due to spillovers within field B) actually cause spillovers back into field A. If the rate of spillovers in its own field, β, is smaller than the rate of titles causing spillovers, then the strength of indirect feedback loops fade out over time. In fact, in this setting spillover coefficients are usually close to zero, while ca. 60% percent of titles were not positively shifted by another field. Hence, within the setting of this papers, indirect feedback loops would not be able to create self-sustained growth. To capture this difference between indirect and direct feedback loops, the paper introduces a formal model of the knowledge production function in appendix B.3. The model shows that indirect feedback loops mainly shift the steady-state of the knowledge production function to a higher level, while a direct feedback loop produces self-sustained growth in knowledge production. Calibrating the model with the estimated feedback loop coefficients shows that changes in the strength of feedback loops can explain a large increase in knowledge production in the eighteenth century.

The paper relates to a broad range of literature. First, it adds to the debate on the causes of the Industrial Revolution by providing empirical evidence on the emergence of a feedback loop between propositional and prescriptive knowledge in the seventeenth and eighteenth century. It shows that a feedback process between propositional and prescriptive knowledge, as introduced by Mokyr (2002), has the potential to account for a significant part of productivity as captured through patenting activity. Thus, it adds to a literature that has stressed the importance of scientific and technical knowledge for modern growth (Lucas, 1988; Romer, 1990; Lehmann-Hasemeyer, Prettner and Tscheuschner, 2023), by studying the mechanism of a feedback loop between propositional and prescriptive model as another mechanism accounting for the transit to modern growth to the literature of existing growth models.

The paper further relates to the role of upper-tail human capital for modern growth and innovations. Multiple recent studies have shown the impact of upper-tail human capital on growth during the Industrial Revolution (Squicciarini and Voigtländer, 2015; Hanlon, 2022; Maloney and Valencia Caicedo, 2022; Kelly, Mokyr and Ó Gráda, 2023). Yet, the literature on upper-tail human capital still is lacking a broad consensus on how upper-tail human capital translated into growth. While, the impact of the engineer (Hanlon, 2022) and highly skilled-mechanics (Kelly, Mokyr and Ó Gráda, 2023) appears straightforward, the impact of the common reader of the *Encyclopédie* (Squicciarini and Voigtländer, 2015), mainly educated members of the early bourgeoisie, appears to run through a more complex channel. It seems that the concept of upper-tail human capital contains a mix of applied skills (as in mechanics or engineers) fused together with access to useful knowledge (as in the case of the engineer, drawing on applied physics). This paper contributes to the component of useful knowledge. Access to useful knowledge could only be as valuable as the stock of useful knowledge. This paper provides new empirical evidence on the origin and growth-dynamics of different fields of both propositional and prescriptive knowledge.

Lastly, the paper contributes to the literature on knowledge spillovers in economics. So far, the literature has mainly used patent,citations and surveys to quantify knowledge flows within an economy (Jaffe, Trajtenberg and Henderson, 1993; Feldman, 1999; Jaffe, Trajtenberg and Fogarty, 2000; Akcigit, Hanley and Serrano-Velarde, 2021). Recently, Hallmann, Hanlon and Rosenberger (2023) have created a technology network for Britain and France during the First Industrial Revolution based on inventors' propensity to patent within different fields. This paper introduces a new approach that uses natural language processing to capture knowledge spillovers between scientific and technological fields. This approach allows us to investigate spaces of the knowledge economy that did not rely on patents and are hard to capture through surveys. To the best of the author's knowledge, this paper is the first to use natural language processing techniques to estimate the dynamics of knowledge spillovers between scientific and technological fields of knowledge — an approach that can productively applied to other settings.

The paper proceeds in the following way. Section 3.2 provides historical examples of knowledge spillovers between propositional and prescriptive knowledge. Section 5.2 introduces the text-data on the universe of titles in Britain from 1600 to 1800 as well as the machine learning techniques used for classifying the data into different fields. Section 3.4 introduces the framework of estimating feedback loop processes built on NLP-based knowledge spillovers. This framework is one of the most important contributions of this paper, the paper spends some time and space on introducing the model and building an intuition on its mechanics. The paper further provides an intuition of the semantic content captured in the spillover measures by using two important historical publications as an example. The paper then shows the inputs and outputs used for the construction of knowledge spillover measures for these two titles — helping the reader to build an intuition of the working of the NLP-based measures. Next, section 3.4 presents the results for the empirical model of section 3.5. It further connects the interpretation of the estimated coefficients to a formal model of feedback loop processes introduced in appendix section B.3. Section 3.7 concludes.

3.2 Historical examples of knowledge spillovers between propositional and prescriptive knowledge

To illustrate the mechanism of how spillovers between propositional and prescriptive knowledge could lead to self-sustained improvements, this section will consider two case studies, the development of water wheels and the development of maritime navigation. The examples illustrate that predictions from scientific theory seldomly led to direct and useful applications. Instead, it were often the problems in scientific theories that provided useful starting places for practical experimentation. This in return, helped to improve theories which ran into new problems, thereby creating new useful starting places. A key mechanism for this process were new facts created by technological innovations that often helped to falsify existing knowledge. Furthermore, technological innovations often profited from the adoption of the scientific toolset, including mathematics and systematic quantification. Last but not least, the direction of scientific change was often influenced by unsolved technological problems at the heart of commerce and trade. The following examples illustrate these mechanism.

The history of the water wheels and early physics dealing with the water wheel is a well studied area in the history of science and technology in the eighteenth century (Reynolds, 1983; Mokyr, 1992; Capecchi, 2013). It further is an area that was of high importance for the early-modern economy where water power was an important source for power. In the eighteenth century, engineers like Polhem, de Parcieux, and Smeaton were actively improving existing systems of water power against a background of new scientific theories of hydrodynamics. These theories were mainly developed by theoretical mathematicians such as Parent, Bernoulli, or Euler. However, given the immaturity of these theoretical works, Reynolds (1983) argues that engineers did not make progress by implementing recommendations from theory.[52] Instead, they followed questions posed by problems in the theory of water power. Their work was characterized by "(1) systematic methods of experimentation, (2) the use of working models, and (3) the application of quantitative measurements to key variables" (Reynolds, 1983, p. 232).[53] All of this was new in comparison to the traditional approach that according to Reynolds circled around the questions of "Will it work if I build it this way? or, If I change this element, will it work any better?" (ibid.). Engineers like Polhem, de Parcieux, and Smeaton now started from specific questions on the efficacy of designs that came from unsettled debates in physics. Thus, it were often the unsolved questions rather than successful predictions, that gave them a specific starting place for experimentation. Furthermore, they applied a mathematical, and mechanical mindset to their experimentation where they thought to quantify effects and gather data (ibid.).

Hence, at least for the study of water wheels, it seems that theoretical physics was more successful in creating starting points for systematic experimentation than in yielding exact predictions. Yet, overall improvements were significant. The efficiency of traditional waterwheel lay between ca. 30–40% (Viollet, 2017). Yet, Smeaton's breast shot wheel, as well as overshot- and Poncelet undershot-wheels[54] delivered efficiencies of 60–80% (ibid.). In return, the scientific theory of hydrodynamics improved with each new practical insights (Reynolds, 1983).

[52] There is some controversy on whether the inability of these theories was due to theoretical errors or idealized assumptions (Capecchi, 2013). This should not matter for the present context, their immaturity in yielding practical implications is clear.

[53] A key input to quantitative experimentation was also the new design of testing devices (Constant, 1983).

[54] Based on theoretical work by Borda in the 1760s, but only designed by Poncelet in the 1820s.

We might expect to see the same dynamic in other scientific and technological fields. One can think of Josiah Wedgwood and the influence of his early Chemistry studies on his pottery products. Here, early Chemistry inspired the development of new materials and productions method even when the exact workings of the science where not yet clear. Similarly, dyeing at the end of the eighteenth century seems to have increasingly relied on Chemical theory and controlled experimentation (Musson and Robinson, 1969, pp. 338–351).

Another well studied area is the interplay between astronomy and navigation. Throughout classical and medieval Western history, astronomical, and astrological studies of the heaven used to be separate from knowledge on navigation that were built on practical observations, trial, and error. First systematic codifications of navigational knowledge in the form of maritime charts appeared with the beginning of the Renaissance. However, it were the Portuguese discoveries in the fifteenth century that were to connect the disciplines of astronomy and navigation. Before, navigation in the Mediterranean had primarily produced solutions for finding basic directions and dead-reckoning, while navigation in the Northern waters had relied on the combination of basic directions and soundings. Finally, it was the Portuguese expansion of trade around Africa that made it necessary for sailors to find their latitude (Taylor, 1957, pp. 151–171). Realizing the challenges of Atlantic navigation, Prince Henry called his court astronomers to solve the navigational questions of Atlantic navigation (ibid.). They produced the first tables for finding latitude and introduced the astrolabe to navigation. Hence, the beginnings of modern astro-navigation were started by applying methods from astronomy to a technical problem at the heart of trade and proto-colonial expansion.

In England by the end of the sixteenth century, astronomers like John Dee or Leonard Digges had started contributing to navigational problems. With the break of the seventeenth century, problems of navigation had spread from professional seamen to occupy a growing number of university men tackling theoretical problems that came along with the Atlantic trade (Howse, 1986; Taylor, 1957, p. 211).[55] It was found that inadequate projections introduced

[55] See e.g. John Flamsteed writing to Samuel Pepys in 1694 that: "All our great attainments in science and in the mechanic part also of Navigation have come out of the Chambers and from the fire-sides of thinking men within doors that were schollers and mechanics, and not from Tarpawlins, tho' of never so great experience" (quoted from Lincoln, 1983, p. 83).

significant biases. Furthermore, existing methods from astronomical and astrological studies needed to be broken down to make them useful for the mathematically less skilled mariner (Howse, 1986, pp. 73 f.). We can say that propositional and prescriptive knowledge grew tighter. Contributions to the construction of practical devices were now also made by men like John Hadley, Vice-President of the Royal Society, who invented Hadley's quadrant (Howse, 1986, p. 79). Likewise, it was the production of new data and the trial of new methods that set the next questions for the mathematicians. By now, both knowledge from astronomy and from applied navigation were actively tied to each other and sending out impulses across fields. Finally, the longitude prize of 1714 created one of history's most famous incentives for the production of useful theoretical knowledge. Astronomers were incentivized to provide the necessary data and astronomical predictions for the lunar method. Likewise, it also incentivized improvements in the construction of watches led to portable watches that offered the most reliable method to finding longitude at sea (Howse, 1986, p. 79–86). Economic gains from solving challenges in navigation were significant. Recent estimates of the impact of solving the longitude question point to up to 3% gains in population size for regions that become more integrated due to falling costs of trade (Miotto and Pascali, 2022).

Altogether, there is strong evidence that theoretical knowledge, scientific practise, and technical applications growing tighter throughout the seventeenth and eighteenth century in some areas such as engineering or navigation. However, the full extent of this interaction has not yet been quantitatively investigated. Therefore, the next sections will introduce data on the universe of publications in Britain and introduce an empirical framework to estimate feedback loops between different layers of knowledge.

3.3 Data

3.3.1 Publication titles 1600–1800

To capture the content of the British stock of knowledge, the paper uses the universe of all unique 285,985 English printed titles from the English Short Title Catalogue (ESTC) between 1600 and 1800. The ESTC was kindly shared by the British Library with the author. It further adds all 10,730 titles from the *Philosophical Transactions*, the journal of the Royal Society. The Royal Society was Britain's first and, up to the second half the eighteenth century, only academic society. The *Philosophical Transactions* were published continuously since 1665. Individual paper titles within the *Philosophical Transaction* were chapters within each volume of the journal., Hence, these are not listed in the English Short Title Catalogue, and therefore had to be added separately. Combining the ESTC and *Philosophical Transaction* offers a comprehensive overview of all relevant publications in British intellectual life, especially with regard to science and technical publications.

The paper uses subject-field classification for the ESTC from the first paper of this thesis. The classification method of the first paper is based on using using 75,856 titles that were assigned subject classes by the British Library to train a BERT model. The trained model is then used to predict the other 210,129 titles from the ESTC. In order to make the output meaningful, the first paper aggregates the ca. $\sim$ 50,000 fine-grained subject classes from the British Library to 47 higher-order classes that are listed in appendix table 35. For this paper, the most relevant classes are the scientific disciplines of *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine* that capture a subset of propositional knowledge and the technical fields of *techniques in trades, techniques in agriculture, and navigational techniques* that capture a subset of prescriptive knowledge. Additionally, this paper uses the pre-trained BERT model to predict subject classes for all titles from the *Philosophical Transactions.* Given that the BERT model was trained for the same time period and on a large sample of scientific publications, the model is well suited to classify titles from the *Philosophical Transactions.*

Additionally, this paper highlights the challenges in coming up with a classification system for titles that include prescriptive knowledge. This challenge has not been discussed in paper 1, but underlies the underlying classification system for the higher-order classes of *techniques in trades, techniques in agriculture, and navigational techniques.*

3.3.2 Propositional and prescriptive knowledge

This subsection describes the definition of fields of propositional and prescriptive knowledge. Defining fields of purely propositional knowledge is relatively straightforward, these are mainly scientific fields such as *mathematics, applied physics, astronomy, chemistry, or biology.* The titles in these fields are generally concerned with describing and classifying phenomena as well as finding general laws of nature. However, assigning titles to prescriptive fields requires more assumptions.

First, we would assume that most practical techniques consist of a combination of propositional and prescriptive knowledge. Thus, a title would often describe the *how* of how to implement a method, but also refer to the *why* behind the method. One example is this collection of methods for carpentry:

> The new carpenters' guide, being a complete book of lines for carpentry, &c. on methods entirely new; founded on geometrical principles, ... By P. Nicholson. (Peter Nicholson, 1792)

The main part of the title refers to the *how*, the prescriptive set of methods for carpentry, while the end of the title refers to the *why*, the methods being *"founded on geometrical principles"*. Thus, finding fields with titles of pure prescriptive knowledge will practically be infeasible. Instead, the paper introduces the higher-order subject fields for techniques in trades, techniques in agriculture, and techniques in navigation that are part of the $\sim 50,000$ British Library classes. These will usually be combinations of prescriptive and propositional concepts. However, the aim of titles within these fields are required to be prescriptive, thus they primarily give technical instructions to the reader.

Having these combinations of prescriptive knowledge together with some references to their epistemic base is actually the source of information that makes this analysis possible. With this we can test how the propositional base collected in scientific fields changed both the topic of prescriptive techniques as well as its epistemic base. In the current version of this paper, the estimation framework is agnostic to whether scientific fields changed the epistemic base of new techniques or influenced the techniques directly (e.g. the discovery of a new metal could directly lead to it being extracted with a new plain method). In the empirical frameowork, the paper will define indices of title influence based on distances between full titles within the set of scientific fields and the set of technical fields.[56]

3.3.3 Patent data

To capture a title's closeness to contemporary inventions, the paper further uses patent descriptions. To quantify a patent's content, the paper draws on two measures, first a patents subject matter taken from the *Reference Index of Patents of Invention, 1617-1852* (Woodcroft, 1855) as collected by Nuvolari and Tartari (2011). Second, it draws on the original short title descriptions as registered by the patentee taken from the *Chronological Index of Patents Applied for and Patents Granted* (Woodcroft, 1854*a*). The paper then calculates sentence transformer based distances between ESTC titles within the field of technical instructions and all patents for both subject headings and short descriptions. One way to check the consistency of both measures is to plot ESTC title distances to both of the patent measures. Figure 19 shows the result. There is a high correlation (p=0.87) between both measures. This is evidence that both measures are consistent with each other, and might disperse worries about idiosyncrasies in the short patent descriptions.

[56] Being agnostic towards the distinction between propositional and prescriptive knowledge in technical titles also has the advantage that the distinction can often be highly complex in practise. For example, sometimes references to the *why* are also hidden in the description of the *how*:

> The principles of pump-work illustrated, and applied in the construction of a new pump without friction, or loss of time, or water, in working; Humbly proposed for the service of the British Marine, with the privilege of His Majesty's Royal letters patent. By Benj. Martin. (Benjamin Martin, 1766)

Here, one might split the text into a propositional part, *principles of pump work* and a prescriptive part, *applied in the construction of a new pump....* Yet, the description of the construction of a new pump makes reference to propositional concepts such as *friction* or *loss of time* or *loss of water*. But also sometimes propositional and prescriptive knowledge are integrated in each other within the same description:

> A treatise founded upon philosophical and rational principles, towards establishing fixed rules, for the best form and Proportional Dimensions in Length, Breadth and Depth of merchant's ships in General and also the management of them to the greatest advantage, by practical seamanship; with Important Hints and Remarks Relating Thereto; from Long Approved Experience. By William Hutchinson, Mariner, And Dock Master at Liverpool (William Hutchinson, 1791)

Here, the propositional knowledge about *"fixed rules, for the best form and Proportional Dimensions in Length, Breadth and Depth"* is also a technique of how to build a ship (e.g. *start with the length of X and width of X*).

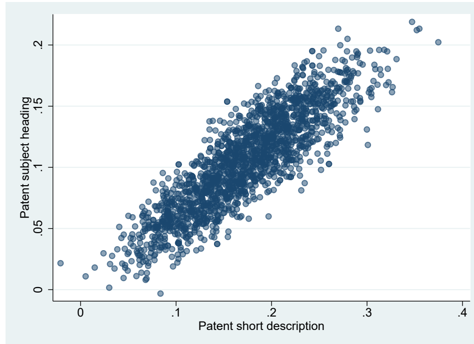


FIGURE 19: Correlation between distance to patent subject headings and distance to patent short descriptions for ESTC titles within the field of technical instructions

3.3.4 Text similarity

The key-input for the spillover-measures introduced in this paper in section 3.4 are similarities between titles. For these, the paper uses a sentence transformer model (Reimers and Gurevych, 2019) that represents each title in a 512×768 dimensional embedding matrix.[57] Similarities between title τ_i and τ_j are calculated as the cosine similarity of the two corresponding embeddings A and B.:

$$d(A, B) = \frac{A \cdot B}{\|A\| \|B\|} = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i^2} \sqrt{\sum_{i=1}^{n} B_i^2}} \tag{8}$$

To the best of the author's knowledge, this paper is the first one to use transformer model derived word embeddings for calculating similarities as inputs to innovation and spillover measures in a Kelly et al. (2021) type of index. This transformer based approach has the advantage over bag-of-word approaches as in Kelly et al. (2021) that it can capture context-sensitive meanings of words. This is an important condition for calculating sentence similarities for corpora of texts without a fixed and precise technical vocabulary. In contrast to the very technical vocabulary in patent texts used by Kelly et al. (2021), early scientific texts from the seventeenth century did not share a fixed technological vocabulary. Instead, the same phenomenon or method is often described using different words. Often the technical vocabulary of the age is also used in different contexts with a different meaning (thinking e.g. about the *reflection* of

[57]Specifically, the paper uses the ll-MiniLM-L6-v2 model from HuggingFace that was pre-trained on over 1 billion sentence pairs and optimzed as as a sentence and short paragraph encoder.

light and a *reflection* on the possibility of salvation). Such ambiguities in meaning cannot be captured by bag-of-word methods (nor simple word2vec word embedding models). However, transformer models allow for the derivation of context-sensitive title embeddings.[58] Appendix section B.1.2 illustrates this argument by comparing the performance of different language models for an exemplary set of seventeenth century scientific titles.

Lastly, a possible concern about calculating similarity measures based on the ESTC titles is that changing title length over time might bias the average of the indices over the time. While the cosine similarity between sentence embeddings is not mechanically sensitive to title length, bias might still arise from a greater suppression of information in shorter title conventions. Hence, appendix figure 31 shows time trends in average title lengths over time for different fields. For the fields of interest of this study, there are no discernible trends in title length. This is reassuring. Apparently, conventions in title length did not change. We can assume that the hard limit always remained the space of a book's title page. We should still note, that looking at the average of all titles, there is a marked spike in average title length following the English Civil War and interregnum. However, this seems to be mainly driven py political and religious pamphleteering and did not affect the fields investigated in this study.

3.4 Empirical model

3.4.1 Spillover measures and regression model

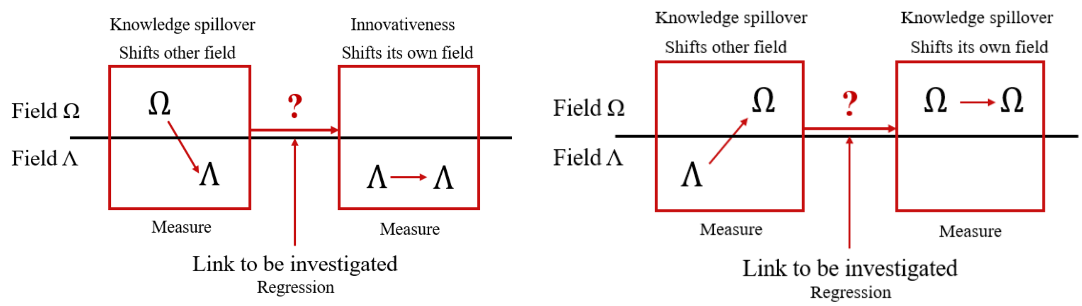
This section derives measures of knowledge spillovers for individual titles based on sentence similarities and introduces an empirical regression model to estimate the strength of indirect and direct feedback loops, β_{indirect} and β_{direct}.

First, it is important to distinguish between indirect and direct feedback loops. Indirect feedback loops are composed of a set of random spillovers between fields. Direct feedback loops are composed of a set of two connected spillovers where one title is first shifted by another

[58] Within the context of the ESTC, we should note that BERT has the additional advantage that it uses word piece tokenization that breaks individual words into multiple tokens. This has the advantage that unknown words are broken down into pieces. For most unknown words a representation exists at least for some of its sub-parts reconstructing its original as close as possible. This feature is especially valuable for dealing with different spellings in the seventeenth century.

field and then causes a spillover back to that very field. The distinction between these two processes is formally modelled in section B.3.

This empirical framework is applicable to the general case of a feedback loop between propositional and prescriptive knowledge, Ω and Λ, independent of how they are measured. This section uses titles in scientific fields, Ω_{science}, as a subset of propositional knowledge, Ω. It further uses titles in technical fields, $\Lambda_{\text{tech}} \in (\Lambda \wedge \Omega_{\text{tech}})$, as a combination of prescriptive and propositional knowledge used for the construction of a given technique.



(a) Spillover from Ω to Λ (b) Spillover from Λ to Ω

Figure 20: Illustration of the estimation framework of an indirect feedback loop

This section starts by outlining the empirical framework for estimating an indirect and direct feedback loop. First, figure 20 illustrates the framework of estimating an indirect feedback loop. Each round of spillovers, e.g. from Ω_{science} to Λ_{tech} and from Λ_{tech} to Ω_{science} is estimated separately. Spillovers are estimated for each individual title. Each round of spillovers is composed of three separate logical steps:

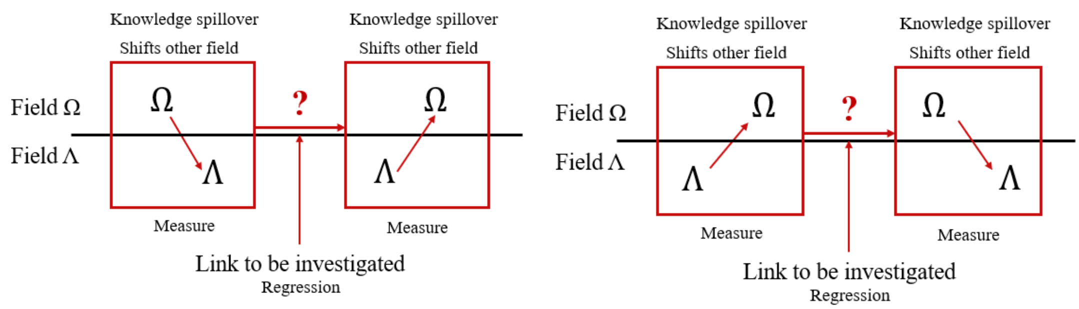
1. Measuring how much a title was shifted by a spillover from another field (illustrated as the left-hand box of 20a and 20b)

2. Measuring how much a title shifts its own field (illustrated as the right-hand box of 20a and 20b)

3. Estimating the link between a title being shifted by another field and it shifting its own field

The final step (3) estimates if titles that were affected by knowledge spillovers from outside their own field were more likely to shift their own field, β_{indirect}. As shown in section B.3,

$\beta_{\text{indirect}} > 1$ can lead to a significant levelling-up of the steady-state of knowledge production. However, within the setting of this paper, indirect feedback loops are unlikely to create self-sustained growth, because within a random spillover, not all ideas that were improved create spillovers back. Hence, the self-reinforcing process fades out over time.



(a) Feedback from Ω to Λ (b) Feedback from Λ to Ω

FIGURE 21: Illustration of the estimation framework of a direct feedback loop

Next, we consider a direct feedback loop. Figure 21 illustrates the basic intuition. In contrast, to the indirect feedback loop, each round of spillovers necessarily includes a spillover back to the original idea. It is composed of three separate logical steps, similarly to the framework of an indirect feedback loop:

1. Measuring how much a title was shifted by a spillover from another field (illustrated as the left-hand box of 20a and 20b)

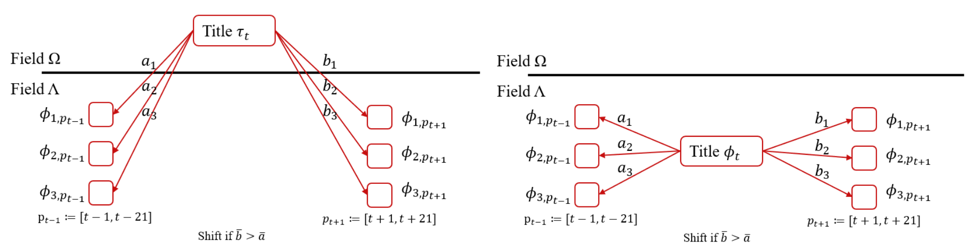
2. Measuring how much a title shifts the other field (illustrated as the right-hand box of 20a and 20b)

3. Estimating the link between a title being shifted by another field and it shifting its own field

In contrast to the framework of an indirect feedback loop, step (2) is a measure of how much title τ_t shifts the very field that had shifted it in (1). Thus, it captures the intuition described before that the continuos improvement of a single concept through several stages of theory and practical experimentation can lead to a process of self-sustained improvements. Thus, step 3) estimates β_{direct}. As shown in appendix section B.3, a $\beta_{\text{direct}} > 1$ can lead to self-sustained growth.

The rest of this section will first introduce the measure for step 2), how much a title shifts another field and then introduce the measure for step 1), how much a title was shifted by another field. At the end, it will will set out the estimation framework for 3).

First to measure how much a title $\tau_t \in \omega$ shifts field λ ($\omega \in \Omega$, $\lambda \in \Lambda$), this paper applies the logic of the Kelly et al. (2021) innovation index to multiple fields. The Kelly et al. (2021) index is based on the intuition that if a title is more similar to titles in its own field in the future than to titles in its own field in the past, it is likely to have shifted its field. This paper argues that if a title from e.g. ω is more similar to titles in a different field λ in the future than to titles in field λ in the past, then it is likely to have shifted field λ. For this, the paper defines title τ_t's backward similarity to field λ (BS), title τ_t's forward similarity to field λ (FS) and the field shifting index (*Shift*):



(a) Spillover: Shifts between two field (b) Innovation: Shifts within one field

FIGURE 22: Illustration of the logic behind field-shifter equation 11

$$BS_{\tau_t}(\tau_t \rightarrow \lambda_{p_{t-1}}) = \frac{1}{N} \sum_{\phi_j \in \lambda_{p-1}}^{N} d(\tau_t, \phi_{j,p-1}) \tag{9}$$

$$FS_{\tau_t}(\tau_t \rightarrow \lambda_{p_{t+1}}) = \frac{1}{N} \sum_{\phi_j \in \lambda_{p-1}}^{N} d(\tau_t, \phi_{j,p+1}) \tag{10}$$

$$Shift_{\tau_t}(\tau_t \rightarrow \lambda_{p_{t-1},p_{t+1}}) = \frac{FS_{\tau_t}(\tau_t \rightarrow \lambda_{p_{t+1}})}{BS_{\tau_t}(\tau_t \rightarrow \lambda_{p_{t-1}})} \tag{11}$$

with $\tau \in \omega$, $\phi \in \lambda$, and p denoting the forward and backward time period of comparison. In the following the paper will use 20 year forward and backward periods. Equation 11 creates an index that measures how much a title in ω shifted λ and how much a title in λ shifted ω. The logic is illustrated in figure 22a. Analogously by subsetting ϕ_t for τ_t, the same formula can be applied to estimate how much a title shifted its own field. Following Kelly et al. (2021), we can interpret this as a title's innovativeness. The logic is illustrated in figure 22b.

Thus, equation 11 yields a measure for a title's spillover effect (measure 2 for the direct feedback loop) and measure for a title's innovativeness (measure 2 for the indirect feedback loop).

However, to calculate step 1) (identical for both the indirect and direct feedback loop), we need a measure how much an individual title ϕ_t in field λ was shifted by title τ_t in field ω (2). This is a more challenging task, because the previous measure only compared a title's relation to past and future fields. Identifying which titles were shifted needs the counter-factual of a non-shifted title. This paper approximates the counterfactual by identifying the titles that were most similar to ϕ_{p_t} in the past. It is assumed that the most similar titles in Δ_{p-1} are a good predictor for ϕ_{p_t} had not a shift from field ω occurred. Figure 23 illustrates the logic. Equation 12–14 formally set out the calculation of how much title ϕ_{p_t} was shifted by ω_{p-1}.

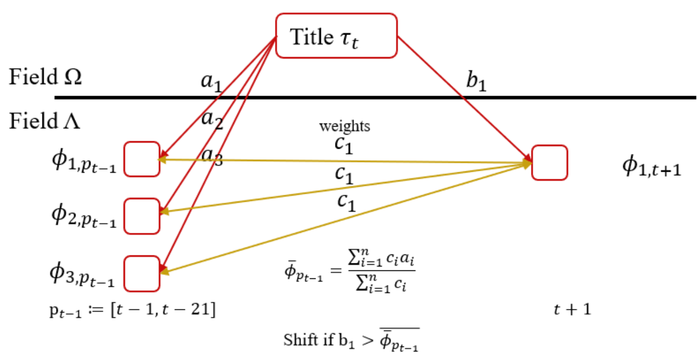


Figure 23: Illustration of the logic behind identifying shifted titles

$$BS_{\phi_t}(\lambda_{p-1} \rightarrow \phi_t) = \frac{1}{N} \sum_{\tau_j \in \omega p-1}^{N} \frac{1}{N} \sum_{\phi_k \in \lambda_{p-1}}^{N} \frac{\sum_{i=1}^{n} d(\phi_t, \phi_{k,p-1}) d(\phi_{k,p-1}, \tau_{j,p-1})}{\sum_{i=1}^{n} d(\phi_t, \phi_{k,p-1})} \tag{12}$$

$$BS_{\phi_t}(\omega_{p-1} \rightarrow \phi_t) = \frac{1}{N} \sum_{\tau_j \in \omega p_{t-1}}^{N} d(\phi_t, \tau_{j,p-1}) \tag{13}$$

$$\mathit{Shifted}_{\phi_t}((\omega_{p-1}|\lambda_{p-1} \rightarrow \phi_t) \rightarrow \phi_t) = \frac{BS_{\phi_t}(\omega_{p-1} \rightarrow \phi_t)}{BS_{\phi_t}(\lambda_{p-1} \rightarrow \phi_t)} \tag{14}$$

To calculate how how much title ϕ_t was shifted by ω_{p-1}, equation 13 calculates the similarity between $\phi_t \in \lambda_t$ and ω_{p-1}. Equation 12 calculates the counterfactual of how title ϕ_t would have looked like in the absence of a shift from ω. The paper assumes that the best counterfactual are the most similar titles to ϕ_t in the past. Thus, equation 12 calculates the average distance of all $\phi_{p-1} \in \lambda_{p-1}$ to $\tau_{p-1} \in \omega_{p-1}$ weighted by the distance of each ϕ_{p-1} to ϕ_t. Finally equation 14 calculates how much title ϕ_t was shifted by calculating the fraction of ϕ_t's similarity to ω_{p-1} over the counterfactual of λ_{p-1}'s similarity to ω_{p-1} weighted by λ_{p-1}'s distance to ϕ_t.

Finally, this allows us to bring together measures (1)-(3) needed to calculate the spillover effects for the indirect feedback loop. We now have both, a measure of how much title ϕ_t was shifted and a measure of how much title ϕ_t shifted its own field (hence how innovative title ϕ_t was). In a next step, the paper estimates whether these two mechanism, a spillover from field ω to field λ, and title ϕ_t's innovativeness, shifting its own field, are related. It does so by regressing the innovation index for ϕ_t in λ on our measure of how much ϕ_t was shifted by ω:

$$\mathit{Innov}(\lambda \rightarrow \lambda)_{it} = \sum_{p=1600-1619}^{1760-1789} (\beta_p \cdot \mathit{Shifted}(\omega \rightarrow \lambda)_{it} \times \eta_p) + \boldsymbol{X'_{it}}\zeta + \eta_t + \varepsilon_{it} \tag{15}$$

Here, the dependent variable $\mathit{Innov}(\lambda \rightarrow \lambda)_{it}$ is a measure of title i's innovativeness at its publication year t within field λ. Innovativeness is measured by equation 11 that captures how much a title shifted its field. The main explanatory variable, $\mathit{Shifted}(\omega \rightarrow \lambda)_{it}$, is measured by equation 14 that captures how much a title in field λ was shifted by titles in ω in p_{t-1}. It is time interacted by 20 year periods. Using this time interaction allows for flexibly estimating the changing strength of the spillover throughout the seventeenth and eighteenth century. $\boldsymbol{X'_{ict}}$ is a set of additional control variables, including title length, language, a dummy on whether a title was from the *ESTC* or *Philosphical Transactions*, and a dummy of whether a title's field was predicted using machine learning. Finally, η_t captures publication year fixed effects. Thus, the model compares titles that were shifted by field ω with other titles that were not shifted within a given publication year, thereby accounting for time dependent trends in innovativeness.

Using publication year fixed effects also eliminates spurious effects from compositional changes in language over time. Because the estimated model only compares titles in the same year with indices constructed by using the same backward and forward similarities, all compositional changes in language should be absorbed by the publication year fixed effects.

Next, we estimate β_{direct} from the direct feedback loop mechanism. Instead of using a measure how much a title shifted its own field as in equation 15, this setup estimates how much a title shifted the very field it was shifted from before (see figure 21).

$$\mathit{Shift}(\lambda \to \omega)_{it} = \sum_{p=1600-1619}^{1760-1789} (\beta_p \cdot \mathit{Shifted}(\omega \to \lambda)_{itp} \times \eta_p) + \boldsymbol{X'_{it}}\zeta + \eta_t + \varepsilon_{it} \tag{16}$$

This model estimates β_{direct} that captures whether a title in λ was more likely to shift field ω if it was shifted by field ω before (or vice versa with λ). If this is the case, then creating a technique in λ produced additional knowledge that in turn was then used in ω. As shown in section B.3, $\beta_{\text{direct}} > 1$ can create self-sustained growth in knowledge.

It should be stressed that this empirical framework is only able to produce associational evidence of the relationship between knowledge spillovers (conditional on a set of control and year fixed effects). Hence, feedback loop coefficients should not be interpreted causally, i.e. title i being shifted by a specific field *automatically causing* future knowledge spillovers. We would always expect future knowledge spillovers originating from each title to depend on other contingent factors, e.g. how many people could access the title, how easy it was for other people to understand the concepts used in the title, etc. Indeed, this paper does not want to abstract away from these factors — instead, it explicitly estimates how the strength of feedback loop processes, influenced by a large bundle of factors as described in e.g. Mokyr (2002), changed over time.

3.4.2 Examples

It is useful to illustrate the mechanics of the shifting fields and shifted titles measures with two examples. First, for calculating how a title shifts its own field, we can look at the title *The description and uses of a new and correct sea-chart of the whole world, shewing the variations of the compass* from Edmond Halley, Astronomer Royal. This was the product from Edmond Halley's oceanic voyage studying the magnetic variation of the world. The map shows the magnetic variation of the world drawn as isometric lines of equal variation (Taylor, 1957, p. 240). Since the magnetic variation of the compass was well known, but its origin and patterns were poorly understood, Halley's publication stands out in the field of navigation. Taylor concludes that: "This was the first isometric map (...) to come into general use, and its appearance was therefore a signal cartographic event quite apart from its intrinsic value to sailors" (Taylor, 1957, p. 240). Meadows (2005) further adds that "From then on [after Halley's publication], observations of the global magnetic field were of concern to both mariners and scientists".

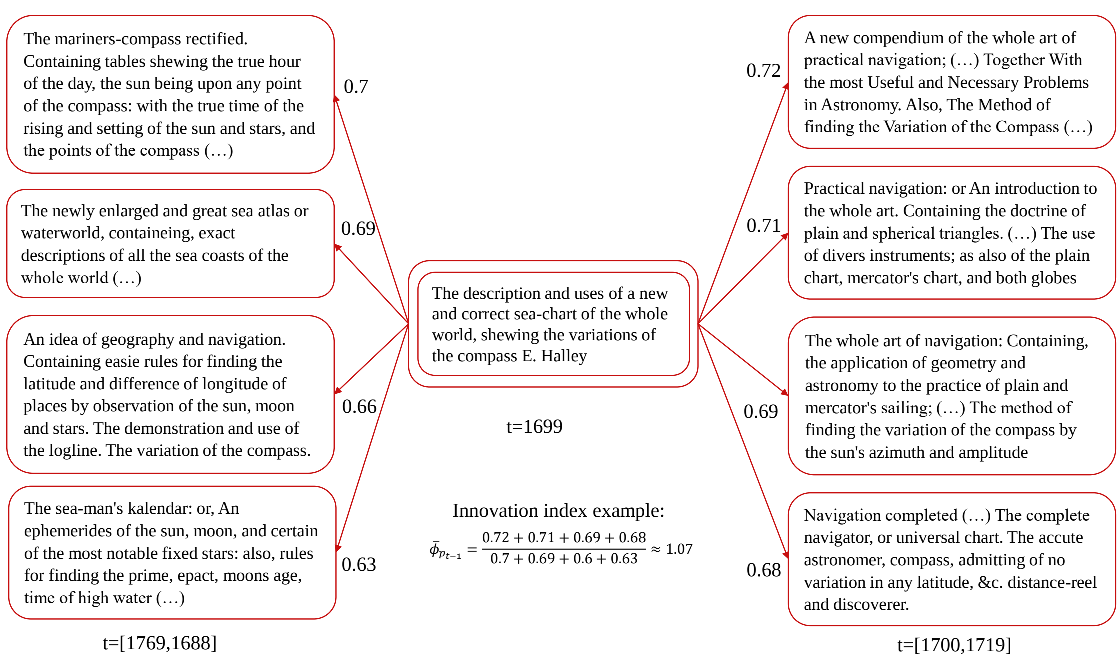


FIGURE 24: Example to illustrate the logic behind the innovation index

The title is interesting from the point of its historical relevance, but also interesting given that it is produced through the practical hands-on-experience from one of the most renowned astronomers. For this example, we will test whether the innovation index from equation 11 reflects the historical opinion that Halley's map significantly increased the interest in the study of magnetic variation. Figure 24 illustrates the basic mechanics of the innovation or field-shifting index from equation 11. The index captures the basic Kelly et al. (2021) style intuition that a title is more innovative or field-shifting if it is closer to the future than to the past of its own field. The right hand side of figure 24 shows the 4 titles in the future of the field of navigation that are closest to Halley's publication. The left hand side of figure 24 shows abbreviations of the 4 titles in the past of the field of navigation that are closest to Halley's publication. It further shows the similarities to all of the top 4 titles. A list of the full text of the 10 most similar titles in the past and future of navigation are shown in appendix table B.2.4 and B.2.3. We see that the simalities to the future are consistently larger than the similarities to the past. Applying equation 11 to this illustrative example and dividing the similarities of future titles by similarities of past titles (thereby ignoring the rest of the field), we get an innovation index of 1.07. This is already relatively close to the value of 1.11 calculated across all titles in the field of navigation in a $+/-$ 20 year period. This value is within the upper percentile of the innovation index for navigation. It shows that Halley's publication significantly shifted its own field, just as we had expected given the historical context.

We can further see that the calculation of the index also opens up itself to a narrative interpretation. Looking at the 4 titles from the past in figure 24 we see that while three publications deal with the handling of the compass, only one mentions the variation of the compass ("An idea of geography and navigation. (...) The variation of the compass"). In contrast, three of the four titles listed in the future of the field mention the variation of the compass explicitly. Also in contrast, to the title in the past who mentions the variation of the compass simply as a phenomenon, two titles in the future explicitly mention "a method to find the variation of the compass". Looking within the most similar title, *"A new compendium of the whole art of practical navigation; (...) Together With the most Useful and Necessary Problems in Astronomy. Also, The Method of finding the Variation of the Compass (...)"* by

William Jones (1675-1749), we find an arithmetic rule of thumb for finding the variation of the compass based on amplitude or azimuth (Jones, 1702, pp. 89–93). While we do not know the exact origin of this rule of thumb method, we find a reference to Halley's map printed earlier in the text (shown in appendix figure 36). It thus appears very likely that the chapter on the variation of the compass was written with the patterns found in Halley's map back in mind. Hence, we see that title similarities seem to correspond well with the actual influence of Halley's work. This exercise is both interesting as a narrative account, but also a useful confirmation that the title similarities calculated with the methods proposed in this paper capture our own intuition about title similarities when studying individual examples in more detail.

Next, for calculating how much a title was shifted by another field, we can look at the title *An experimental enquiry concerning the natural powers of water and wind to turn mils, and other machines, depending on a circular motion* written by civil engineer John Smeaton and published in the *Philosophical Transaction* in 1759. The article sums up Smeaton's results from systematic experimentation with water wheels and showed the superiority of the overshot and breastshot wheel over the undershot wheel (Musson and Robinson, 1969; Reynolds, 1983). The subsequent adoption of the overshot and breastshot wheel is widely credited with significant improvements in the efficiency of water power during the early Industrial Revolution (Musson and Robinson, 1969; Mokyr, 1992; Smil, 2018). The following example, illustrated in figure 25, looks at how much this title, τ_t, from Λ was shifted by applied physics from Ω:

The *shifted index* from equation 14 is calculated by first finding the most similar titles in applied physics and the most similar titles in its own field, technical instructions, in the past. Then, we calculate how much closer Smeaton's publication τ_t is to applied physics than to the most similar publication in technical instructions. Figure 25 illustrates this process. First, we see the high similarity to works from applied physics that describe various theories of hydrodynamics. Yet, to measure whether Smeaton's work was really shifted by these works from applied physics, we first need to evaluate whether other works from the same field of techniques in trades were already using similar concepts. We can see that the closest title in technical instructions in the past was *The experiment was lately made of the force of fire*

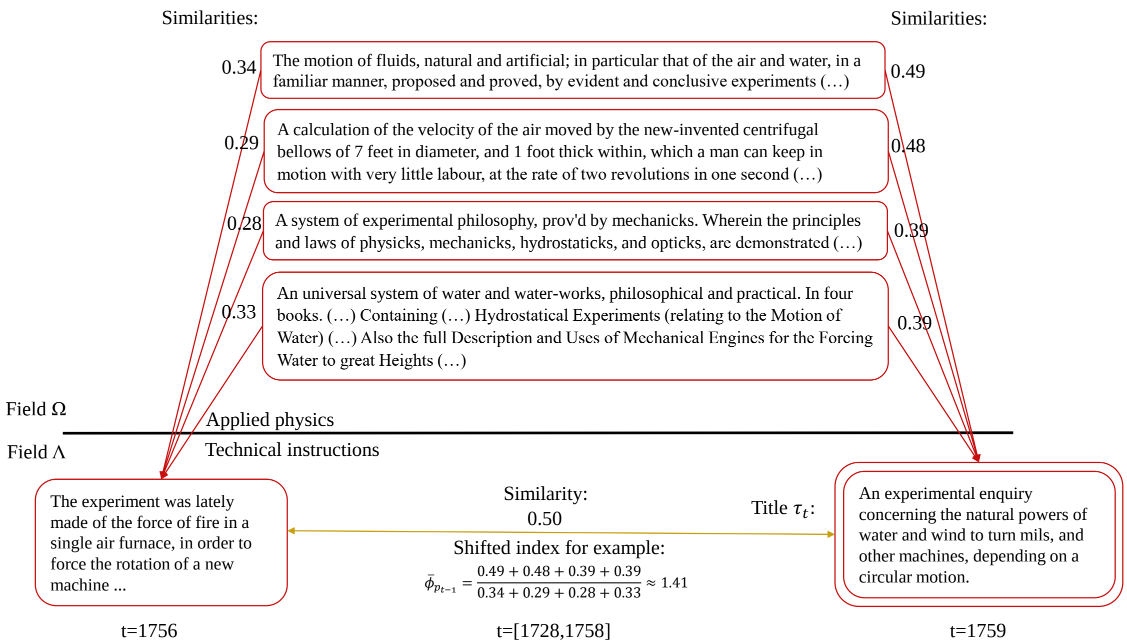


FIGURE 25: Example to illustrate the logic behind the shifted titles index

in a single air furnace, in order to force the rotation of a new machine published by John Duncan in 1756. Intuitively, we can already see that this was a work on aerodynamics rather than hydrodynamics. Looking at a list of the 10 most similar titles in the past, we only find two other titles that are directly related to the study of water wheels, *An imitation of a model for water-works, contrived after the nearest manner to save friction* by Hugh Roberts in 1742 and *Part of a letter from Mr. Wm. Arderon, F. R. S. to Mr. Baker, F. R. S. containing a description of a water-wheel for mills invented by by Mr. Philip Williams. With an Extract of a Letter from the Rev. Dr. Samuel Salter to Mr. Arderon, concerning the Bark Preventing Catching Cold* by William Arderon and Samuel Salter in the *Philosophical Transactions* in 1746. However, these appear purely descriptive without reference to forces of physics or principles of hydrodynamics. Yet, the plain titles might be deceiving. To test the external validity of the text similarities, we can adopt a narrative approach and study the actual content of the two works:

Arderon and Salter (1746)'s article in the Philosophical Transaction only covers four pages and is a technical description of a technical drawing of a newly invented water wheel for slow currents (the technical drawing is reproduced in appendix figure 34 and 35. The described water wheel consists of a hexagonal body with several holes into which sails made out of iron plates are inserted. The hexagonal body is then supposed to be placed vertically to the flow of the river. However, the article restricts itself to describing the design of the water wheel as well as giving some observations on its performance in a "local river". Its only theoretical statement seems sufficiently vague "And as the *Momentum* (sic) will be in proportion to the Number of the sets of Sails that are employed, its Force is capable of being greatly augmented with the same Quantity of Water: A Thing not to be admitted without sufficient Experiment, but what seems extremely plain in Theory, and whatt I am apt to think will answer when brought to Practise." (Arderon and Salter, 1746, p. 3) Hence, the information taken from the the title seems to correspond well to the actual content of the the publication. It conveys a technical description of a newly invented water wheel as observed by the author but verges little into the realm of theory or practical experimentation.[59]

This discussion of the most similar titles in the past seems to sufficiently show that Smeaton's work combining hydrodynamic theory with experiments on water wheels was novel in its own field. Next, we test whether this novelty was caused by a spillover from applied physics. For this, figure 25 shows short abbreviations of the 5 most similar titles to τ_t in applied physics. A list of the full text of the 10 most similar titles in applied physics is shown in appendix table B.2.1. Figure 25 then shows how similar these titles from applied physics are to τ_t and the most similar titles to τ_t in the past. It can be seen that the similarties of the titles in applied physics are consistently greater for τ_t than the most similar titles in the past. If the full catalogue only consisted of the depicted titles, we could calculate the shifted index as the similarities to τ_t divided by the the most similar titles in the past, $\Phi_{t-1} = \frac{0.49+0.48+0.39+0.39}{0.34+0.29+0.28+0.33} \approx 1.41$. This is already close to the actual shifted index of τ_t calculated over all titles in applied physics and technical instructions of 1.65.

Thus, through inspecting the titles and content of the individual influence pairs, the approach is also open to a narrative interpretation of knowledge spillovers between fields.

[59]The text from Hugh Roberts is only accessible as a manuscript in the British Library. Accessing it was not possible due to the persistent failure of the British Library's digital catalogue after being hacked.

3.4.3 Discussion

This section will discuss various sources of bias in the estimation framework owing to the definition of the *shifting* and *shifted measures*.

First, misclassifications of titles could lead to significant bias. In the case of random spillovers, misclassifications would simply create noise in the dependent and independent variable. Hence, they would lead both to a loss of efficiency and a downward bias for the estimated feedback loop coefficients. However, under the presence of moderate downward bias, we could still interpret the results as conservative estimates of the true feedback loop. Yet, systematic misclassifications could also create upward bias. Systematic misclassifications would e.g. entail classifying works of applied physics as technical instructions and vice versa. A title that belongs to the field of physics would be automatically more similar to the field of physics than technical instructions. Yet, only if misclassified titles were also more likely to shift the field of physics would these misclassifications also create upward bias.

Ex-ante, it is not clear why misspecified titles should have a higher likelihood of shifting their true field. We can also empirically judge the extent of misclassifications between related fields by studying the spillover matrix in appendix figure 30. Here, we see that most misclassifications appear between similar fields, e.g. *religious* and *religious sermons*. Yet, we see little evidence of misclassifications between fields of propositional knowledge (e.g. *applied physics, astronomy, mathematics, or chemistry*) an fields of prescriptive knowledge (*instructions in trades, agriculture, or navigation*). However, the spillover matrix only addresses misclassifications from using machine learning. Misclassifications might also arise from the underlying subject classes from the ESTC. In this context, the line of distinction might be blurry for some titles. A way to address these concerns would be to manually check the final assignments for subject fields of interest and to use the corrected version for a robustness test. Yet, it remains unclear what should count as the gold standard in terms of classifications.

Relatedly, the current approach only classifies titles to a single field. In some cases, titles might cover multiple fields. This is especially true for works summarizing the state of knowledge within different fields, e.g.

> *The path-way to knowledge, according to those undeniable grounds and axiomes delivered by the ancient philosophers and astronomers, Pythagoras, Aristotle, Haly, Albert, Philo Judæus, and Ptolomey. Shewing the effects of the planets, and other astronomical constellations, with several other weighty matters concerning husbandry, medicines for cattle, and other excellent rarities, both pleasant and profitable. Experienced by the 21. years study and practice of Poor Robin a well willer to the mathematicks. Licenced and entered according to order.* (William Winstanley, 1663)

The paper adopts the strategy of classifying these works within the additional subject field of *Encyclopedias and dictionaries.* This takes account of titles explicitly dealing with different fields. For other titles, the paper prioritizes a title's main contribution as revealed through the use of sentence similarity. A potential danger with this approach that a title from physics that draws on multiple fields, e.g. technology in trades, navigation, and mathematics might be less similar to each of these fields than a title only drawing on one field alone, because the similarities are dissoluted by the extra information. However, experimentation with the sentence transformer model (Reimers and Gurevych, 2019) has shown that the model is robust to adding unnecessary information.

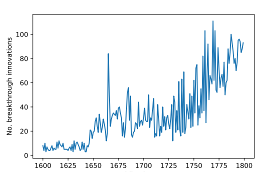
Furthermore, the British system of knowledge creation was not a closed-system, but additionally drew on new knowledge produced on the continent. As far as we miss these inputs from foreign knowledge and foreign technologies, we might wrongly classify publications as not being influenced by a given field, because the actual title of influence came from abroad and was not part of the ESTC. This case would create noise in both the independent and dependent variable and thus lead to both, a loss of efficiency and a downward bias for the estimated feedback loop coefficients. However, we can note that many important foreign works were published in England as well and even often translated into English. Appendix figure 33 shows the number of titles published in a foreign languages. We see that Latin as the lingua franca dominated, but we also see the circulation of titles in other European languages. After 1760, French started to become the most important non-English language in the ESTC. While this alleviates some of the previously discussed bias, we might still worry that only breakthrough innovations from the continent would be adopted in England, without republishing their continental inputs from other fields. Thus, it is likely that limiting the analysis of the ESTC, creates some downwards bias by excluding the full image of knowledge creation on the continent.

Overall, the estimated coefficients from the suggested estimation framework should be interpreted as conservative estimates due to the likely presence of noise in the dependent variable, because of a) miss-classifications and b) omitted works from knowledge production on the continent.

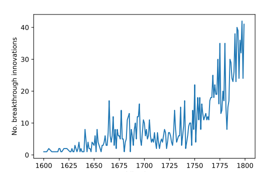
3.5 Results

3.5.1 Development of scientific and technical fields

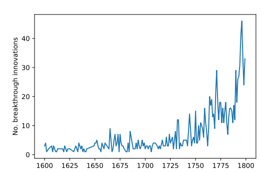
Figure 26 plots the development of the total number publications for all scientific publications, publications in technical instructions in trades, technical instructions in agriculture, and publications on maritime navigation. It further plots the number of upper quartile publications of the measure of publications shifting their own field from equation 11. In the spirit of Kelly et al. (2021), we can interpret them as breakthrough publications or highly innovative publications.



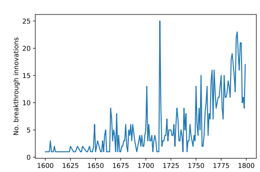
(a) All publications: All scientific fields



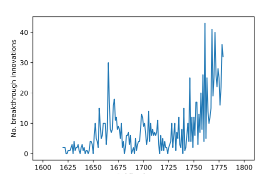
(c) All publications: Instructions in trade



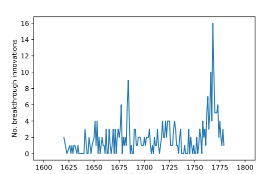
(e) All publications: Instructions in agriculture



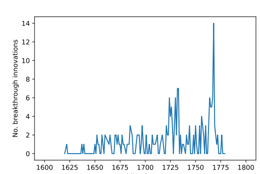
(g) All publications: Maritime navigation



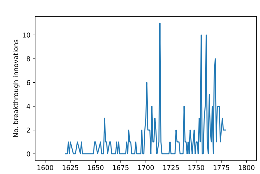
(b) Upper quartile of innovation index: All scientific fields



(d) Upper quartile of innovation index: Instructions in trade



(f) Upper quartile of innovation index: Instructions in agriculture



(h) Upper quartile of innovation index: Maritime navigation

FIGURE 26: Total number of publications and breakthrough publications by field

We can derive a few stylistic facts from the plots: The number of scientific publications increased significantly after 1650.[60] They then remained at this new high level until a structural break occurred around 1750 when the number of scientific publications started to rise continuously. The number of upper quartile publication within the innovation index shows the presence of an initial wave of breakthrough publications between 1650 and 1670. After this, there is a mini-wave of breakthrough publications between 1700 and 1720. Finally, we also witness a structural break in breakthrough publications around 1750, with a highly significant and continuos increase in breakthrough publications in the sciences.

Both technical instructions in trades and agriculture show a similar pattern. There was an initial increase in the number of publications at the middle of the seventeenth century which raised the level of technical publications for the next century. Then, there is a structural break at the middle of the eighteenth century, with an increase in the number of publications starting after 1725 and an increase in the number of breakthrough publications starting post 1750. Additionally, it is noteworthy that technical publications grew faster post 1750 than scientific publications: While the number of scientific publications roughly doubled, technical publications increased by at least four times.

Finally, publications in navigation increased more gradually than in science or technical instructions. However, there is also a structural break around 1750 leading to a continuous increase in publications. When looking at the number of breakthrough publications, we can identify two waves. First, there is a pronounced wave around 1700 to 1720, coinciding with the introduction of the longitude prize. The publication of the longitude prize in 1714 goes along with a one off spike in the number publications in navigations. Still, it is noteworthy, that the years following the decades after the publication of the longitude prize are associated with a decline in breakthrough publications. A second wave of breakthrough publications started post 1750.

[60] Indirect evidence for the Merton thesis?.

3.5.2 Results on the feedback loop process

This section presents the results for estimating $\beta_{\text{indirect}_p}$ and β_{direct_p} from equation 15 and 16. Figures 27–46 show the estimated coefficients. Feedback loop processes are estimated seperately depending on whether the origin spillover occurred in Ω_{science} or Λ_{tech}. This corresponds to β_1 and β_2 in equation 21–22 and 24-25, where β_1 captures spillovers first coming from Λ_{tech} and β_2 captures spillovers first coming Ω_{science}. For the analysis of feedback loop processes, $\beta_{\text{indirect}_p}$ and β_{direct_p} are estimated for the following pairs of fields from Ω_{science} and Λ_{tech}:

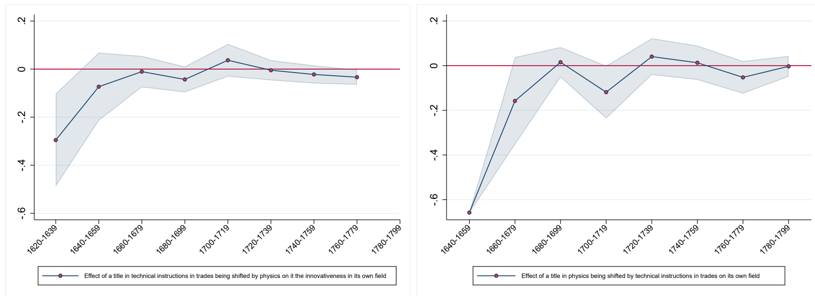
1. (Applied physics, technical instructions in trades)
2. (Applied physics, technical instructions in agriculture)
3. (Mathematics, Technical instructions in trades)
4. (Astronomy, Navigation)

This way, the paper focuses on a set of fields from Ω and Λ that lie at the core of the literature on knowledge and innovation during the Industrial Revolution (Mokyr, 1992, 2002; Jacob, 1997, 2014; Allen, 2011). Limiting the set of analysed fields also allows for the in depth discussion of single fields. Estimating the feedback loop process for further fields will be the object of future work.

In order to discuss the interpretation of the feedback loop process in more detail, the next paragraphs will focus on the interaction between applied physics and technical instructions in trades. These two fields underlie the classical narrative of knowledge spillovers between Newtonian science and applied engineering that have been argued to have been a driver of British Industrialisation (Jacob, 1997, 2014). Then, the paper will draw broader conclusions by assessing the general trends of the feedback loop processes of other fields.

3.6 The feedback loop process between applied physics and technical instructions in trades

Figure 27 a)–b) show the estimated coefficients for $\beta_{\text{indirect}_p}$ from equation 15 between technical instructions in trades and applied physics. Figure 28 a)–b) show the estimated coefficients for



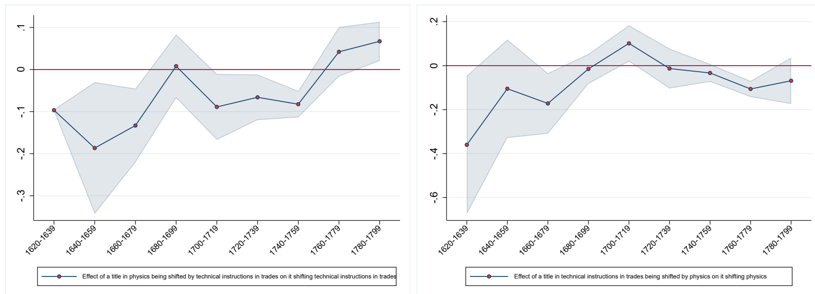
(a) Spillover: Physics → tech → tech

(b) Spillover: Tech → physics → physics

FIGURE 27: Spillover effects and feedback loop for applied physics and technical instructions in tech

Notes: The figure shows the coefficients from estimating equation 15 for the fields of applied physics and technical instructions via OLS. The unit of observation are titles at their time of publication. Figure a) shows spillover results of estimating the effect of titles in applied physics that were shifted by technical instructions on shifting the field of applied physics itself. Figure b) shows spillover results of estimating the effect of titles in technical instructions that were shifted by applied physics on shifting the field of technical instructions itself. Results are estimated using publication year fixed effects and controlling for language, title length, and catalogue of origin. Standard errors are clustered at the publication year level.

β_{direct_p} from equation 16. First, in figure 27 a) we see that $\beta_{\text{indirect}_p}$ from physics to technical instructions increased throughout the seventeenth century and converged to 1. $\beta_{\text{indirect}_p}$ is estimated as the likelihood of a title in technical instructions to shift its own field if it was itself shifted by a publication in applied physics. In 1620, increasing a title's *shifted by applied physics index* by 1 would have decreased its *innovation index* (how much it shifted its own field) by 0.295. More intuitively, shifting its *shifted by applied physics index* by one standard deviation of 0.327, leads to a decrease in the *breakthrough index* of 0.097. This is more than one standard deviation in the innovativeness index (0.089). Effectively, this means that a title that draws heavily on the early field of applied physics in 1600–1620 would have had a dismal chance of influencing other titles in the future. If a title picked up ideas from physics, the spillover would have almost immediately been forgotten. In contrast, by 1700, a title that was shifted by applied physics had the same likelihood of influencing its own field as all other titles. This means that technical spillovers from applied physics did not have a positive replication rate, but neither were they crowded out directly. Likewise, the coefficients for the impact of spillovers from technical publications on applied physics increased similarly throughout the seventeenth century. Hence, by 1700 the field of applied physics and technical instructions were sufficiently integrated for spillovers not to be crowded out. Knowledge from spillovers persisted, even if it did not replicate.



(a) Feedback loop: Tech → physics → tech

(b) Feedback loop: Physics → tech → physics

FIGURE 28: Spillover effects and feedback loop for applied physics and technical instructions in tech

Notes: The figure shows the coefficients from estimating equation 16 for the fields of applied physics and technical instructions in trades via OLS. The unit of observation are titles at their time of publication. Figure c) shows the results of estimating the effect of titles in applied physics that were shifted by technical instructions on shifting the field of applied physics in turn. Figure d) shows the results of estimating the effect of titles in technical instructions that were shifted by applied physics on shifting the field of technical instructions in turn. Results are estimated using publication year fixed effects and controlling for language, title length, and catalogue of origin. Standard errors are clustered at the publication year level.

Second, 28 a)–b) show the dynamics of the direct feedback mechanism between technical publications in trades and applied physics. It shows a complex dynamic where overall β_{direct_p} increased throughout the seventeenth and eighteenth century to a level where it could set of small, but significant feedback dynamic of self-sustained growth. Figure 28 a) shows the estimated coefficients for how much a title in applied physics that was shifted by technical instructions would in turn shift the field of technical instructions. In 1620, increasing a title's *shifted by technical instructions index* by 1, would have led to a decline in it *shifting technical instructions* in turn by -0.196. More intuitively, increasing its *shifted by technical instructions index* by one standard deviation of 0.258, leads to a decrease of it *shifting technical instructions* by -0.025. This is more than a quarter of its standard deviation (0.092). Hence, titles in applied physics that were influenced by technical instructions were less likely to be useful for technical instructions in turn than all other publications at the same time. This is substantive evidence speaking against the presence of a self-reinforcing feedback loop between technical instructions and applied physics at the beginning of the seventeenth century. Combining ideas from the field of technical instructions with the field of applied physics, made them less useful for technical instructions.

However, starting in 1760, the coefficients become positive, indicating the presence of a self-reinforcing feedback loop. Now increasing the *shifted by technical instructions index* of a title in applied physics in 1780-1800 by its standard deviation of 0.258 would have led to a 0.017 increase in it *shifting technical instructions.* This is about 19% of its standard deviation. Thus by 1760, combining ideas from the field of technical instructions with the field of applied physics would have made them more useful for technical instructions. The literature section provides an example of the study of water wheels, where the systematic collection of data on the performance of water wheels by engineers like Smeaton would have led to an improvement on the physical theory of water wheel. An improved theory of the hydrodynamics of water wheels would have been useful in turn to engineers. Although throughout the eighteenth century theoretical predictions usually fared badly in practise, a new theory of hydrodynamics might have yielded new starting points for experiments and new designs.

Figure 28 b) shows the estimated coefficient for how much a title in technical instructions that was shifted by applied physics would in turn shift the field of applied physics. The results shows that this feedback mechanism running from applied physics to technical instructions and back to applied physics was not yet fully developed by the end of the eighteenth century. First, we see that the feedback loop coefficient turned positive in 1700-1720. An increase in the *shifted by applied physics index* by one standard deviation of 0.327 would have led to a decrease of 0.0323 of it *shifting applied physics.* This is about 20% of its standard deviation. This was the period shortly after the publication of Newton's *Principia* and possibly a moment where early theories were actively refined. However, the coefficient became negative in the 1760s and 1780s where a one standard deviation increase in the *shifted by applied physics index* would have led to a decrease of 0.0348 in 1760 and 0.0226 in 1780, a similar magnitude as before however with a different sign.

Overall, these results show a nuanced picture of the interactions between science and technology within the eighteenth century. By the 1760s, works in physics that incorporated new insights from technical fields, e.g. by formally describing patterns found in practice, would have in turn influenced technical inventions that would have incorporated the theoretical additions. For example, we can easily imagine how engineers would have started to work with more precise mathematical models of patterns they only knew roughly from experience. On the other hand, incorporating these theoretical additions seems only to have created positive spillovers back into applied physics at the beginning of the century. We can e.g. imagine that theories got refuted after having been tried out in practise. Afterwards, this effect declined. We might attribute this to Newtonian mechanics having reached a mature state as a discipline that however still struggled with more complex phenomena. For example, the first theory of thermodynamics that could explain the workings of the steam engine was developed by Sadi Carnot in 1824 (Mokyr, 1999), about 100 years after the development of the first commercially viable steam engine. A closer analysis of the drivers in decrease of this feedback mechanism will be the object of future work.

Altogether we find a wide range of results for the development of the feedback loop between applied physics and technical instructions in trades:

1. Spillovers for (applied physics → tech → tech) and (tech → applied physics → applied physics) were negative at the beginning of the seventeenth century and reached parity in the eighteenth century

2. Feedback loop processes for (applied physics → tech → applied physics) and (tech → applied physics → tech) were negative at the beginning of the seventeenth century and reached parity by the beginning of the eighteenth century

3. The feedback loop process for (applied physics → tech → applied physics) was negative by the end of the eighteenth century

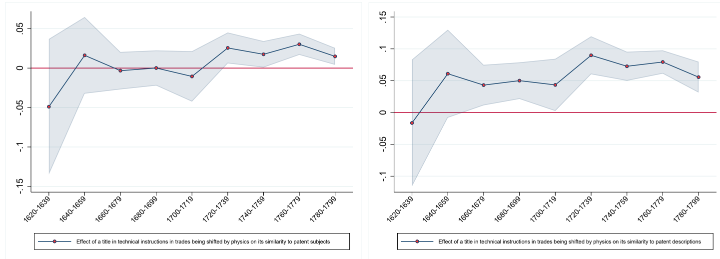
4. The feedback loop process for (tech → applied physics → tech) was positive at the beginning end of the eighteenth century

What is the overall effect of the processes on the stock of knowledge production? Section B.3 provides a simple model that combines a direct and indirect feedback loop mechanism in a production function of knowledge. Section B.4 then calibrates the model with coefficients estimated in this section. We see that the disappearance of negative spillover effects can account for shifting the production function to a higher steady state. As shown in the calibrated results, the process of moving to a higher-steady state can take time. Additionally by 1780, the estimated positive coefficient for (tech → physics → tech) is larger than the negative coefficient for (physics → tech → physics). Hence, within this simple model, by 1780 we reached a steady growth path — within the modelled economy 1780 is the turning point where for the first time in history self-sustained growth has become possible.

Overall, these results should be interpreted with some caution. As discussed before, the analysis is not yet able to account for several sources of bias, including downwards bias from misclassifications and missing publications from the continent. Furthermore, the underlying estimation framework only operates with a concept of Granger causality. We cannot rule out that spillovers between fields are confounded by the impact of other knowledge fields. Lastly, it would be desirable to extend the time-frame of the analysis beyond the year 1800 to study the development of the feedback process during a time when both science and technology became more mature. The method developed in this paper would also be applicable to a sample composed of the full text of scanned publications that might contain more information than titles alone. Hence, compiling a dataset of all scanned documents in Britain during the time of early industrialisation would be a fruitful route for future research.

3.6.1 Effects on the real economy

An open question that should be answered is how much of these changes in the knowledge production in technical instructions in trades actually influenced real production. Although it is hard to link the set of technical instructions to actual production methods on the ground, it is as least possible to link them to patents that have been historically identified as drivers of innovation and growth. Undoubtedly, patents are an imperfect indicator of innovation. First, not all inventions were patented and second, not all that was patented was an invention (see



(a) Physics → tech → patents - patent subjects

(b) Physics → tech → patents — patent short descriptions

Figure 29: Spillover: Physics → tech → patents

Notes: The figure shows the coefficients from estimating equation 15 for the fields of applied physics and technical instructions via OLS. As a proxy for innovativeness and a title's usefulness the model uses distance to all patent descriptions between 1700 and 1800. Figure a) shows the results for using distance to patents' subject headings and figure b) shows the results for using distance to patent's short descriptions. The unit of observation are titles at their time of publication. Results are estimated using publication year fixed effects and controlling for language, title length, and catalogue of origin. Standard errors are clustered at the publication year level.

Griliches, 1990). Yet, they should serve as a useful proxy for general trends in innovation, although they are likely not to be representative for all sectors of the economy (Moser, 2012).

Figure 29 presents the coefficients from equation 15 using textual similarity to patents as the outcome. Thus, the model regresses textual similarity to patents on whether a title in technical instructions was shifted by applied physics. Figure 29 uses two measures of patent text for the calculation of text similarities. First it uses a short descriptions of a patent's technical subject. Second it uses the original text of the patentee's short-description of his or her patent from the historical patent register. In principle, the short-descriptions should yield a richer and better measure that can also incorporate the technical details of an invention as well as the methods used for the construction of the invention. Yet, we might worry that the historical texts might not be standardized enough to yield a consistent measure. Hence, comparing it to the text of the subject description adds a useful standard of comparison.

Reassuringly, both figure 29 a) using distance of technical instructions to patent subjects as well as figure 29 b) using distance of technical instructions to patent short-descriptions yield the same trend. There is a marked increase in the distance between technical instructions shifted by applied physics and patent texts. Using the preferred measure of patent short-descriptions, we see that in 1760–1780, increasing a title's *shifted by applied physics index* by one standard deviation of 0.327 led to an increase in the distance to patents of 0.026, an increase of 44% of its standard deviation of 0.059. This is a sizeable effect showing that combinations of technical instructions and applied physics also increased the practical value of a new technical idea with respect of it being patentable. It further shows that the innovation economy of the early Industrial Revolution was already significantly influenced by knowledge dynamics between applied physics and technical instructions.

3.6.2 The feedback loop process across different fields

After having assessed the feedback loop process between applied physics and technical instructions in trades, the paper sets out to assess overall trends in feedback loop processes across the fields of:

1. (Applied physics, technical instructions in trades)
2. (Applied physics, technical instructions in agriculture)
3. (Mathematics, Technical instructions in trades)
4. (Astronomy, Navigation)

Table 34 classifies the broad trends in the estimated coefficients for indirect and direct feedback loop processes based on the plots of coefficients shown in appendix figure 40–47. Comparing the broad trends of both the strength of the indirect feedback loop and direct feedback loop per field pairs allows for a systematic inquiry into which knowledge fields dynamically interacted during the seventeenth and eighteenth centuries.

Table 34: Classification of results

Field pairs	Presence of indirect feedback loop	Presence of direct feedback loop
Physics → Tech	First negative, increasing throughout 17th century	First negative, increasing until 1700, stalling
Tech → physics	First negative, increasing throughout 17th century	First negative, increasing throughout 1600-1800, positive after 1760
Physics → agriculture	First negative, increasing throughout 17th and 18th century	No trend
Agriculture → physics	First negative, increasing throughout 17th century	Different waves, no clear trend
Mathematics → tech	Neutral, no clear trend	Neutral, positive after 1780
Tech → mathematics	Positive in the early 17th century, decreasing	Neutral, positive after 1760
Navigation → astronomy	First negative, increasing throughout 17th century	Firstly negative, increasing throughout 17th century
Astronomy → navigation	Different waves, sometimes positive	Different waves, sometimes positive

We see that we find evidence of a positive feedback loop arising at the end of the eighteenth century for the feedback loop processes between (applied physics → technical instructions in trades → applied physics), (mathematics → technical instructions in trades → mathematics), and (mathematics → technical instructions in trades → mathematics). We further find evidence of a positive feedback loop at the beginning of the eighteenth century that then became negative for (applied physics → technical instructions in trades → applied physics). We further find completely neutral effects for (applied physics → instructions in agriculture → applied physics) and (instructions in agriculture → applied physics → instructions in agriculture). Lastly, we find mixed effects with varying sizes of the feedback loop process over time for (astronomy → navigation → astronomy) and (navigation → astronomy → navigation).

The results show that there is evidence of a positive feedback loop process for *some* of the core fields of the Industrial Revolution and science at the end of the eighteenth century. Especially the rising size of the feedback mechanism between (technical instructions in trades → applied physics → technical instructions in trades) might have been important for knowledge production at the core of the technical knowledge required for the Industrial Revolution. Yet, it is clear that some fields did not yet exhibit a positive feedback loop process as seen by the example of applied physics and technical instructions in agriculture. Also, the declining size of the coefficient in (applied physics $\rightarrow$ technical instructions in trades $\rightarrow$ applied physics) shows that there were still some counter-acting forces that inhibited the full development of a positive feedback loop. For navigation and astronomy, we find evidence of a positive feedback loop both at the beginning of the seventeenth century and the end of the eighteenth century. These findings are compatible with the prior discussion of positive interactions between astronomy and navigation that started earlier than in other fields. It is noteworthy that we do not find positive interaction effects during the first centuries of the eighteenth century when the longitude prize was announced.

The overall evidence indicates that there were significant changes within the knowledge economy of Britain between 1600 and 1800. We find evidence of negative spillover and feedback loop processes disappearing. Furthermore, we for the fields of applied physics and technical instructions as well as mathematics and technical instructions we find some evidence of a positive feedback loop by the end of the eighteenth century. These finding that are compatible with Mokyr's (2002) hypothesis that the eighteenth century witnessed the arrival of a positive feedback loop between subsets of propositional and prescriptive knowledge. Importantly, the fields of physics and mathematics as well as technical instructions in trades feature prominently in Mokyr's (2002) analysis. Calibrating a simple feedback loop model with the coefficients found for applied physics and technical instructions in trades has revealed that the changes to the feedback loop processes were sufficient to lead to shifting the steady state of knowledge production.

However, the analysis also reveals substantial heterogeneity between fields. Overall, the evidence indicates early signs of the arrival of a feedback loop mechanism in some areas of knowledge production. Yet it appears that effects were still some-times counteracted by negative effects. Furthermore, it appears that some fields remained virtually unaffected by changes in feedback loop processes. In the end, this is compatible with our modern understanding of the Industrial Revolution. Despite it being a turning point in virtually every aspect of the economy, growth was slow in the beginning and only affected a few sectors of the economy (Harley, 1982; Crafts, 1983; Crafts and Harley, 1992). Likewise, it appears that initial changes to the knowledge economy might have been slow and only affected a few fields. Yet, its importance might not be its original size, but the beginning of a new growth regime.

To further interpret the results found in this analysis in a long-run history of the British knowledge economy, extending the text catalogue to areas before and after 1800 will be desirable. Furthermore it should be stressed that the present results might still suffer from downwards bias from misclassifications and missing publications from the continent.

3.7 Conclusion

The paper has introduced a new natural language processing based framework to estimate the development of feedback loop processes between propositional and prescriptive knowledge between 1600–1800. With this new framework it has tested Mokyr's (2002) hypothesis that a positive feedback loop between propositional and prescriptive knowledge started to take form within the eighteenth century. To estimate feedback loop processes between fields of propositional and prescriptive knowledge, the paper has introduced a new framework that uses natural language processing to quantify knowledge spillovers between fields. The framework relies on a BERT large language model that is able to capture complex and context-sensitive content. The paper uses these spillover measures to estimate whether spillovers into a different field created spillovers back to the field of origin.

The paper finds evidence of a structural break in the development of feedback loop processes between different fields of propositional and prescriptive knowledge between the seventeenth and eighteenth century. First, at the beginning of the seventeenth century, feedback loop processes between important fields of propositional and prescriptive knowledge were still negative. They become neutral within the seventeenth century. Additionally, the paper finds evidence of the presence of positive feedback loops between propositional and prescriptive knowledge for a select number of fields at the end of the eighteenth century. However, the analysis also reveals a large heterogeneity in the strength of feedback loops across fields. Overall, the evidence indicates that the end of the eighteenth century might have been the beginning of a transition period towards self-sustained growth in knowledge based on a positive feedback loop between propositional and prescriptive knowledge. This evidence is compatible with Mokyr's (2002) description of the gradual development of a feedback loop process between propositional and prescriptive knowledge against the background of the industrial enlightenment. These findings contribute to to the literature on the causes of modern growth (Jacob, 1997, 2014; Mokyr, 2002, 2016) and to the literature on knowledge spillovers in economics (Jaffe, 1986; Jaffe, Trajtenberg and Fogarty, 2000; Akcigit, Hanley and Serrano-Velarde, 2021; Hallmann, Hanlon and Rosenberger, 2023).

There are still many promising ways to extend this analysis. First, it would be desirable to extent the time period of analysis into the nineteenth century to capture the development of feedback loop processes during a time when science and technology became strongly integrated. Furthermore, we should note that Mokyr (2002) provides an analysis of the full European knowledge economy. Therefore, it would also be desirable to to extent the analysis to publications in further European countries. Such extensions would make it possible to place the current findings into a larger context within time and within the knowledge economies of other European nations.

Appendices

B Appendix for paper 2

B.1 Text data

Table 35: Text classification based on ESTC subjects

Category	Description
Scientific Revolution	
Alchemy	Occult studies, purification of materials
Astrology	The study of the heavens in relation to signs, omens, and prophecies
Astronomy	The physics of the heavens
Almanacs	All almanacs and calendars
Applied physics	Mechanical philosophy that is not part of astronomy, e.g. optics, heat, and mechanical forces.
Biology	Natural histories including the study of plants and animals
Chemistry	Systematic study of the elements, minerals, metals, etc.
Geography	Geography, Cartography, Geology
Scientific Instruments	All scientific instruments (including nautrical instruments)
Mathematics	All mathematical treatments
Medicine	Medical studies, incl. anatomy, and surgery
Political economy	Political economcy, society wide study of improving agriculture, manufactures, or trade, does not include administrative reasonings on the economy, e.g. famines or other scarcities[61]
Higher education	
Philosophy	Philosophical treatises (excludes political philosophy)
Political Philosophy	All philosophical treatises on political institutions
Classical Education	Latin, Greek, ancient mythology, drama and poetry

[61] A note of warning: By placing a focus on the study of the economy independent of the administrative proceedings of the state, this category might be ill-suited to fully capture early mercantilist ideas as well as some early physiocratic ideas.

Logic and rhetoric	Logic and rhetoric as classical categories of education
University matters	University administration and politics
Languages	Foreign languages as well as English (excluding Latin and Greek learning, see classical education)
Business, trade, and innovation	
Technical instructions in trades	Technical instructions, improvements in trades manufactures
Technical instructions in agriculture	Technical instructions in agriculture
Encyclopedias and dictionaries	Systematic collections of knowledge on a given topic, usually with lists and explanations of terms or concepts
Navigation	Publications on navigation, incl. finding latitude and longitude at sea and nautical instruments
Business	Business endeavours, communication, and advertising
Printing and book trades	Anything related to printing and publishing
Public sphere	
Stories and public discourse	Descriptions and tales of any kind of notable event or personal experience, pamphlets, periodicals, and discussion of politics
Moral tales	Moral advise often linked to stories with a moral core
Biographies	Biographical description of the life of noteworthy individuals
Drama	Drama, excluding classical drama (see classical education) as well as prosaic fiction
Poetry	Poetry and songs
Music	Music and music theory
Supernatural	All descriptions of magical events, wonders, and ghosts (both held to be authentic as well as with sceptical attitude)
History	State history
Curiosities and wonders	Strange, phenomena, and sightings
Antiquities and archaeology	Antique collections, archaeological findings
Amusements	Games, food, and festivities
Societies	All kind material (statutes, transactions) on all societies except for economic societies,

Economic societies	All kind material (statutes, transactions) on economic societies
Religion	
Religion	All religious topics
Religion – Sermons	Sermons (often relating other topics to religious themes)
Religion – Catholicism	All works on Catholicism
Religion – Judaism	All works on Judaism
Religion – Dissenters	All works on dissenters (Quakers, Baptists, Methodists etc.)
Prophecies	
Public administration	
Administrative	Administration and politics, proceedings of the House of Commons and local administrative bodies
Legal	Legal questions
Military	Management of the military and navy, military strategy and practises
State affairs	Diplomacy, Royal privileges, Treaties, and Peace negotiations
Wars	Reports on military campaigns, battles, and wars
Colonial exploration	Overseas expeditions, including description of natives, and descriptions of the slave trade

Subject classes are constructed as classifiers for the more than 50,000 subject classes from the ESTC subject index classification. A short note on the distinction between astronomy and astrology as well as between chemistry and alchemy: While the distinction is arguably artificial and spurious from a perspective of the history of science (see e.g. Yates (1964) for the relevance of the Hermetic tradition linking alchemy, medicine, and applied science), it is actually a useful distinction for practical purposes. Thus, for example, the category of Astrology is mainly composed of several ephemerides and early almanacs that are mainly concerned with the calender years and prophecies. As these could relate to any other discipline, it is useful to exclude these works from astronomy to avoid spurious spillover effects.

B.1.1 Classification – Evaluative statistics

Table 36: Classification Report – DistilBERT

Subject class	Precision	Recall	F1-score	Support
Administrative	0.8	0.8	0.7	8726
Alchemy	0.1	0.1	0.1	28
Almanacs	0.7	0.7	0.7	284
Amusements	0.6	0.6	0.6	377
Antiquities	0.4	0.4	0.4	87
Applied physics	0.6	0.6	0.6	183
Architecture	0.6	0.6	0.6	97
Art	0.7	0.7	0.7	213
Astrology	0.5	0.5	0.5	220
Astronomy	0.5	0.5	0.6	181
Biography	0.3	0.3	0.4	132
Biology	0.7	0.7	0.7	312
Chemistry	0.6	0.6	0.6	99
Church administration	0.5	0.5	0.5	934
Classical education	0.6	0.6	0.6	755
Curiosities and wonders	0.3	0.3	0.4	80
Drama	0.8	0.8	0.8	2422
Economic societies	0.0	0.0	0.0	15
Economics	0.4	0.4	0.5	48
Education	0.6	0.6	0.6	357
Encyclopedias and dictionaries	0.5	0.5	0.5	212
Exploration	0.6	0.6	0.6	508
Foreign languages	0.7	0.7	0.8	467
Geography	0.6	0.6	0.6	141
Geology	0.1	0.1	0.2	22
History	0.3	0.3	0.4	167
Legal	0.5	0.5	0.6	1932
Mathematics	0.8	0.8	0.8	351
Medicine	0.9	0.9	0.8	2127
Mercantile	0.4	0.4	0.4	1190

Military	0.5	0.5	0.6	327
Military Wars	0.6	0.6	0.6	701
Moral tales	0.3	0.3	0.4	692
Music	0.6	0.6	0.6	251
Navigation	0.6	0.6	0.7	192
Philosophy	0.5	0.5	0.5	316
Poetry	0.8	0.8	0.7	4042
Political philosophy	0.3	0.3	0.4	198
Printing and book trades	0.8	0.8	0.8	800
Prophecies	0.6	0.6	0.6	171
Religious	0.7	0.7	0.7	7390
Religious Catholicism	0.3	0.3	0.4	297
Religious Judaism	0.6	0.6	0.6	116
Religious Sects	0.5	0.5	0.5	1827
Religious Sermons	0.8	0.8	0.8	2788
Scientific instruments	0.7	0.7	0.6	85
Societies	0.6	0.6	0.6	130
State affairs	0.4	0.4	0.5	392
Stories	0.5	0.5	0.5	3222
Supernatural	0.6	0.6	0.6	148
Technical instructions Agriculture	0.7	0.7	0.7	276
Technical instructions Trades	0.5	0.5	0.5	358
Travel descriptions	0.0	0.0	0.0	23
University learning	0.5	0.5	0.6	184
University matters	0.3	0.3	0.3	57
Macro Avg	0.5	0.5	0.5	47650
Weighted Avg	0.7	0.7	0.7	47650
Accuracy: 0.7				

Notes: Precision measures the ratio of true positives over true and false positives. Recall measures the ratio of all true positives over all true positives and false negatives. The F1-score is a weighted harmonic mean between precision and recall. Higher values indicate better performance. Support is the number of observations of classes in the test dataset. Accuracy is the overall number of correct predictions over all predictions.

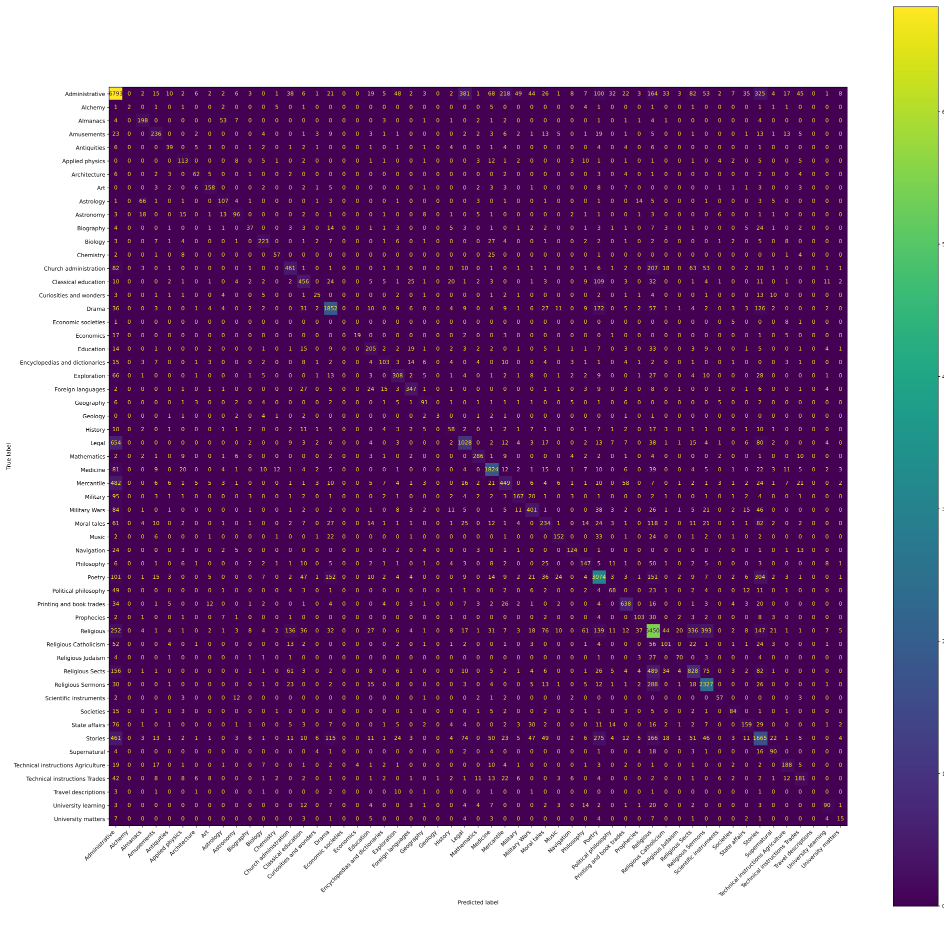


Figure 30: Confusion matrix – DistilBERT classification

B.1.2 Comparison of different natural language models for deriving measures of textual similarity

In order to illustrate the differences between different ways of measuring sentence similarities, e.g. bag-of-words methods, word-embeddings, sentence embeddings, and the BERT model, we can take a look at a stylized example of titles. We compare Isaac Newton's famous work *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* to a work that is known to have been an important influence for Newton, Christian Huygen's *Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection* and a later work on optics that was likely inspired by Newton's work, David Gregory's *Elements of catoptrics and dioptrics.* We further compare Newton's Optics to a set of unrelated titles that mentions similar words such as "light" or "reflexions", but in an unrelated context. Table 37 shows the comparative statistics. A good measure of sentence similarity should be able to a) identify titles of similar content that are described with different words and b) distinguish related from unrelated titles using the same words, but in a different context.

Comparing Newton's *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* and Huygen's *Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection* is relatively straightforward. Both titles essentially describe the same set of phenomena that are explained, although described slightly differently. However, the challenge set by David Gregory's *Elements of catoptrics and dioptrics* in comparison to Newton's *Opticks* is significant as both works do not have an overlapping technical vocabulary. In order to identify the similarity between both works we need the additional information that catoptrics deals with the phenomeon of reflacted light and that dioptrics is the branch of optics studying refraction. Hence, the similarity exists between the meaning of the words, and not the technical vocabularly itself. Looking at the unrelated placebo titles, we see that titles such as *The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints* or *A true and impartial account of the dark and hellish power of witchcraft* use the same technical vocabulary of light and colour, but in a different context. Thus, distinguishing

Newton's *Optics* from these placebo titles not only involves comparing the meaning of words (e.g. "dark" and "colour" might be similar), but understanding the context of its use.

Table 37 compares a tf-idf bag-of-words approach, word-embeddings in spacy, sentence embeddings in Google's Universal Sentence Encoder, and a BERT transformer model.[62] It shows that the bag-of-words tf-idf method succesfully identifies a high similarity between Newton's and Huygen's works, but shows a similarity of 0 between Newton's and Gregory's works on optics. Comparing Newton's work to a group of unrelated placebo titles, it picks up on the use of "light" and "reflexions" in a completely different context, although the similarity scores are still relatively low. In general, we see that the main shortcoming of bag-of-word methods is its inability to account for the similar meaning of different words, leading to a significant loss of information in comparing scientific articles.

These shortcomings of bag-of-words methods might lead us to prefer similarity measures based on word embeddings. Column (2) presents the average of the similarity of word-vectors using spacy. This method is able to successfully capture the similarity between Newton's, Huygens's, and Gregory's work. However, the vector representation of words also recognizes a similar meaning in the unrelated controls that also use phrases of light - although in a religious, or figurative meaning. The method still gives a higher similarity score to the true works on optics. However, the difference in similarity scores is less than we might prefer. Thus, the results on word-embedings highlight the need for a method that can account for different meanings based on context. This leads to transformer models based on deep neural networks that can compute context-aware representations (Vaswani et al., 2017). Column (3) shows the results for Google's Universal Sentence Encoder (Cer et al., 2018) that uses sentence embeddings from a pre-trained transformer model and column (4) shows results for the BERT transformer model (Devlin et al., 2018). The results for the USE are disappointing. It gives a lesser similarity score to Gregory's work than to *The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints.* However, the BERT model successfully identifies the true

[62] Before running the similarity measures for Tf-idf and spacy, titles are broken down into only nouns, adjectives, and adverbs – terms that are most likely to capture the relevant topic of the words.This avoids an overweighting of usual stop-words such as "that" or "and" or of verbs with versatile meanings. Nouns, adjectives, and adverbs are identified using spacy. Both USE and BERT use context-information from the whole sentence and thus require the complete use of complete use of the text-structure.

works of optics and gives a significantly lower similarity score to the unrelated placebos. Thus, it is able to distinguish between the context of physical treatments of light and colours and the context of religious and figurative use of light and colours. These results indicate that using transformer models can lead to more comprehensive and accurate similarity measures between book titles than tf-idf bag-of-word models or word-embedding models. However, it still shows the presence of false positives within a lower probability limit. Hence, this paper will combine the transformer models for measuring novelty with a prior categorization of topics. Similarity measures are then only calculated for documents within each topic.

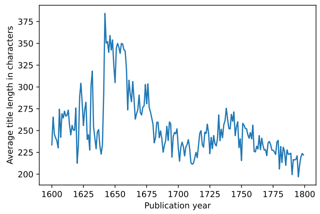
Table 37: Comparing title similarities with different NLP methods

Similarity between:	Tf-idf	Spacy	USE	BERT
Newton's famous work on optics:				
"Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light"1)				
and				
Prior works on optics:				
"Treatise on Light: In Which Are Explained the Causes of That Which Occurs in Reflection & Refraction"2)	0.24	0.67	0.38	0.64
Later works on optics:				
"Dr. Gregory's Elements of catoptrics and dioptrics. To which is added, I. A method for finding the foci of all Specula as well as Lens's universally. As also for Magnifying or Lessening a given Object by a given Speculum or Lens in any assign'd Proportion, &c. A particular account of microscopes and telescopes, from Mr. Huygens. With an introduction shewing the Discoveries made by Catoptrics and Dioptrics."3)	0	0.55	0.21	0.41
Unrelated placebo titles:				
"The words of the everlasting and true Light, vvho is the eternal living God, and the King of saints"	0.08	0.46	0.28	0.23
"A true and impartial account of the dark and hellish power of witchcraft"	0	0.47	0.22	0.18
"A new torch to the Latine tongue: so enlightned, that besides the easie understanding of all classical authours, there is also laid open a ready way to write and speak Latine well and elegantly"	0	0.48	0.18	0.12
"Political reflections upon the finances and commerce of France; shewing the causes which formerly obstructed the advancement of her trade"	0.11	0.41	0.19	0.20

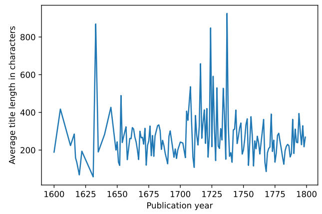
1): Isaac Newton, 1704, 2): Christiaan Huygens, 1690, 3): David Gregory, 1715.

List of natural language processing models used: Tf-idf: term frequency-inverse document frequency implemented with Python's sklearn. Spacy: Word-embeddings implemented in spacy with similarity calculated as average cosine similarity accross words. USE: Universal Sentence Encoder, a sentence embedder based on a transformer model (Cer et al., 2018). The paper uses the TF2-v5 model from Tensorflow. BERT: Bidirectional Encoder Representations from Transformers, a state-of the art transformer model (Devlin et al., 2018). The paper uses the ll-MiniLM-L6-v2 model that was pretrained on over 1 billion sentence pairs and optimzed as as a sentence and short paragraph encoder. The text of the titles is presented in the original spelling. For the presentation of this stylized example the "unrelated controls" titles have been shortened but remain otherwise unchanged.

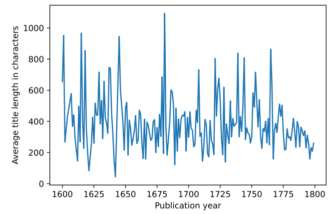
B.1.3 Publication title statistics



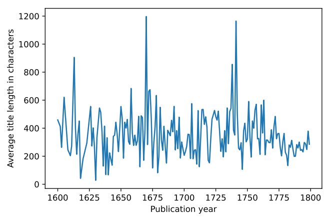
(a) All publications



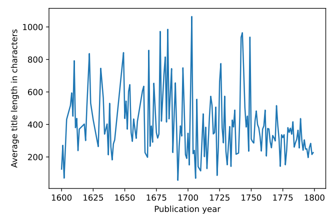
(b) Physics



(c) Mathematics

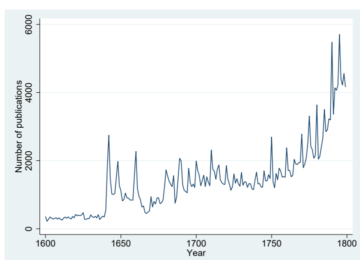


(d) Instructions — trades

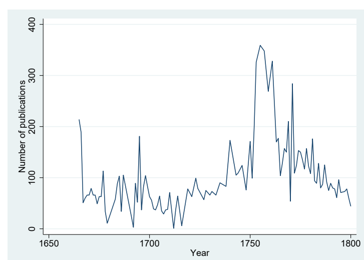


(e) Instructions — agriculture

FIGURE 31: Trends in title lengths in the number of characters over time



(a) ESTC catalogue



(b) Philosophical transactions

FIGURE 32: Yearly number of publications

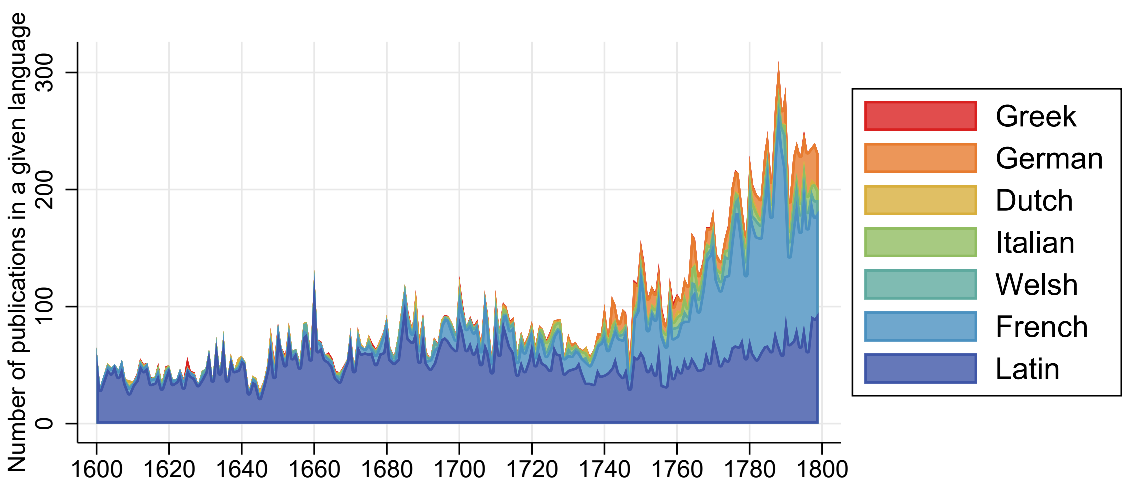


Figure 33: ESTC titles published in foreign languages over time

B.2 List of titles for examples of NLP indices

B.2.1 Example, calculation of backward similarity to applied physics for *An experimental enquiry concerning the natural powers of water and wind to turn mils, and other machines, depending on a circular motion*

Author	Title	Year	Similarity score
Clare, M. (Martin), -1751.	the motion of fluids natural and artificial in particular that of the air and water in familiar manner proposed and proved by evident and conclusive experiments with many useful remarks done with such plainness and perspicuity as that they be understood by the unlearned for whose sake there is added short explanation of such uncommon terms which in treating on this subject could not without affectation be avoided with plain draughts of such experiments and machines which by description only might not readily be comprehended by clare	1735	0.49
John Theophilus Desaguliers	II. A calculation of the velocity of the air moved by the new-invented centrifugal bellows of 7 feet in diameter, and 1 foot thick within, which a man can keep in motion with very little labour, at the rate of two revolutions in one second	1735	0.48
Desaguliers, J. T. (John Theophilus), 1683-1744.	A system of experimental philosophy, prov'd by mechanicks. Wherein the principles and laws of physicks, mechanicks, hydrostaticks, and opticks, are demonstrated and explained at large, by a great Number of curious Experiments: With a full Description of the Air-Pump, and the several Experiments thereon: As also of the different Species of Barometers, Thermometers, and Hydrometers; as shewn at the publick Lectures in a Course of Mechanical and Experimental Philosyphy. As performed by J. T. Desaguliers. M. A. F. R. S. Illustrated with several copper plates. To which is added, Sir Isaac Newton's colours: the description of the condensing engine, with its Apparatus: and Rowley's horary; a Machine representing the Motion of the Moon about the Earth; Venus and Mercury about the Sun, according to the Copernican System.	1719	0.39
John Theophilus Desaguliers	III. A farther examination of the machine's said to be without friction.	1730	0.39

Switzer, Stephen, 1682?-1745.	an universal system of water and water works philosophical and practical in four books faithfully digested from the most approv writers on this subject by stephen switzer containing an historical account of the chief water works that were and are remarkable in ancient and modern times more particularly the roman aqueducts and the honour they have contributed to the respective places where they have been used the different hypotheses which have been laid down concerning the original and rise of springs of the good and bad properties of water the best manner of discovering and searching for springs and the taking of true levels in order for the conducting water to its several intended uses hydrostatical experiments relating to the motion of water selected from the most celebrated foreign and english authors more particularly boyle hooke wallis lowthorpe also the full description and uses of mechanical engines for the forcing water to great heights and applying the same to the waterin...	1734	0.39
William Watson	VIII. Further experiments and observations, tending to illustrate the nature and properties of electricity	1746	0.39
John Theophilus Desaguliers	V. An experiment to shew that the friction of the several parts in a compound engine, may be reduced to calculation; by drawing consequences from some of the experiments shewn before the Royal Society last Year, upon simple machines, in various circumstances, by me. Now exemplified by the Friction in a Combination of Pullies	1731	0.38
—	A short essay upon the cause and usefulness of the W. and S. W. wind's frequent blowing in England, by way of solution to a passage in Mr. Ray's Wisdom of the creator, in the works of creation: with some observations upon the weather ... Also a diary during the wet seaso which succeeded the drought in 1737 ... in prose; intermix'd with verses.	1742	0.38
Annely, Bernard.	A theory of the winds, shewing by a new hypothesis, the physical causes of all winds in general: With the Solution of all the Variety and Phaenomena thereof, as it was read to the Royal Society. By Bernard Annely	1729	0.38

Horsley, John, 1675-1732.	A brief and general account of the most necessary and fundamental principles of statics, mechanics, hydrostatics, and pneumatics; adapted more especially to a course of experiments perform'd at morpeth in the country of Northamberland. By John Horsley, A.M.	1731	0.37

B.2.2 Example, calculation of backward similarity to technical instructions for *An experimental enquiry concerning the natural powers of water and wind to turn mils, and other machines, depending on a circular motion*

Author	Title	Year	Similarity score
Duncan, John, active 1756.	The experiment was lately made of the force of fire in a single air furnace, in order to force the rotation of a new machine ...	1756	0.44
Christianus Hee	I. On the pressure of weights in moving machines	1755	0.43
Emerson, William, 1701-1782.	The principles of mechanics; explaining and demonstrating the general laws of motion, the laws of gravity, motion of descending bodies, Projectiles, Mechanic Powers, Pendulums, Centers of Gravity, &c. Strength and Stress of Timber, Hydrostatics, and Construction of Machines	1754	0.43
Emerson, William, 1701-1782.	The principles of mechanics. Explaining and demonstrating the general laws of motion, the laws of gravity, motion of descending bodies, projectiles, mechanic powers, pendulums, centers of gravity, &c. strength and stress of timber, hydrostatics, and construction of machines. A work very necessary to be known, by all gentlemen, and others, that desire to have an insight into the works of nature and art. And extremely useful to all sorts of artificers; particularly to architects, engineers, shipwrights, millwrights, watchmakers, &c. Or any that work in a mechanical way.	1758	0.43
Walter Churchman	II. An account of a new engine for raising water, in which horses or other animals draw without any loss of power (which has never yet been practised) and how the strokes of the pistons may be made of any length, to prevent the loss of water, by the too frequent opening of valves, with many other advantages altogether new ; the model of which was shewm to the Royal Society on the 28th of November, by Walter Churchman, the Inventor of it	1733	0.42
John Theophilus Desaguliers	II. A description of an engine to raise water by the help of quicksilver, invented by the late Mr. Joshua Haskins, and improv'd by J. T. Desaguliers, LL. D. R. S. S	1723	0.42

Hulls, Jonathan, 1699-	A description and draught of a new-invented machine for carrying vessels or ships out of, or into any harbour, port, or river, against wind and tide, or in a calm. For which, His Majesty has granted letters patent, for the sole benefit of the author, for the space of fourteen years. By Jonathan Hulls.	1737	0.41
Roberts, Hugh, (Engineer)	An imitation of a model for water-works, contrived after the nearest manner to save friction, ...	1742	0.41
William Arderon; Samuel Salter	I. Part of a letter from Mr. Wm. Arderon, F. R. S. to Mr. Baker, F. R. S. containing a description of a water-wheel for mills invented by by Mr. Philip Williams. With an Extract of a Letter from the Rev. Dr. Samuel Salter to Mr. Arderon, concerning the Bark Preventing Catching Cold	1746	0.40
Cay	V. An account of the manner of bending planks in His Majesty's Yards at Deptford, by a sand-heat, invented by Captain Cumberland	1742	0.37

B.2.3 Example, calculation of forward similarity in navigation to *The description and uses of a new and correct sea-chart of the whole world, shewing the variations of the compass E. Halley*

B.2.4 Example, calculation of backward similarity in navigation to *The description and uses of a new and correct sea-chart of the whole world, shewing the variations of the compass E. Halley*

Author	Title	Year	Similarity score
Wakely, Andrew.	The mariners-compass rectified. Containing tables shewing the true hour of the day, the sun being upon any point of the compass: with the true time of the rising and setting of the sun and stars, and the points of the compass that the sun and stars rise and set with: and tables of amplitude. All which tables are calculated from the equinoctial to 60 deg. of latitude. Hereunto is added an appendix, containing the description and use of those instruments most in use in the art of navigation. With a table of the latitude and longitude of places: composed after a new order. By Andrew Wakely, math.	1694.0	0.70
—	The newly enlarged and great sea atlas or waterworld, containeing, exact descriptions of all the sea coasts of the whole world, according to theyre scituation true uppon the globe in latitude & longitude as well as in flat.	1682.0	0.69

Newton, Samuel, Master of the Math. School at Christ's Hospital.	An idea of geography and navigation. Containing easie rules for finding the latitude and difference of longitude of places by observation of the sun, moon and stars The demonstration and use of the logline. The variation of the compass. The doctrine of plain triangles. The construction and use of all manner of mapps and charts. To keep a journal, and to work a traverse both by plain and Mercators sayling. The solution of all nautical questions, geometrically, arithmetically, and instrumentally. Also, tables of the sun's declina[t]ision [sic] and right ascension for ever. A table of the most eminent fixed stars in both hemispheres, rectified for the year 1700, with their use, and other tables necessary in navigation. By Samuel Newton, Master of the Math. School at Christ's Hospital, founded by King Charles II.	1695.0	0.66
Tapp, John, active 1596-1615.	The sea-man's kalendar: or, An ephemerides of the sun, moon, and certain of the most notable fixed stars: also, rules for finding the prime, epact, moons age, time of high water, with tables for the same; and the courses distances, and soundings of the coasts of England, Scotland, Ireland, France, &c. And a table of latitude and longitude, of the principal ports, head-lands, and islands in the world, first calculated by John Tap: now rectified and enlarged with many additions. Viz. A new exact table of the north-star, and new tables of 65 of the principal fixed stars, their coming upon the meridian every day, with their right ascension and declination, &c. With a discovery of the long hidden secret of longitude, by Henry Bond, teacher of the mathematicks. and many other rules and tables added, very usefull in the art of navigation. By Henry Philippes, philo nauticus.	1680.0	0.63

Blackborow, Peter.	Navigation rectified: or, The common chart proved to be the onely true chart. With an answer to a question given by some navigatours in the practical part of navigation, with an addenda upon the same question, proving Mercator's practical rules in navigation to be notoriously false: with several observations proving longitude cannot be found by observation from the stars or from the planets, unless it be when the sun or moon are eclipsed in the equinoctial. To which are added several observations, proving the globe of the earth to be the centre of the heavens. As likewise an answer to two propositions of Mr. Flamsteed: with a letter from a friend, concerning his behaviour in this affair. By Peter Blackborow.	1687.0	0.61
Gadbury, John, 1627-1704.	Nauticum astrologium	1696.0	0.56
English pilot. Book 4.	The English pilot, the fourth book. Describing the sea-coasts, capes, head-lands, rivers, bays, roads, havens, harbours, streights, islands, depths, rocks, shoals, sands, banks, and dangers from the river Amazons to New-found-Land; with all the West-India navigation, and the islands therein, as Cuba, Hispaniola, Jamaica, Barbadoes, Porto Rico, and the rest of the Caribbe Islands. With a new description of New-found-Land, New-England, Virginia, Mary-Land &c. shewing the courses and distances from one place to another, the ebbing and flowing of the sea, the setting of the tides and currents, &c. By the information of divers navigators of our own, and other nations.	1689.0	0.53
Fyler, Samuel, 1638-1703.	Longitudinis inventæ explicatio non longa, or, Fixing the volatilis'd, and taking time on tiptoe, briefly explain'd; by which rules are given to find the longitude at sea by, as truly and exactly as the latitude is found by the star in the tayle of Ursa Minor, call'd the Pole-star. BY S.F. A.M. rector of Stockton in the county of Wilts.	1699.0	0.53
Flamsteed, John, 1646-1719.	A correct tide table, shewing the true times of the high-waters at London-Bridg, to every day in the year, 1683. By J. Flamsteed, M.R.	1683.0	0.51

Collins, Greenville, active 1679-1693.	Great Britain's coasting-pilot. The first part. Being a new and exact survey of the sea-coast of England, from the River of Thames to the westward, with the islands of Scilly, and from thence to Carlile. Describing all the harbours, rivers, bays, roads, rocks, sands, buoys, beacons, sea-marks, depths of water, latitude, bearings and distances from place to place, the setting and flowing of tydes, with directions for the knowing of any place; and how to harbour a ship in the same with safety. With directions for coming into the channel between England and France. By Captain Greenvile Collins Hydrographer in Ordinary to the King and Queens most excellent Majesties.	1693.0	0.51

Author	Title	Year	Similarity score
Jones, W. (William), 1675-1749.	A new compendium of the whole art of practical navigation; containing the elements of plain trigonometry, and it's application to plain, Mercator's and middle-latitude sailing. Together With the most Useful and Necessary Problems in Astronomy. Also, The Method of finding the Variation of the Compass, Working an Observation, the Reason and Use of the Log-Line, Allowances for Lee-Way: With New Tables of the Sun's Declination, &c. By William Jones.	1702	0.72
Seller, John, active 1658-1698.	Practical navigation: or An introduction to the whole art. Containing the doctrine of plain and spherical triangles. Plain, mercator, great circle sailing; and astronomical problems. The use of divers instruments; as also of the plain chart, mercator's chart, and both globes. Sundry useful tables in navigation: and a table of 10000 logarithms, and of the logarithm sines, tangents, and secants. All carefully corrected. By John Seller, hydrographer to the king.	1714	0.71
Newhouse, Daniel.	The whole art of navigation: Containing, the application of geometry and astronomy to the practice of plain and mercator's sailing; both performed either with, or without the logarithms. The description and use, at large, of the most necessary instruments for observations at sea the explanation of sea-terms, in an alphabetical order. The method of finding the variation of the compass by the sun's azimuth and amplitude; as also keeping a sea-journal, and the several ways of correcting the dead-reckoning, &c. with the most useful tables in navigation. The whole delivered in a very easy and familiar stile, by way of dialogue between a tutor and his scholar. The third edition, corrected. By Captain Daniel New-House.	1708	0.69

Cawood, Francis.	Navigation compleated: Being a new method never before attain'd to by any. Whereby the true longitude of any place in the world may be found, whether differing in longitude only, or both in longitude and latitude from any place in the habitable world, by new invented mathematical instruments, viz. The complete navigator, or universal chart. The accute astronomer, compass, admitting of no variation in any latitude, &c. distance-reel and discoverer. By the uses whereof, the certainty of the easting and westing of the globe may be discovered as exactly as the northing and southing already are, and to give at any altitude (having the suns declination, the true latitude, longitude, hour and azimuth all at once by ocular inspection, thereby making the sea barring winds, &c. as direct and plain a path for ships to sail, as the land for travelling. By Francis Cawood, London, student in the mathematicks.	1710	0.68
Wakely, Andrew.	The mariner's compass rectified: containing tables shewing the true hour of the day, the sun being upon any point of the compass: ... By Andrew Wakely, Math. Carefully corrected, and very much enlarged, with many useful additions. By Ja. Atkinson, ...	1704	0.67
Atkinson, James, active 1667-1715.	Epitome of the art of navigation; or, A short and easy methodical way to become a compleat navigator. Containing practical geometry, plain and spherical, superficial and solid; with its uses in all kinds of mensurations. Trigonometry, plain and spherical, both geometrical, instrumental, logarithmical, with its uses in navigation, viz. In plain, Mercator's, and great circle sailing. Geography. Astronomy. The projection of the sphere, &c. The description and use of the plain chart, Mercator's chart, both globes, hemispheres, and divers other instruments. A new form of keeping a sea-reckoning, or account of a ship's way. A traverse table; a table of meridional parts; a table of 10,000 logarithms, and logarithmical sines, tangents and secants, carefully corrected. By James Atkinson, teacher of the mathematicks.	1707.0	0.64
Wakely, Andrew.	The mariner's compass rectified ... Also a description and use of those instruments most in use in the art of navigation. By Andrew Wakely ... Carefully corrected, and very much enlarged, with many useful additions. By Ja. Atkinson ...	1709	0.63

—	Atlas maritimus novus, or the new sea-atlas. Being a book of new and large charts of the sea-coasts, capes, ... in most of the known parts of the world. ...	1702	0.62
Pitot, Allain.	L'automate de longitude. Nouveau systéme d'hydrométrie ; par les périodes d'un mouvement nautique, qui marque à un cadran, les lieuës qu'un navire fait dans sa route. Présenté à nos seigneurs les Commissaires de la Grande Bretagne pour l'examen des découvertes sur la longitude. Par Allain Pitot.	1716	0.60
Whiston, William, 1667-1752.	A new method for discovering the longitude both at sea and land, humbly proposed to the consideration of the publick. By William Whiston, M. A. sometime Professor of the Mathematicks in the University of Cambridg. and Humphry Ditton, Master of the New Mathematick School in Christ's Hospital, London.	1714	0.60

B.2.5 Reproductions of technical figures and text

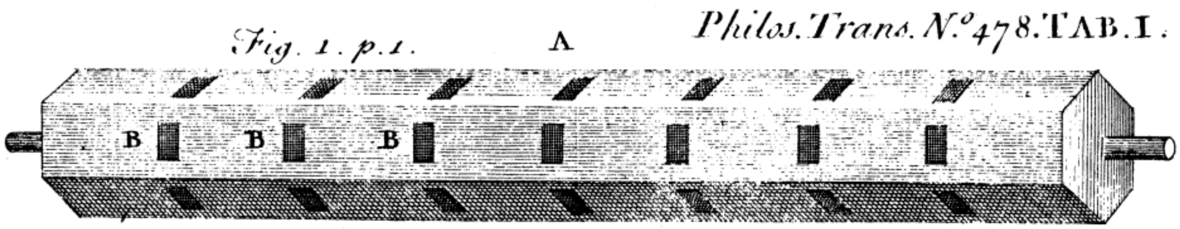


FIGURE 34: Technical drawing from Arderon and Salter (1746) on the water wheel invented by Philip Williams

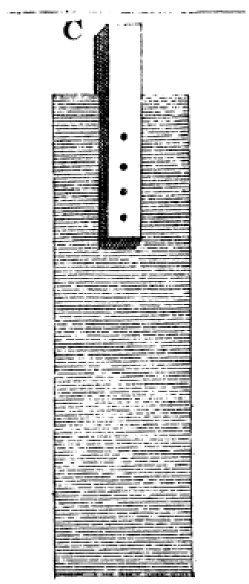
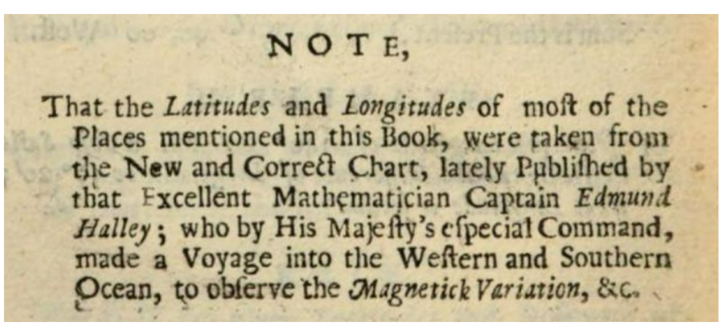


FIGURE 35: Technical drawing from Arderon and Salter (1746) on the water wheel invented by Philip Williams



NOTE,

That the *Latitudes* and *Longitudes* of moſt of the Places mentioned in this Book, were taken from the New and Correct Chart, lately Publiſhed by that Excellent Mathematician Captain *Edmund Halley*; who by His Majeſty's eſpecial Command, made a Voyage into the Weſtern and Southern Ocean, to obſerve the *Magnetick Variation*, &c.

FIGURE 36: Reference to Halley's map from Jones (1702, p. 52)

B.3 A simple growth model of a feedback loop in knowledge production

We can formalize a minimal version of a growth model to capture the basic intuition of a feedback loop between propositional knowledge, Ω and prescriptive knowledge Λ. The model will produce three main predictions: First, it shows that an indirect feedback loop with random spillovers between Ω and Λ leads to a higher steady-state level in the production of ideas. Second, it shows that a direct feedback loop where specific knowledge runs through a multi-iterated feedback loop can create self-sustained growth. Third, it shows that this process is amplified by a deeper reliance of Ω on Λ and Λ on Ω, denoted as α. Thus, the model shows that while an indirect feedback loop and a deeper integration of fields might have produced singular advances in knowledge production, only the presence of a direct feedback mechanism would have led to modern self-sustained growth.

In the spirit of usual growth models, knowledge is modelled as distinct and countable ideas. The paper distinguishes between two types of ideas: First, we assume there are ideas that are produced solely relying on knowledge from the same epistemic set, that is propositional knowledge built on propositional knowledge, $\Omega_{\Omega\to\Omega}(t)$, and prescriptive knowledge built on prescriptive knowledge, $\Lambda_{\Lambda\to\Lambda}(t)$. Second, we assume the existence of ideas that are built on knowledge spillovers, prescriptive knowledge built on propositional knowledge, $\Lambda_{\Omega\to\Lambda}(t)$, and propositional knowledge built on prescriptive knowledge,$\Omega_{\Lambda\to\Omega}(t)$.

The total sum of $\Omega(t)$ is given as a Cobb-Douglas function of knowledge produced within its own epistemic set and knowledge spillovers:

$$\Omega(t) = \Omega_{\Omega\to\Omega}(t)^{\alpha} \cdot \Omega_{\Lambda\to\Omega}(t)^{1-\alpha} \tag{17}$$

$$\Lambda(t) = \Lambda_{\Lambda\to\Lambda}(t)^{\alpha} \cdot \Lambda_{\Omega\to\Lambda}(t)^{1-\alpha} \tag{18}$$

Here, $1-\alpha$ measures the strength of how much ideas from knowledge spillovers are integrated into the production of ideas. A high $1-\alpha$ indicates that Ω and Λ are deeply integrated, with many titles referring to concepts from the other set. However, a high integration of Ω

and Λ does not imply higher growth rates on its own. This depends on the specification of the production of the two different types of ideas, ideas produced in their own field, and ideas produced through knowledge spillovers.

We start by modelling the production of ideas within its own epistemic set. It can be defined as a process consisting of a deprecation of old ideas, θ, and the production of new ideas, ϵ:

$$\Omega_{\Omega\to\Omega}(t) = \Omega_{\Omega\to\Omega}(t-1)^{\theta} \cdot \epsilon(t)^{1-\theta} \tag{19}$$

where ϵ is a stochastic variable that captures the production of new ideas. There is some scope for defining θ and ϵ within this model. We would imagine plausible specifications to yield a constant or slowly increasing growth rate.[63] However, to illustrate the results of the feedback mechanism more clearly, we assume that $\theta = 1$ for the rest of the model section. Under these assumptions, the stock of knowledge is constant over time.

Next, we define the production of ideas from outside their epistemic set, $\Lambda_{\Omega\to\Lambda}(t)$ and $\Omega_{\Lambda\to\Omega}(t)$. These types of ideas originate from a spillover of ideas from one epistemic set into the other that leads to new ideas in the epistemic set receiving the spillover. Here, the model introduces a central distinction between an indirect and direct feedback loop. In an indirect feedback loop, spillovers occur from the full set of the other epistemic set (Λ and Ω), i.e. all ideas from the other field are equally likely to influence the other field. In a direct feedback loop, only ideas in the set of ideas drawing on outside its epistemic set ($\Lambda_{\Omega\to\Lambda}(t)$ and $\Omega_{\Lambda\to\Omega}(t)$ themselves) cause spillovers, i.e. only ideas that were already influenced by the other field lead to spillovers. In reality, we would expect the combined occurrence of direct and indirect

[63] In a straightforward specification we can, for example, assume that new ideas arrive from a random Gaussian process. For convenience, we assume that negative values from the stochastic are set to zero, capturing periods with inventions. We can write the random innovation shock ϵ as:

$$\epsilon(t) = \max \epsilon(t), 0 \quad \sim \begin{cases} \mathcal{N}(\mu_\epsilon, \sigma_\epsilon^2), & X(t) \geq 0 \\ 0, & X(t) < 0 \end{cases} \tag{20}$$

In the spirit of Romer (1990) we can assume that new ideas follow population size and set σ_ϵ^2 to L_A with L_A representing the researcher share of the population.

feedback loops. However, to understand the dynamics of the feedback loop system, it makes sense to introduce the two cases separately. First, we define the indirect feedback loop:

$$\Omega_{\Lambda\to\Omega}(t) = \Omega_{\Lambda\to\Omega}(t-1)^{\phi} \cdot \beta_1 \Lambda(t-1)^{1-\phi} \tag{21}$$

$$\Lambda_{\Omega\to\Lambda}(t) = \Lambda_{\Omega\to\Lambda}(t-1)^{\phi} \cdot \beta_2 \Omega(t-1)^{1-\phi} \tag{22}$$

We assume that ideas originating from outside its own epistemic set are depreciating at rate $1-\phi$. Furthermore, the stock of ideas in the other epistemic set ($\Lambda(t-1)$ for $\Omega_{\Lambda\to\Omega}(t)$ and $\Omega(t-1)$ for $\Lambda_{\Omega\to\Lambda}(t)$) create new spillovers at rate β_1 and β_2. Equation 21 and 22 create a feedback loop, because both $\Omega_{\Lambda\to\Omega}(t)$ and $\Lambda_{\Omega\to\Lambda}(t)$ are inputs into the knowledge production function in equation 17 and 18 that define the stock of ideas Ω and Λ. The loop is closed by Ω and Λ being inputs into equation 21 and 22. For simplicity's sake we consider the case of parallel spillovers, β_1=β_2. With this, the steady state of Ω is characterized as:[64]

$$\Omega^* = (\Omega_{\Omega\to\Omega}(t)^a \cdot \beta^{\frac{1}{1-\phi} - \frac{a}{1-\phi}})^{\frac{1}{a}} \tag{23}$$

The steady-state of Λ follows by parallel construction. We see that Ω^* is increasing in β. Higher spillovers shift the knowledge production function to a higher steady state. Furthermore, for $\beta > 1$, Ω^* is increasing in α. For $\beta < 1$, Ω^* is decreasing in α. Thus, a deeper integration of Λ into the knowledge production function of Ω only shifts Ω^* upwards if spillovers from Λ have a larger effect than ideas produced within Ω. Otherwise, a larger α leads to a downward shift.

Next, we define the the direct feedback loop for $\Omega_{\Lambda\to\Omega}(t)$ and $\Lambda_{\Omega\to\Lambda}(t)$. Here, spillovers do not originate from Ω or Λ as in equations 21 and 22. Instead spillovers originate from $\Omega_{\Lambda\to\Omega}(t)$ or $\Lambda_{\Omega\to\Lambda}(t)$ themselves. In the light of the historical discussion of science and technology during the seventeenth and eighteenth century in section 3.2, we can call this the Smeaton case. Not only did Smeaton in his practical experiments with water wheels adopt the theories

[64] There is a further trivial solution for the steady-state with Ω^*=0.

and predictions from the savants at the French academy and not only did the savants at the French academy study the practical knowledge of water wheels (actually they did so quite sparingly), but Smeaton's tests of the theoretical predictions of the performance of water wheels disproved some theories and provided new quantitative data that could be used for a further improvement of the theory (Reynolds, 1983). Thus, the link became direct, applying predictions of one specific theory to practise helped to improve this very theory. We write the direct feedback loop as:

$$\Omega_{\Lambda\to\Omega}(t) = \Omega_{\Lambda\to\Omega}(t-1)^{\phi} \cdot \beta_1 \Lambda_{\Omega\to\Lambda}(t-1)^{1-\phi} \tag{24}$$

$$\Lambda_{\Omega\to\Lambda}(t) = \Lambda_{\Omega\to\Lambda}(t-1)^{\phi} \cdot \beta_2 \Omega_{\Lambda\to\Omega}(t-1)^{1-\phi} \tag{25}$$

This can easily be rewritten as a simple recursive process:

$$\Omega_{\Lambda\to\Omega}(t) = \beta_1 \Lambda_{\Omega\to\Lambda}(t-1) \tag{26}$$

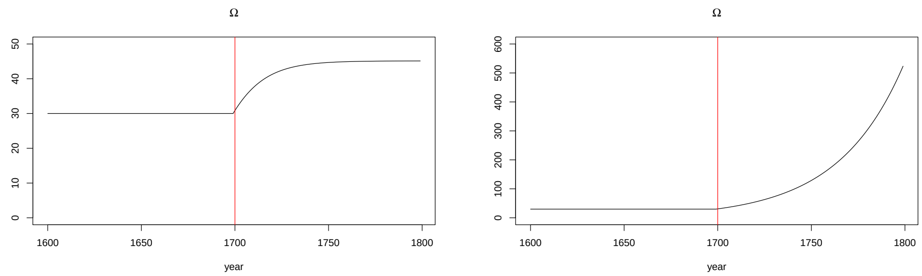
$$\Lambda_{\Omega\to\Lambda}(t) = \beta_2 \Omega_{\Lambda\to\Omega}(t-1) \tag{27}$$

This system yields exponential growth for $\beta > 1$. The steady-state of the growth rate of Ω is given by:

$$\delta\Omega^* = \beta^{1-\alpha} - 1 \tag{28}$$

Thus, growth in knowledge is increasing in β as well as in $1-\alpha$. Thus, if ideas that originate from a direct feedback loop (e.g. $\Omega_{\Lambda\to\Omega}(t) \to \Lambda_{\Omega\to\Lambda}(t) \to \Omega_{\Lambda\to\Omega}(t)$) are more valuable than the previous stock of ideas, then β is greater than 1 and knowledge in Ω is growing at a fixed rate. If the Ω and Δ are more deeply integrated, then the growth rate is further increased.

To illustrate the two different dynamics of a direct and indirect feedback loop, figure 37 simulates an exogenous shock where β is increased from 1 to 1.1 for a) an indirect feedback loop



(a) Indirect feedback loop (b) Direct feedback loop

FIGURE 37: Level of Ω with an exogenous increase of β

Notes: The plot shows the simulated values of Ω after exogenously increasing β within a indirect feedback loop system (equation 21 and 22) and a direct feedback loop system (equation 26 and 27). The system starts with an initial value of $\Omega_{\Omega\rightarrow\Omega}(t)$=30 and β=1 ($\beta_1 = \beta_2$). After 1700, β is exogenously increased to 1.1. The Cobb-Douglas parameters are specified as $\alpha = 0.7$, and $\phi = 0.9$.

and b) a direct feedback loop. The plots shows show the stock of knowledge in Ω as a function of the strength of β with a set of example parameters, $\Omega_{\Omega\rightarrow\Omega}(t)$=30, $\alpha = 0.7$, and $\phi = 0.9$. It can easily be seen that a stronger indirect feedback loop leads to a levelling up process, while a stronger direct feedback loop produces self-sustainable growth at a stable growth rate.

Section 3.4 will set up a micro-model to estimate the parameters β_{indirect} and β_{direct} between fields of propositional and fields of prescriptive knowledge. With this we can evaluate whether the fundamental structure of feedback loops between propositional and prescriptive knowledge changed during the seventeenth and eighteenth century. Furthermore, the estimated coefficients should indicate whether growth in knowledge production was already partly driven by a self-sustainable direct feedback mechanism.

B.4 Back of the envelope model calibration

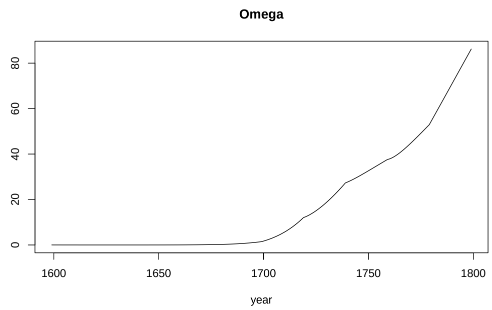
Lastly, to help with the interpretation of the previously estimated coefficients for β_{direct} and β_{indirect} between technical instructions in trades and applied physics, this section simulates how the estimated coefficients would affect a system of knowledge creation as modelled in section B.3. Appendix section B.4.1 presents the fully integrated model. Note that currently not all parameters in the model have been estimated, especially the rate of combination between the indirect and direct feedback loop, σ, is not yet empirically determined. Nonetheless, proceeding with a set of plausible parameters shows the dynamics that can be possible when using the estimated coefficients for β_{direct} and β_{indirect}.

Specifically, the model uses $\Omega_{\Omega \to \Omega} = 300$ and $\Lambda_{\Lambda \to \Lambda} = 300$,$\lambda = 1$, $\alpha = 0.7$ and $\sigma = 0.7$, capturing the strength of the indirect feedback loop in comparison to the direct feedback loop.

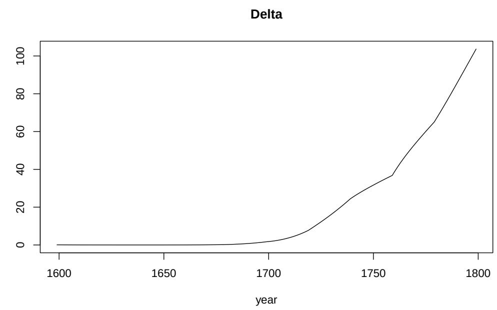
Figure 38 shows the simulated development of the stock of ideas in Ω, Δ as well as the development of the number of patents.

Comparing these simulations to the actual development of Ω and Δ in figure 26 as well as the development of patents in figure 39 shows that the simulated feedback loop system with the estimated values for β_{indirect} and β_{direct} does well in capturing the broad trends in knowledge and patent production. Leaving the bad equilibrium of isolated fields shifts knowledge production to a higher steady-state around 1700 with relatively slow growth. We then observe a "hockey-stick" type of structural break around 1760 where, for the first time, a self-sustained growth mechanism partially increased growth rates. Mapping the growth of technical instructions to the production of patents using the estimated coefficients from regressing similarity to patents on whether a title was shifted by applied physics similarity provides a similar picture. The feedback loop mechanism predicts a slow growth in patenting post 1700 that accelerates throughout the eighteenth century yielding a hockey-stick type of graph, similar to the predicted growth of technical instructions.

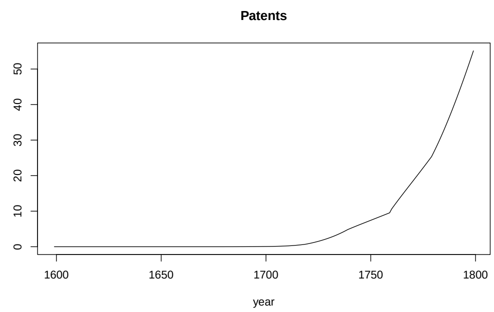
However, in interpreting the simulated coefficients, it should be stressed that much of this growth still comes from a transition towards the stable equilibrium of β_{indirect} and $\beta_{\text{direct}} = 1$. Only parts of the growth post 1760 come from a positive direct feedback loop where ideas



(a) Ω



(b) Δ



(c) Patents

FIGURE 38: Model simulation with calibrated values for β_{indirect} and β_{direct}

Notes: The figure calibrates the model from section B.3 with the estimated $\beta_{indirect_t}$ and β_{direct_t}. estimated in section 3.5.2. The red line shows the steady state of the model for all $\beta s = 1$.

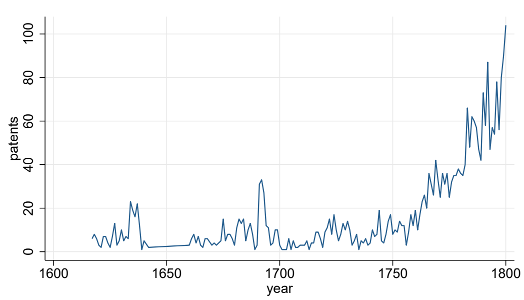


FIGURE 39: British patents over time

in technical publications are improved by influencing the field of applied physics and then being reintegrated into technical publications from applied physics. The fact that β_{direct} is still negative throughout most of the seventeenth to mid-eighteenth century shows that this was still a time period full of dead-ends and immature ideas. Hence, this part of the analysis supports the accounts questioning the usefulness of early science for technical innovations (Mathias, 1972; Hall, 1974; Ó Gráda, 2016). Much of the growth in the calibrated simulation originates from the transition from a steady-state with negative interactions between applied physics and technical instructions to a steady state of neutral interactions. Although we see the beginning of self-sustained growth through a direct feedback loop mechanism at the end of the eighteenth century, it appears that this is more powerful in foreshadowing the growth regime of the next decades to come rather than being representative for the main part of the seventeenth and eighteenth century. Yet, the centuries to come would be the most transformative moment in human history with regard to growth in useful knowledge and economic growth. Hence, finding evidence of a transition towards self-sustained growth is significant in itself.

B.4.1 Model with two-sided direct and indirect feedback loop processes

Production function of knowledge:

$$\Omega(t) = \Omega_{\Omega\to\Omega}(t)^{\alpha} \cdot \Omega_{\Lambda\to\Omega}(t)^{1-\alpha} \tag{29}$$

$$\Lambda(t) = \Lambda_{\Lambda\to\Lambda}(t)^{\alpha} \cdot \Lambda_{\Omega\to\Lambda}(t)^{1-\alpha} \tag{30}$$

Production of knowledge within its own epistemic set:

$$\Omega_{\Omega\to\Omega}(t) = \Omega_{\Omega\to\Omega}(t-1)^{\theta} \cdot \epsilon(t)^{1-\theta} \tag{31}$$

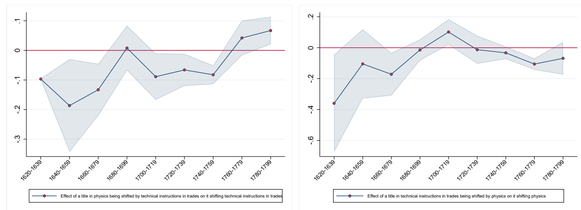
$$\Lambda_{\Lambda\to\Lambda}(t) = \Lambda_{\Lambda\to\Lambda}(t-1)^{\theta} \cdot \epsilon(t)^{1-\theta} \tag{32}$$

Spillover effects between fields:

$$\Omega_{\Lambda\to\Omega}(t) = \Omega_{\Lambda\to\Omega}(t-1)^{\phi} \cdot (\beta_{\text{indirect}_1}\Lambda(t-1)^{1-\phi})^{\sigma} \cdot (\beta_{\text{direct}_1}\Lambda_{\Omega\to\Lambda}(t-1))^{(1-\sigma)})^{1-\phi} \tag{33}$$

$$\Lambda_{\Omega\to\Lambda}(t) = \Lambda_{\Omega\to\Lambda}(t-1)^{\phi} \cdot (\beta_{\text{indirect}_2}\Omega(t-1)^{1-\phi})^{\sigma} \cdot (\beta_{\text{direct}_2}\Omega_{\Lambda\to\Omega}(t-1))^{1-\sigma})^{1-\phi} \tag{34}$$

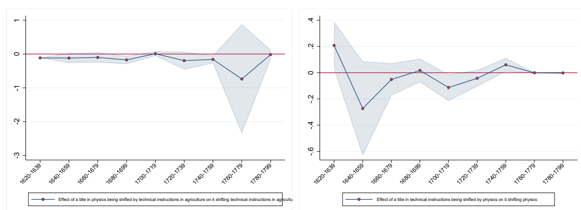
B.5 Spillover and feedback loop coefficients across all fields



(a) Feedback loop: Tech → physics → tech

(b) Feedback loop: Physics → tech → physics

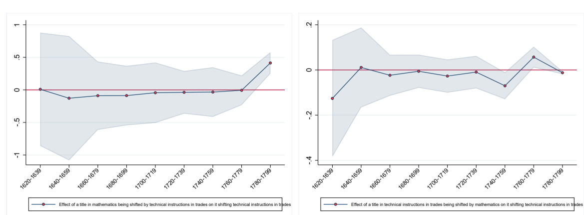
Figure 40: Feedback loop: Applied physics and technical instructions in trades



(a) Feedback loop: agriculture → physics → agriculture

(b) Feedback loop: Physics → agriculture → physics

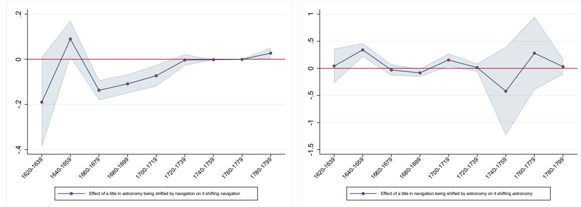
Figure 41: Feedback loop: Applied physics and technical instructions in agriculture



(a) Feedback loop: Tech → mathematics → tech

(b) Feedback loop: mathematics → tech → mathematics

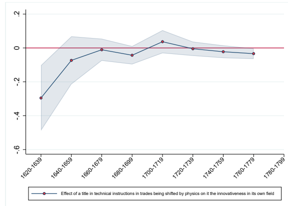
Figure 42: Feedback loop: Mathematics and technical instructions in tech



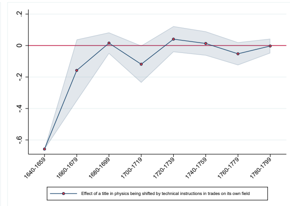
(a) Feedback loop: navigation → astronomy → navigation

(b) Feedback loop: astronomy → navigation → astronomy

FIGURE 43: Feedback loop: Astronomy and navigation

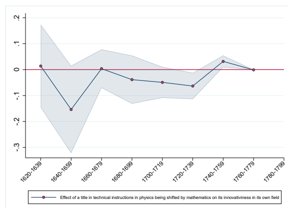


(a) Spillover: Physics → tech → tech

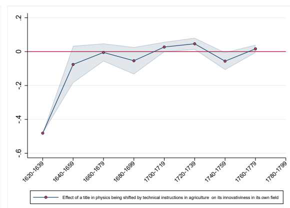


(b) Spillover: Tech → physics → physics

Figure 44: Spillover: Applied physics and technical instructions in trades

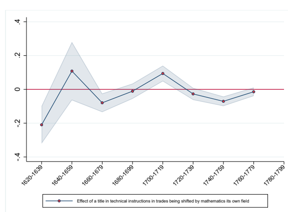


(a) Spillover: Physics → agriculture → agriculture

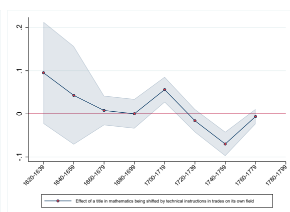


(b) Spillover: agriculture → physics → physics

Figure 45: Spillover: Applied physics and technical instructions in agriculture

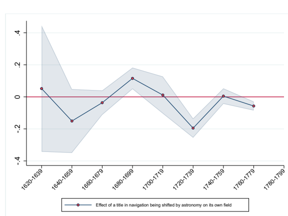


(a) Spillover: mathematics → tech → tech

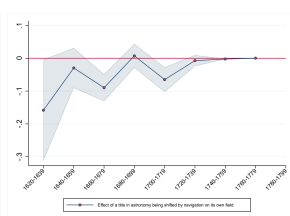


(b) Spillover: Tech → mathematics → mathematics

Figure 46: Spillover: Mathematics and technical instructions in tech



(a) Spillover: astronomy → navigation → navigation



(b) Spillover: navigation → astronomy → astronomy

Figure 47: Spillover: Astronomy and navigation

4 Attracting science: The impact of industrialisation on upper-tail human capital during the early English Industrial Revolution

Abstract

What was the effect of early industrialisation on the local presence of upper-tail human capital? Did it lead to a deskilling or upskilling of upper-tail of human capital? The literature often assumes that there is a positive feedback loop between industrialisation and the local presence of upper-tail human capital. However, while the effect of upper-tail human capital on industrialisation has been intensively studied, there is little quantitative work on the effect of industrialisation on upper-tail human capital. This paper provides first estimates of the effect of early coal-based industrialisation in Britain for the period of 1740–1840. Using a dataset on the location of birth and death of notable people and another dataset on the lifetime location of Royal Society members, the paper captures a broad spectrum of British upper-tail human capital. To capture the causal effect of early industrialisation, the paper exploits the activation of carboniferous strata following coal-extraction technological innovations in synthetic difference-in-differences approach. It finds that early coal-based industrialisation led to a higher presence of upper-tail human capital. The evidence is compatible with the presence of a positive feedback loop between industrialisation and upper-tail human capital.[65]

Keywords: Human Capital, Long-Run Growth, Economic History

JEL Classification: N33, N63, O33, O31, O14

[65] I would like to thank my supervisors Prof. Max-Stephan Schulze and Dr. Jeremiah Dittmar at LSE for their invaluable guidance and support. I would also like to thank the Royal Society for kindly sharing their data on their historical fellows with me. I also gratefully recognize PhD funding by the Economic Social and Research Council (ESRC), Doctoral Training Centre Studentship no. 201825826, that helped to make this paper possible.

4.1 Introduction

In studying the causes of the Industrial Revolution, the recent literature has highlighted the role of upper-tail human capital for facilitating innovations, productivity and growth (Mokyr, 2002, 2016; Squicciarini and Voigtländer, 2015; Hanlon, 2022). Yet, little quantitative evidence is available for how the Industrial Revolution shaped the formation and attraction of upper-tail human capital, especially scientific upper-tail human capital, itself. Did the Industrial Revolution lead to a deskilling or upskilling at the upper-tail of human capital? Did the Industrial Revolution open up labour market opportunities for people with highly specialized knowledge? Or did the early Industrial Revolution lead to a separation of the spheres of low-skill tinkering and business on the one hand and knowledge elites on the other hand?

This paper tests the effect of coal-based based industrialisation on the formation and attraction of upper-tail human during the English Industrial Revolution during the eighteenth and early nineteenth century. For this purpose, the paper introduces a systematic quantification of the presence and migration of knowledge elites in Britain during the eighteenth century. Thereby, the paper provides new results on the forces that shaped the distribution of upper-tail human capital. Upper-tail human capital has been widely cited as an important input for early industrialisation (Mokyr, 2002, 2016; Squicciarini and Voigtländer, 2015; Kelly, Mokyr and Ó Gráda, 2014, 2023; Hanlon, 2022; Cinnirella, Hornung and Koschnick, 2022). Hence, understanding the forces that shaped the formation and attraction of upper-tail human capital is important for our understanding of the Industrial Revolution.

This is also an important addition to the existing literature on upper-tail human capital that allows us to judge whether there existed a feedback loop between local industrialisation and the presence of upper-tail human capital. Based on the existing literature (Mokyr, 2002, 2016; Squicciarini and Voigtländer, 2015; Hanlon, 2022), we can easily imagine that upper-tail human capital contributed to industrialisation and that industrialisation contributed to the presence of upper-tail human capital, thereby instilling a virtuous feedback loop that helped to accelerate the onset of modern growth. However, it is not prima facie clear whether industrialisation would actually have increased the presence of upper-tail human capital. One could assume that the negative externalities of the Industrial Revolution (e.g. smoke, precarisation of the working classes, slum like structures in cities, and social unrest) could have led to local deskilling at the upper-tail of human capital, thereby inhibiting the development of newly industrialising regions.

The hypothesis of a feedback loop between local industrialisation and local upper-tail human capital is usually stated in the form of a feedback loop between industrialisation and access to knowledge. It is argued that access to knowledge fuelled local industrialisation (see e.g. Mokyr, 2002; Dowey, 2017; Curtis and de la Croix, 2023), while industrial growth increased local access to knowledge. Since, in an age before public libraries and relatively expensive book production, personal contact was the foremost means of accessing knowledge, the presence of upper-tail human capital was closely linked to access to knowledge. At the aggregate level such a feedback loop is a usual feature of most endogenous growth models (Romer, 1986, 1990; Galor and Tsiddon, 1997). This paper moves beyond the aggregate level and tests whether local industrialisation affected local levels of upper-tail human capital as an important factor for accessing knowledge.

To quantify the presence of upper-tail human capital, the paper uses two different datasets on the location of British knowledge elites, one for general upper-tail human capital, and one for specifically scientific upper-tail human capital. First, to proxy general upper-tail human capital, it uses the database of notable people from Laouenan et al. (2022) including notable people in England for the paper's time-frame between 1600 and 1840. Second, to proxy scientific upper-tail human capital, the paper introduces a novel dataset on the lifetime locations of the fellows of the Royal Society, Britain's most prestigious and (up to the 1760s only) scientific society. The dataset is based on the short biographies of Royal Society members from the *Raymond and Beverly Sackler archive resource project* (Nixon, 1999) that was kindly shared by the Royal Society with the author. By further drawing on entries in national dictionaries of biographies and the election certificates of Royal Society members, the paper is able to reconstruct the lifetime locations of Royal Society members between the foundation of the Royal Society in 1660 and 1800. Additionally, for both notable people and Royal Society members the paper adds information on people's occupation at all of their lifetime places.

The paper then tests the effect of local industrialisation on the formation and attraction of upper-tail human capital. The econometric challenge in this setup is to separate the effect of industrialisation on the presence of upper-tail human capital on the one hand and the effect of upper-tail human capital on industrialisation on the other hand. To address this challenge, the paper exploits exogenous variation from the exploitation of coal reserves that provided cheap energy for early industrialisation. Concretely, it uses the presence of carboniferous strata to avoid endogeneity from location choice of coal-mines. Carboniferous strata was formed 360 to 60 million years ago and would only have become economically important with the arrival of the steam engine that was able to exploit new reserves and turn coal into industrial energy. The use of carboniferous strata as an an exogenous predictor for coal pits was pioneered by Fernihough and O'Rourke (2021). Based on exposure to carboniferous strata as an exogenous shock, Fernihough and O'Rourke (2021) show that modern European city size was significantly determined by proximity to coal.

However for the case of Britain, the presence of carboniferous strata correlates with the core-periphery structure of British regions. We might reasonably expect that regions in the periphery had different historical trends in the local presence of upper-tail human capital elites compared to the core. To avoid bias from the location of carboniferous strata within Britain's core-periphery structure, the paper uses a synthetic difference-in-differences approach (Arkhangelsky et al., 2021). Treatment comes from the exploitation of coal as a cheap source of energy once new mining technologies became available, within the period of 1740–1760. The synthetic difference-in-differences model uses areas without carboniferous strata as a control group that are individually weighted according to their prior trends in the presence of upper-tail human capital. This way, the study compares treated and untreated units that are plausibly similar with regards to upper-tail human capital.

The paper finds that the coal-activation shock led to a significant increase in the local presence of upper-tail human capital, a 6.8% increase of Royal Society members and a 19.1% increase in notable people. Hence overall, coal-based industrialisation had a stronger effect on the presence of general upper-tail human capital than for scientific upper-tail human capital. The paper further estimates the differential effects on coal-based industrialisation on the formation of upper-tail human capital and the attraction of upper-tail human capital through migration. The results show that coal-based industrialisation had a large impact on the local formation of upper-tail human capital, however it also increased the rates of out-migration. Yet overall, the net effect of the formation of upper-tail human capital and net-migration still is positive. Hence, industrialisation increased the presence of both scientific and general upper-tail human capital.

If we assume that the local presence of upper-tail human capital also increased access to knowledge, then we find evidence compatible with the presence of a feedback loop mechanism between industrialisation and access to knowledge. Specifically, the paper shows causal evidence that coal-based industrialisation in Britain between 1740–1840 increased the stock of upper-tail human capital, thereby increasing the stock of highly skilled people and potential access to human capital.

To evaluate the usefulness of this higher-stock of upper-tail human capital for industrialisation, the paper conducts a heterogeneity analysis of the effect across different occupational categories. The paper finds that for broad upper-tail human capital as proxied by notable people from Laouenan et al. (2022), coal-based industrialisation had a positive and significant effect all occupational categories of the *nobility, clergy, merchants and factory owners, teachers, medical professionals, public office, technical specialists, craftsmen, independents, and artists*. The effect was strongest for public office, artists, and technical specialists. However, for scientific upper-tail human capital, as proxied through Royal Society members, the paper only finds a positive and significant effect of coal-based industrialisation on the occupational category of merchants and factory owner.

Hence, it appears that at least for scientific upper-tail human capital, coal-based industrialisation might not have increased the broad stock of scientific upper-tail human capital, but only seems to have worked through one particular group, merchants and factory owners. This means that access to scientific knowledge through most occupational groups remained constant for early industrialising areas. However, as argued by Jacob (2014) and Stewart (2007), the group of scientific merchants and manufacturers played an important role in creating a bridge between commercial interest and the specialists working with new complex technology on the shop-floor.

Overall, the paper shows that early industrialisation increased the local presence of upper-tail human capital. It finds a larger effect for general upper-tail human capital, as proxied through notable people, and a smaller effect for scientific upper-tail human capital, as proxied through Royal Society members. Furthermore, the effect of early industrialisation on scientific upper-tail human capital seems only to have worked through the group of merchants and manufacturers. Yet, given the importance of this group, even the smaller estimated effects, could have been potentially game changing for local industries on the ground.

Furthermore, these results allows us to judge whether there existed a feedback loop between local industrialisation and local access to knowledge during the early English Industrial Revolution. Before, the literature had primarily focused on the effect of upper-tail human capital and access to knowledge on growth (Squicciarini and Voigtländer, 2015; Dowey, 2017; Hanlon, 2022) and hence only on one side of the feedback loop between industrialisation and access to knowledge (the right hand side of the feedback loop). This paper investigates the other side of the feedback loop, the effect of industrialisation on local access to knowledge, as captured through upper-tail human capital. Given the positive effects found both in this paper for the left-hand side of the feedback loop and in the literature for the right-hand side of the feedback, it appears likely that the English Industrial Revolution was accelerated by a positive feedback loop between industrialisation and local access to knowledge.

The paper contributes to a wide literature on the dynamics of upper-tail human capital and growth. Most growth theories include a feedback loop between access to ideas and economic growth as part of their dynamics (Romer, 1986, 1990). As argued before, upper-tail human capital was an important facilitator access to knowledge. Furthermore, models from unified growth theory (Galor, Moav and Vollrath, 2009; Galor, 2011) imply that technical change led to an increased valuation of human capital. However, these studies do not distinguish between broad human capital and the scientific elites at the extreme upper-tail of the human capital distribution. An exception is Hanlon (2022) who integrates the arrival of the engineer as a new occupational group into an endogenous growth model. In this framework, the arrival of the new occupation of the engineer acts as the key driver towards an economy's transition towards modern economic growth. The paper contributes to this growth literature by producing first empirical evidence on the effect of industrialisation on the formation and attraction of upper-tail human capital.

Additionally, the paper contributes to the literature on the elasticity of the supply of human capital as a response to the Industrial Revolution. Previous studies have mainly investigated human capital at a lower level than scientific upper-tail human capital. Here, Feldman and van der Beek (2016), Franck and Galor (2021), and De Pleijt, Nuvolari and Weisdorf (2020) have found evidence on the elastic response of apprenticeships, craftsmen, and literacy to industrialisation during the late eighteenth and early nineteenth century. Such evidence of a sufficiently elastic supply in the training and mobility of highly skilled craftsmen seems plausible given new research on apprenticeship markets that show that apprenticeship markets were open and relatively efficient (Zeev, Mokyr and van der Beek, 2017; Leunig, Minns and Wallis, 2011). Furthermore, Feldman and van der Beek (2016) analyse the aggregate dynamics between technical change and the elasticity of supply in the apprenticeship of craftsmen in a VAR setting. They find that apprenticeship rates reacted elastically to the number of inventions used as a proxy of technical change. This paper extends this literature, by investigating the effect of industrialisation on British knowledge elites that constituted the extreme upper-tail of human capital. In contrast, to human capital at the level of craftsmen, educated knowledge elites were key actors in the diffusion of formalized knowledge (Mokyr, 2002; Curtis and de la Croix, 2023).

4.2 Data

4.2.1 Proxies for upper-tail human capital

In order to capture the presence and mobility of English upper-tail human capital, the paper draws on two different subsets of important people with upper-tail human capital. First, it uses the cross-verified database of notable individuals from Laouenan et al. (2022). Following a broad literature in economic history, (De la Croix and Licandro, 2015; Cabello and Rojas, 2016;

Dittmar and Meisenzahl, 2020; Becker, Pino and Vidal-Robert, 2021; Cinnirella, Hornung and Koschnick, 2022) this paper assumes that being included in works of notable people broadly correlates with outstanding skills and proxies the upper-tail distribution of human capital. Second, it uses the fellows of the Royal Society as a proxy for specifically scientific upper-tail human capital. The Royal Society was Britain's leading scientific society and being elected as a fellow required a good knowledge about the new sciences and a practical involvement in the scientific discussions of the day (see section C.4.4 for a discussion of the entry requirements into the Royal Society). We find almost all great scientists of the seventeenth and eighteenth century like Isaac Newton, Robert Boyle, Robert Hooke, or Joseph Priestley within the ranks of the Royal Society. Hence, the fellows of the Royal Society are used to capture the subset of upper-tail human capital with scientific knowledge. Comparing these two different layers of upper-tail human capital allows a deeper understanding of which skills were valued during the early Industrial Revolution.

First, capturing general upper-tail human capital, Laouenan et al. (2022), have collected all 3,578 notable individuals with a Wikipedia article between 1600 and 1800 in Britain for whom both the place of birth and death is known.[66] This measure of notable people captures the extreme end of the upper-tail human capital distribution. It is narrower than e.g. the 7,081 subscribers to the Encyclopédie from Squicciarini and Voigtländer (2015). However, it has the advantage of including a rich set of information on the individuals, including places and dates of birth, death, and occupation.

Second, this paper uses the list of the fellows of the Royal Society from Nixon (1999), kindly shared with the author by the Royal Society, as a proxy for the British scientific elite. The paper then matches the fellows of the Royal Society with biographical material based on the Royal Society's Raymond and Beverly Sackler archive resource project (Nixon, 1999), the *Oxford Dictionary of National Biography* and the *Dictionary of Scientific Biography* and added all available places of lifetime activity through a manual coding of these biographical sources (see appendix section C.4.2). Overall, there are 3,051 fellows born in or before 1785 with 9,079

[66] Laouenan et al. (2022) create their dataset by matching and cross-verifying Wikipedia and Wikidata articles across different languages to create a comprehensive measure of historical notable people across time and space. Their full dataset includes 2.29 million individuals from 3500BC to 2018AD.

individual places of lifetime activity. This offers a unique dataset on the universe of lifetime activity for the fellows of the Royal Society. Having the universe of lifetime activities allows for estimating migration flows at the actual year of migration. It further allows for identifying the actual place of occupation during an individuals most active years. With this, the papers offers a dataset of completely lifetime activities that goes beyond available databases of notable including only places of birth and death (see e.g. Laouenan et al., 2022; Bayerische Akademie der Wissenschaften, 2022). Using all lifetime places offers more precise estimate, reduces general bias from lifecycle effects, and allows for estimating sequential migration models.

A challenge in the use of the concept of upper-tail human capital is the need to understand which societal and occupational groups are driving the effect. Existing coding schemes like HISCO are usually not suitable to classify high-status and high-education groups. Hence, this paper develops a new occupational coding scheme suited for classifying the different occupational groups within groups of European upper-tail human capital and classifying both the cross-verified database of notable individuals from (Laouenan et al., 2022) and the lifetime event database of the fellows of the Royal Society according to this scheme. This coding scheme offers three advantages: a) In contrast to e.g. HISCO it takes account of the tripartite structure of the European elite with a nobility, clergy, and commoners. b) It differentiates its main groups across different technical/practical capabilities (e.g. practitioners in medicine, early technical specialists, or craftsmen) that capture the differences in education, knowledge, and method between e.g. a millwright and an academy trained army engineer (even if both were building a dam). c) It offers a second level of high-granularity occupations that can be used for tracing individual groups and occupations for case studies and prosopographical research. It is hoped that this coding scheme will be useful for other researchers on European upper-tail human capital and that it will be expanded by others. The occupational categories and the rules for applying the coding schemes to the notable people database from (Laouenan et al., 2022) and the fellows of the Royal Society are described in appendix C.4.1.

Distinguishing between different occupational groups is especially important for the study of the British scientific elite. Throughout the seventeenth and eighteenth century, the British scientific elite mostly practised their scientific studies as a side activity. Indeed, becoming a scientist by occupation would only truly become possible in the nineteenth century.[67] Thus, even people like John Harris or John Theophilus Desaguliers who were primarily interested in scientific studies and earned significant amount of money as public lecturers of the new mechanical science hedged their careers by still pursuing a career in the Church (see Stewart, 1992, pp. 108–141). Others like Erasmus Darwin were practising physicians who integrated the scientific spirit into their professional lives, but also spent much time on their private research pursuits. The only truly scientific occupation were the academics, university professors, librarians or paid astronomers at observatories.[68] However, looking at figure 49 and 50, we see that the academics never made up more than 20% of all members of the Royal Society and less than 10% of all notable people. Hence, it is important to take account of the professionally heteregenous composition of Britain's scientific elite to understand its heterogenous responses to the new opportunities of resource based industrialization.

[67]The term "scientist" itself was coined by Cambridge philosopher William Whewell at a meeting of the British Association for the Advancement of Science in 1833 (Janiak, 2019; Snyder, 2011).

[68]Although one should add that within the seventeenth and eighteenth century most university professors or fellows understood themselves foremost as teachers and not researchers.

4.3 Empirical analysis

4.3.1 Descriptive patterns

(a) Areas without carboniferous strata

(b) Areas with carboniferous strata and lifetime location of Royal Society members, 1600–1800

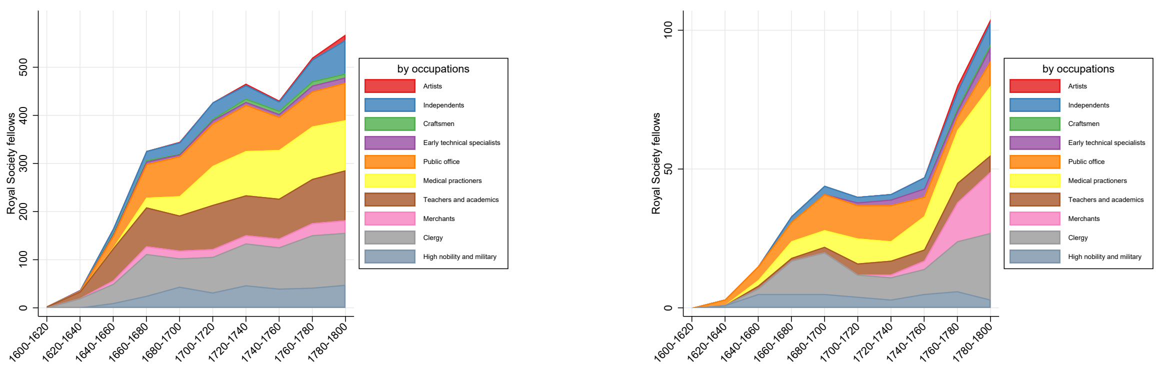
(c) Areas with carboniferous strata and places of death for notable people, 1600–1840

FIGURE 48: Carboniferous strata and upper-tail human capital in England

Based on the location of Royal Society members and notable people as a proxy for scientific and general upper-tail human capital, this section develops a framework to estimate the forces that determined the presence of these groups of upper-tail human capital. The section starts by presenting a set of descriptive statistics that tracks the development of upper-tail human capital in regions with and without the presence of carboniferous strata.

Following the works of Fernihough and O'Rourke (2021) carboniferous strata is taken as an exogenous shock that drove early coal-based industrialisation. Figure 48 plots the geographical distribution of carboniferous strata within England and Wales. It further maps the distribution of the presence of Royal Society members, 1600–1800, and notable people, 1600–1840. It can be seen that, by chance, carboniferous strata clusters in regions that are distant to London. The density of the local presence of Royal Society members and notable people further reflects the core-periphery structure of Britain, with upper-tail human capital clustering a) around London and b) in the rich South with fertile grounds.

Yet, the levels of local upper-tail human capital are fairly uninformative in evaluating the effects of coal-based industrialisation. Hence, figures 49 and 50 plot the development of the presence of upper-tail human capital over time splitting the sample into areas with and without carboniferous strata. As a first pattern, we see that the number of people in places without carboniferous strata seems to have been continuously rising, while total membership in places with carboniferous strata stayed flat until ca. the 1750s when fellow numbers started to double. Going into occupations, it appears that the jump in places with carboniferous strata is mainly explained by an increase in the clergy, merchants, teachers, and medical practitioners. Within these groups, the group of merchants (that is, merchants, factory or manufacture owners etc.) stand out as they start from zero in 1740 to about 20 in 1770. In contrast, the number of merchants in areas without carboniferous strata remained relatively constant between 1660 and 1800. These results map well with the historical literature on the Industrial Revolution that has stressed the role of scientifically minded entrepreneurs during the early Industrial Revolution (Schofield, 1957, 1963; Musson and Robinson, 1969; Jacob, 1997, 2014; Stewart, 2007). Yet, the parallel rise of the numbers of the clergy, teachers, and medical practitioners points towards a deeper shift in the presence of scientific upper-tail human capital.

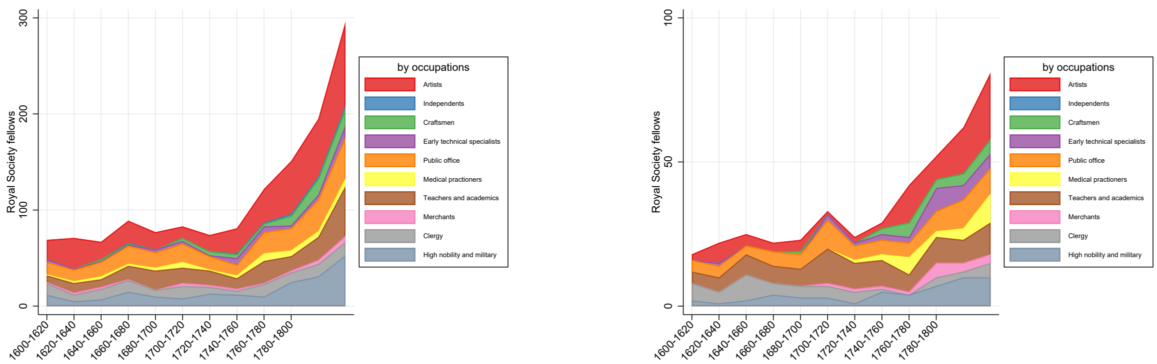


(a) Areas without carboniferous strata

(b) Areas with carboniferous strata

FIGURE 49: Occupations of Royal Society members by presence of carboniferous strata

Yet, we should be careful not draw causal conclusion from these basic patterns. Areas with and without carboniferous strata also differ by population, population size, and capital endowments. Therefore, the next section will conduct a synthetic difference-in-differences strategy to account for different pre-treatment trends of different regions. The treatment for the difference-in-differences approach is the exploitation of coal reserves through new technology. One of the key inventions that made the large-scale exploitation of coal reserves feasible



(a) Areas without carboniferous strata

(b) Areas with carboniferous strata

FIGURE 50: Occupations of notable people from by presence of carboniferous strata

was the steam engine (along with other techniques in mining). The paper assumes that the exploitation of coal reserves became economically feasible within the period of 1740–1760. This is a conservative choice covering different periodisations of the Industrial Revolution within the literature.

A more precise indicator for the shifting of the technology frontier for exploiting coal reserves is the number of new steam engines and the number of newly available horse power from steam engines between 1720 and 1800, shown in appendix figure 54 (Kanefsky and Robey, 1980; Bogart et al., 2017*b*). It can be seen that the number of new engines started to grow at the middle of the century, approximately after 1740. Yet, only the early 1770s mark the beginning of exponential growth in the number of steam engines. In contrast to the number of engines, the development of all available horse power is most of all shaped by the arrival of the Boulton & Watts engine by the end of the 1770s. However, looking at estimates of total coal output from Pollard (1980) in appendix figure 55 shows that coal output was already on a stable growth path post 1750 (estimates are not available for earlier periods). Therefore, it appears that using the end of the 1770s would miss much of the earlier industrial coal exploitation. Instead, the paper chooses the period 1740–1760 as the beginning of the industrial exploitation of coal as a conservative choice.

The next section will estimate a synthetic difference-in-differences model (Arkhangelsky et al., 2021) to estimate the causal impact of coal-based industrialisation on the local presence of upper-tail human capital.

4.3.2 Empirical Framework

This section estimates the effect of the activation of coal resources on the local presence of upper-tail human capital. This approach exploits the exogenous distribution of carboniferous strata with respect to supply and demand side factors. Yet, the presence of carboniferous strata correlates with the general pre-industrial structure of Britain: Stylistically, we can imagine a wealthy agricultural South and a poor North specializing in the secondary sector (see Kelly, Mokyr and Ó Gráda, 2023). By geographical accident, the North is also endowed with a great amount of coal reserves. If we assume that the presence of upper-tail human capital within such a two-sector economy developed differently over time, classical estimation approaches like difference-in-differences designs are likely to be biased due to violations of the parallel trend-assumption — note the different pre-trends between coal and non-coal areas in figure 49 and 50.

However, the presence of carboniferous strata does not perfectly overlap with the stylized two-sector economy of Britain. This paper's identification strategy rests on comparing areas with carboniferous strata with areas without coal reserves that are similar to the areas with coal reserves. This strategy could be implemented through either a) matching on relevant hundreds-characteristics (e.g. such as population size, sectoral composition, etc.) or b) through a synthetic approach that matches on similar trends on the outcome (the presence of upper-tail human capital). Since, historical data on hundreds characteristics prior to the 1801 census are imperfect, this paper instead chooses a synthetic difference-in-differences approach (Arkhangelsky et al., 2021) that matches on prior trends for the outcome.

This setup is ideal for a synthetic difference-in-differences approach since it involves an exogenous treatment shock that, due to spatial correlation, is unequally distributed with respect to centres of economic activity and hence units' pre-trends. Furthermore, in this setting unit outcomes, both post- and pre-treatment, are observed over multiple time period. Hence, it becomes possible to construct a synthetic control group that is a) similar in terms of pre-trends to the treated group and b) not affected by selection into treatment, a common issue in many synthetic control studies (carboniferous strata was geographically determined millions of years ago).

Arkhangelsky et al. (2021) show that the synthetic difference-in-differences estimator is doubly robust and reduces the bias of both, synthetic controls and differences-in-differences approaches. The synthetic difference-in-differences estimator solves the following minimization problem, combining a two-way fixed effects difference-in-differences (TWFE) design with the weights from a synthetic control (SC) approach (see Arkhangelsky et al., 2021; Clarke et al., 2023):

$$(\hat{\tau}^{sdid}, \hat{\mu}, \hat{\alpha}, \hat{\beta}) = \underset{\tau,\mu,\alpha,\beta}{argmin}\left\{ \sum_{n=1}^{N} \sum_{t=1}^{T} \left(Y_{it} - (\mu + \alpha_i + \beta_t + C_{it}\tau\right)^2 \hat{w}_i^{sdid} \hat{\lambda}_t^{sdid} \right\} \tag{35}$$

in our case, Y_{it} is the local presence of upper-tail human capital in hundred i at time t. Upper-tail human capital is either proxied through the location of the lifetime movements of Royal Society members or through the places of birth and death of notable people from Laouenan et al. (2022). To account for overdispersion in the count of both Royal Society members and notable people, the dependent variable is being transformed using the inverse hyperbolic sine transformation. The hyperbolic sine transformation is a close approximation for the logarithmic transformation, with the advantage that it is defined at zero and can be interpreted as an elasticity similar to the log-transformation (Bellemare and Wichman, 2020). C_{it} captures the treatment variable, the presence of carboniferous strata post 1760. α_i and β_t are county and time fixed effects. $\hat{w}_i^{sdid}$ and $\hat{\lambda}_t^{sdid}$ denote unit and time weights needed to create the synthetic control across both units and time.

In the model, we exclude the greater area of London, based on the assumption that the economy of London was structurally different form the rest of the country. Results are robust to including the greater area of London (see appendix figure 56 and table 48).

4.3.3 Main Results

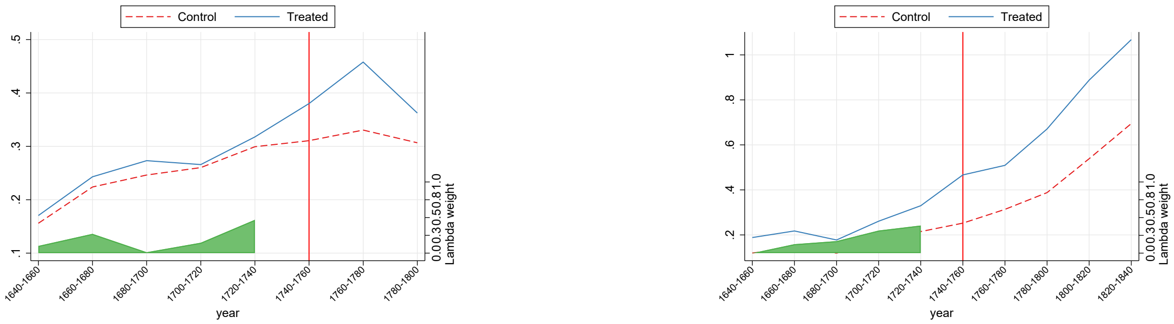
Figure 51 shows the main results from the synthetic difference-in-differences model from equation 35. It shows the the average trend of the treated group, the number of knowledge elites in areas with carboniferous strata, and the re-weighted trend of the control group, the number of knowledge elites in areas without carboniferous strata. Through re-weighting both the unit weights and time weights for the control groups, the SDID estimator creates a synthetic control group with similar pre-trends as the treated group. The post-trends are shown for the period of 1740–1800 when carboniferous strata got activated. We see, that the treatment shock increased both the number of Royal Society members and notable people relative to the control group.

To evaluate the synthetic control group, figure 52 plots the geographical weights assigned by the SDID estimator. We see that weights are relative even distributed. For Royal Society members the highest weight of a single hundred is 0.002 and for notable people the highest weight of a single hundred is 0.0015. Hence, we can be sure that the synthetic control group is not overly reliant on a few single observations that might have special characteristics.[69] We further see that highly weighted hundreds are not selected from areas that are close to the treatment border. Instead we see, that at least for Royal Society members, the area around London receives very small weights, reflecting the fact that London and the rest of the country were on different pre-trends in terms of the formation and attraction of upper-tail human.

Next, table 42 reports the estimated coefficients from equation 35. We find that being treated by the activation of carboniferous strata post 1740 led to an average treatment effect of a 6.8% increase in local Royal Society members and a 19.1% increase in local notable people. The effect is sizeable and shows that early coal-driven industrialization increased the local stock of upper-tail human capital. This is a relevant finding for evaluating the presence of a feedback loop between access to scientific and technical knowledge and industrial growth. While there is a broad literature that has investigated the first part of the feedback loop that runs from access to science to industrial growth, these findings are strong evidence that the second part

[69] As argued in Arkhangelsky et al. (2021), SDID weights are less sparse than in SD settings.

of the feedback loop, industrialisation leading to increased access to knowledge, was already strongly in place during the early British Industrial Revolution.



(a) Royal Society members

(b) Notable people

FIGURE 51: SDID trends for carboniferous strata treatment post 1740

Notes: Figure shows trends in a synthetic difference-in-differences design (SDID) (Arkhangelsky et al., 2021) of equation 35 for the treatment of activated carboniferous strata post 1760. The figure shows the re-weighted trend of the unexposed control units and the trend of the treatment units. The green area shows the time-specific weights (lambda).

(a) Royal Society members

(b) Notable people

FIGURE 52: Estimation weights by hundreds

Notes: Figure shows weights from the synthetic difference-in-differences estimation (SDID) (Arkhangelsky et al., 2021) of equation 35. White colours indicate the treatment group. Yellow colours denote weights close to one. For the Royal Society weights, red colours denote weights of up to 0.002. The hundreds with the highest values are Norwich and Whitley. For notable people weights, red colours denote weights of up to 0.0015. Note that since London is excluded from the model, weights are not calculated for London.

Table 42: Synthetic difference-in-differences estimate for carbon activation shock post 1740

	Presence of upper-tail human capital	
	(1)	(2)
	R.S. members	Notable people
Carbon activation post 1740	0.0678**	0.191***
	(0.0332)	(0.0346)
Year fixed effects	Yes	Yes
Hundred fixed effects	Yes	Yes
Observations	8608	10760

Notes: The table shows results from estimating equation 35 in a synthetic difference-in-differences design (SDID) model (Arkhangelsky et al., 2021). Jackknife standard errors in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

It is further notable that the effect is larger for notable people. One possible explanation for the different effect sizes between notable people and Royal Society members could be to the longer coverage of notable people, 1640–1840 in contrast to 1640–1800 for Royal Society members. However, figure 51 shows that the treatment effect for notable people stayed constant over time. Hence, it seems likely that coal-based industrialization led to a much wider demand for general upper-tail human capital than scientific upper-tail human capital specifically.

Next, we want to understand whether the increase in the stock of local upper-tail human capital was driven by a) the local formation of upper-tail human capital or b) migration driven by local demand for upper-tail human. Table 43 shows the SDID results for places of birth, places of birth, and the net difference between places of birth and death showing the net effect of in and out-migration. Perhaps surprisingly, we find that coal-based industrialization led to negative net migration numbers for both Royal Society members and notable people. Being exposed to coal-based industrialization made people with upper-tail human capital more likely to move outside of coal-industrializing areas.

In detail, only estimating the local stock of Royal Society members at their place of birth and their time of death in column 2 and 3 of table 43, does not yield significant results. Yet, we find a negative and significant net migration effect where being treated by the activation of carboniferious strata leads to a -4.8% decrease in net migration numbers of Royal Society members. For notable people, we find a positive and significant effect of the coal-activation shock on places of birth in column 4. Being treated by the activation of carboniferous strata post 1740 leads to an increase in the number notable people being born locally by 12.6%. We also find a positive effect for notable people's places of death, albeit a smaller one. Being treated by the activation of carboniferous strata post 1740 leads to an increase in the stock of notable people who died at a local place by 5.8%. Although the effect is still net-positive, it is clear that the difference in the effect of on people being born locally and dying locally can only be explained by out-migration. Estimating the effect on net migration in column 6, we find that being treated by the activation of carboniferous strata post 1740 leads to a decrease of net migration numbers by 17%.

TABLE 43: Mechanism: Places of birth, places of death, and net-migration for both Royal Society members and notable people

	Royal Society members			Notable people		
	(1)	(2)	(3)	(4)	(5)	(6)
	Place of birth	Place of death	Net migration	Place of birth	Place of death	Net migration
Carbon activation post 1740	0.0332	0.000204	-0.0482*	0.126***	0.0579***	-0.170***
	(0.0235)	(0.0166)	(0.0288)	(0.0296)	(0.0181)	(0.0372)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Hundred fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8608	8608	8608	10760	10760	10760

Notes: The table shows results from estimating equation 35 in a synthetic difference-in-differences design (SDID) model (Arkhangelsky et al., 2021). Jackknife standard errors in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 44: Mechanism: In-migration, out-migration, and net-migration for Royal Society members

	Royal Society members		
	(1)	(2)	(3)
	In-migration	Out-migration	Net migration
Carbon activation post 1740	0.0401	0.0667**	-0.0477*
	(0.0287)	(0.0316)	(0.0288)
Year fixed effects	Yes	Yes	Yes
Hundred fixed effects	Yes	Yes	Yes
Observations	8608	8608	8608

Notes: The table shows results from estimating equation 35 in a synthetic difference-in-differences design (SDID) model (Arkhangelsky et al., 2021). Jackknife standard errors in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

In interpreting these effects we should be cautious whether the net difference between places of death and places of birth is a good measure of net migration. Especially places of birth might be biased towards late-life choices of living. Thus, the measure might be biased towards the places of senior positions or places of retirement. While we lack information on lifetime places for notable people form Laouenan et al. (2022), this paper introduces a dataset on the full lifetime mobility of Royal Society members. Table 44 uses this information to estimate the effect of the activation of carboniferous strata post 1740 on the full numbers of in-migration and out-migration in column 1 and 2. Column 3 further adds an estimate for net migration calculated from all migrations movements. The 43, the results show that carboniferous strata had a positive and significant effect on out-migration. In contrast, the coefficient for in-migration is insignificant and notably smaller than the one for out-migration. Given that out-migration was larger than in-migration, we would expect net migration to be negative. Indeed, column 3 shows that the activation of carboniferous strata post 1740 led to a local decrease of net migration numbers by 4.8%. The effect size is almost exactly of the same magnitude as the one found in table 43. Hence, it appears that at least for Royal Society members, the difference between places of death and places of birth seems to be a relatively good proxy of migration numbers. Given the similarity of the construction of the

Royal Society and notable people measure, the paper also assumes that the difference between places of death and places of birth of notable people is a good proxy for net migration as well.

Overall, these results show that coal-based industrialisation increased the *formation* of upper-tail human capital, but also led to higher rates of out-migration. How can we explain that coal-based industrialization led to migration out of the industrializing centres? First, we can note that since the greater area of London is excluded in these specifications, these effects are not purely driven by a London- or capital-effect. However, the data used in this analysis does include little information on individual's incentives. Instead the paper draws on three case studies of famous inventors during the Industrial Revolution, Joseph Priestley, James Watt, and Charles Hutton to give an exemplaric overview over the incentives to move facing people with high upper-tail human capital. The case studies are described in appendix section C.1. Overall, we find evidence of migration due to incentives from a) accessing special knowledge, b) forming own business ventures, c) family ties, d) location-specific job opportunities. Especially for the latter point, location-specific job opportunities, it appears that many of the best renumerated jobs were still often located in the South of England. Furthermore, many of these jobs also came with high social capital and might have been important stepping stone for rising within British eighteenth century society.

Yet, we should note that despite significant out-migration, the net effects for the presence of Royal Society members and notable people as estimated in figure 51 and table 42 are still positive. In the treated areas, formation of upper-tail human increased faster than the out-migration of upper-tail human capital. Hence, despite the negative forces of out-migration, coal-based industrialisation led to an increase in access to knowledge through the presence of upper-tail human capital. Hence, if we assume that upper-tail human capital facilitated access to knowledge, we also find that these regions had an increased access to knowledge. To further understand which kind of knowledge could be accessed, the rest of the section conducts a heterogeneity analysis of the treatment effect by different occupational groups of upper-tail human capital.

4.3.4 SDID results by occupation

To estimate the heterogeneous effects of the activation of carboniferous strata post 1740 on occupations, we estimate the model in equation 35 separately for each of the 10 broad occupational categories listed in appendix table 49. Results are presented in table 45. Crucially, we find that for Royal Society members only one occupational group, merchants, is significantly increased by the treatment shock. If we interpret Royal Society members a proxy for the British scientific elite, we see that neither scientifically adapt academics or medical doctors were attracted to the industrialising regions. Note that the coefficient for the group of technical specialists should be judged with caution, given the low numbers within this group for Royal Society members, see figure 49. In contrast, for notable people, we find that the treatment shock caused a significant increase throughout all occupational groups of notable people. Within these groups, the effect is largest for public office, artists, and technical specialists.

The results for notable people seem to indicate that coal-based industrialisation created ample room for careers in all occupations for people at the upper-tail of human capital. For example, industrial growth and wealth seem to have created a strong demand for famous medical doctors, teachers, and artists. Moreover, we can imagine that merchants and manufacturers would have directly profited from coal-based enterprises. Likewise, technical craftsmen and technical specialists are likely to have been employed in the new coal-based enterprises. Lastly, the high rise in public office occupations seems to reflect the new political influence that came along with coal-based industrialisation. Yet, this demand e.g. for famous medical doctors does not seem to have translated itself into demand for doctors with a specifically pronounced scientific background (as proxied through Royal Society members). Furthermore, the occupational groups within Royal Society members that would have been most important for transmitting new scientific knowledge, academics and the clergy, seem not to have have been positively influenced.

The findings seem to caution against a feedback loop story that places undue weight on access to scientific knowledge through scientific elites throughout all occupations. Yet, the findings also show that there was one very important group within Royal Society members that was positively influenced by coal-based industrialisation, the group of merchants and factory owners. These would have been active in setting up enterprises in new industries, using new methods and machineries such as steam engines or semi-automated machinery. Hence, it might just have been this group that could have mattered most for access to scientific knowledge at the science-technology interface.

This view of entrepreneurs that entrepeneurs were central in bridging the gaps between practice and science has been forcefully made by Jacob (2014) and Stewart (2007). They argue that industrial entrepreneurs and scientists increasingly started to interact following Britain's early industrialisation. According to Jacob (2014) and Stewart (2007) this interaction meant both, the creation of shared social circles, e.g. through provincial societies, but also the creation of a shared common language that helped both sides to communicate their problems and findings across the spheres of science and technology.

Another branch of the literature has interpreted the creation of scientific societies and the emergence of a scientific culture as a signalling of social-status (Thackray, 1974). One could imagine that this signalling was distinct from any real interest in science. Yet, this interpretation seems to offer little explanatory power for the findings in table 45, where we do not find a rise in scientifically interested elites accross all occupations (as we would expect, if scientific culture were only simple status signalling). Instead, we only find an effect for merchants and manufactory owners, the only group that had a practical interest in applied technology as an input to their enterprises and manufactories.

Overall these findings indicate that early coal-based industrialisation had the following effects on access to knowledge through the presence of upper-tail human capital:

1. Access to broad knowledge, through the local presence of notable people, increased throughout all occupations. The largest effects are found for occupations in public office that might rather reflect access to political power than access to useful knowledge. However, significant increases in medical professionals, technical specialists, and craftsmen.[70]

[70] Artists might simply be seen as a provider of consumer goods. However, some painters were also at the forefront of spreading enlightenment culture. For example, Joesph Wright of Derby or Joshua Reynolds not only painted many of the leading scientists and industrialists in the North, but also showed a personal interest in scientific culture (Hunter, 2015).

2. Access to scientific knowledge, through the presence of Royal Society members, only increased for merchants and manufacturers.

3. Overall, access to broad knowledge increased faster and more broadly, while access to specifically scientific knowledge only increased for the occupational group of entrepreneurs.

The results show the importance of considering heterogeneity across different occupational groups in interpreting how coal-based industrialisation increased access to knowledge through the local presence of upper-tail human capital. If we consider the implications of these findings for the mechanism of a feedback loop between industrialisation and access to knowledge, it shows that at least for scientific knowledge the feedback loop might only have been present for a small group of occupations, merchants and manufactory owners. Yet, this small group might have been crucial for innovation in the production sector.

If we assume that increased access to knowledge drove early industrialisation (based on e.g. Mokyr (2002) or specifically for scientific knowledge, paper 4 of this thesis), then the overall results of this paper point towards the existence of a positive feedback loop between (coal-based) industrialisation and access to knowledge.

TABLE 45: SDID for carboniferous strata activation shock by occupation

	Royal Society members by occupational group										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	All	Nobility	Clergy	Merchants	Academics	Medical	Public office	Technical specialists	Craftsmen	Independents	Artists
Carbon activation post 1740	0.0678**	-0.00439	0.0230	0.0286**	-0.00188	-0.00876	-0.00538	0.00171	0.00513	0.00231	0.00284
	(0.0332)	(0.00774)	(0.0145)	(0.0126)	(0.00808)	(0.0137)	(0.0101)	(0.00609)	(0.00441)	(0.00716)	(0.00353)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hundred fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8608	8608	8608	8608	8608	8608	8608	8608	8608	8608	8608

	Royal Society members by occupational group										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	All	Nobility	Clergy	Merchants	Academics	Medical	Public office	Technical specialists	Craftsmen	Independents	Artists
Carbon activation post 1740	0.191***	0.0296**	0.0187*	0.0213***	0.0291*	0.0297***	0.0876***	0.0376***	0.0210**	0.00266	0.0718***
	(0.0346)	(0.0119)	(0.00980)	(0.00707)	(0.0160)	(0.00916)	(0.0175)	(0.0117)	(0.00842)	(0.00278)	(0.0206)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hundred fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10760	10760	10760	10760	10760	10760	10760	10760	10760	10760	10760

Notes: The table shows results from estimating equation 35 in a synthetic difference-in-differences design (SDID) model (Arkhangelsky et al., 2021). Jackknife standard errors in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

4.4 Conclusion

The paper shows that early coal-based industrialisation in Britain contributed to an increase in the local presence of upper-tail human capital. For this purpose, the paper distinguishes between general upper-tail human capital, as proxied through notable people from Laouenan et al. (2022), and scientific upper-tail human capital, proxied through Royal Society members. To capture causal effects of early industrialisation, the paper exploits the technological activation of coal resources based on carboniferous strata that was formed 360 to 60 million years ago (Fernihough and O'Rourke, 2021). To account for bias in pre-trends due to the spatial clustering of carboniferous strata, the paper adopts a synthetic difference-in-differences strategy. Results show that the activation of carboniferous strata post 1740 led to a 6.8% increase in the local presence of Royal Society members and a 19.1% increase in the presence of notable people.

The paper further investigates how much of this effect on the net presence of upper-tail human capital was due to the formation of upper-tail human capital on the one hand and migration forces on the other hand. It finds that early coal-based industrialisation primarily increased the formation of local upper-tail human capital. At the same time it had a negative effect on net migration numbers. Yet, comparing both effects, we find that the positive effect of upper-tail human capital formation offset the negative effects of out-migration, so that the net effect on the local presence of upper-tail human capital still remained positive.

The paper further conducts a heterogeneity analysis for different occupational groups. It finds that coal-based industrialisation led to a significant increase in all occupational groups of notable people, with largest effects for public office, artists, and technical specialists. In contrast for Royal Society members, the analysis only finds a positive and significant effect for the group of merchants and manufactory owners. These findings weaken the association between scientific upper-tail human capital, as proxied through Royal Society members, and industrialisation since the effect seems to have been driven by only one single occupational group. Yet, we should note that merchants and manufactory owners were a key-group for initiating technological change through investments. Furthermore, they played a key role in in bridging the social circles between high-science and practical inventors on the shop-floor of manufactories (Jacob, 2014; Stewart, 2007).

Overall, this paper's results are compatible with the presence of a feedback loop between industrialisation and upper-tail human capital. The paper has presented new evidence on the effects of industrialisation on the local presence of upper-tail human capital. These findings add to the conclusions found by the pre-existing literature that have found positive effects of upper-tail human capital on industrialisation (Squicciarini and Voigtländer, 2015; Kelly, Mokyr and Ó Gráda, 2014; Hanlon, 2022). Since both channels so to have been positive, the evidence points towards the existence of a feedback loop between industrialisation and upper-tail human capital during the early Industrial Revolution. The presence of such a feedback loop might have contributed to the take-off of the modern growth regime that was unleashed by technological change.[71]

The paper further contributes to a broad literature that has investigated the impact of industrialisation on the elasticity of the supply of human capital (Feldman and van der Beek, 2016; Franck and Galor, 2021; De Pleijt, Nuvolari and Weisdorf, 2020). While these studies have mainly concentrated on human capital found in skilled mechanics and craftsmen, this paper has investigated the upper-tail of human the human capital distribution in the form of knowledge elites. The paper supports the findings of the literature in showing that industrialisation not only lead to an expansion of the supply of skilled mechanics and craftsmen, but also to an expansion of the supply of knowledge elites at the upper-tail of human capital. It further contributes to the literature by showing that effects of industrialisation on the formation and migration of knowledge elites differed significantly. In the end, industrialisation increased the formation, but not the attraction of knowledge elites. Hence, effects of industrialisation on the elasticity of the supply of human capital could have run through different channels. Understanding these channels can help to understand the mechanism at play and to introduce policies for early industrialising areas. Given the importance of access to knowledge for industrialisation and the empirical evidence of the out-migration of knowledge elites, this paper

[71] See also paper 2 of this thesis.

suggests that some early industrialising places might profit from creating additional incentives to retain knowledge elites.

Appendices

C Appendix for paper 3

C.1 Case studies on migration

It has long been recognized that a flourishing scientific culture was a key feature of the early English Industrialization (Mokyr, 2002, 2016; Jacob, 1997; Stewart, 1986*a*). Scientific theories were increasingly seen as useful to technical problems and the advancement of society (Mokyr, 2002). Entrepreneurs, and promoters of the enlightenment increasingly used the language of science in public (Wootton, 2015). Local groups of entrepreneurs and scientific practitioners interacted with each other and formed small societies Schofield (1957, 1963). Furthermore, this happened against the background of a general British enlightenment culture (Porter, 2000) spreading from London into the periphery. This section investigates the individual motives of famous inventors to migrate during their lifetime while reflecting their life choices against the value of their human capital and scientific knowledge.

The radical chemist: Joseph Priestley

Joseph Priestley was born in Birstall Fieldhead at the outskirts of Leeds in 1733. During Priestley's youth, Leeds was already a fast growing town. Improvements to waterways were already taking place within the early eighteenth century. In Leeds, rivers were made navigable through the construction of locks. Furthermore, Leeds featured an ever-expanding cloth industry. Lastly, Leeds had easy access to close coal mines that provided a cheap source of energy for the expanding number of mills.

Priestley was educated at Batley grammar school (Schofield, 2013). Coming from a dissenting family, he could not attend the universities of Oxford or Cambridge and was sent to a dissenting academy in Daventry, between Birmingham and Northampton (ibid.). At Daventry he first came into contact with contemporary natural philosophy (ibid.). Next, he moved to Needham Market in Suffolk to minister to a dissenting congregation. Moving far away from the industrialising North created its own problems, as the congregation had problems with both Priestley's radicalism and never warmed up to his Yorkshire accent (ibid.). Next, Priestley ministered to a congregation in Nantwich, Cheshire before he got accepted to a teaching position at the Warrington Academy, close to the industrialising Manchester (ibid.). The Warrington Academy was one of the largest dissenting academies and profited from Priestley's reform of the curriculum that he restructured towards a more practical education with an emphasis on scientific disciplines such as natural history and natural philosophy (ibid.). We can note that Priestley's background from the newly industrialising Leeds had surely made him aware of the necessities of a practical education. It is also noteworthy that the new sciences were regarded as useful subjects by both Priestley and the parents sending their boys to the Warrington Academy.

After a successful teaching career at Warrington and the publication of his works on electricity, Priestley accepted a call as a minister to a dissenting congregation in Leeds. The decision to migrate was based on his financial insecurity at Warrington, his wish to become a minister, and his family roots around Leeds (ibid.). It was during his time in Leeds that Priestly isolated, among other gases, oxygen, an achievement he received the Copley medal for in 1773. Soon, Priestley decided to migrate away from the industrialising North and to take up the well renumerated position as librarian and tutor to the earl of Shelburne in Calne in Wiltshire in southwestern England (ibid.). Still, the old money was located in the South of England. And it was still the old money that offered many lucrative positions for upraising scientists from the middling sorts. In 1780, Priestley returned to Birmingham to minister to Birmingham's largest dissenting congregation. In this position he still pursued his scientific interests and became a member of the Lunar Society, a scientific society that comprised many Birmingham's leading entrepreneurs such as James Watt, Matthew Boulton, or Josiah Wedgwood (Schofield, 1957, 1963). In Birmingham, Priestley concentrated on applied science and advised Joseph Wedgwood on the applications of electrical experiments for gilding pottery, Matthew Boulton on the elasticity of new gases, and James Watt and John Wilkinson on the interaction of steam and iron (Schofield, 1957, 2013). He further advised William Withering on how to generate hydrogen for a balloon flight (Schofield, 2013). Thus, Priestley's knowledge in experimental chemistry was actively used in industrial applications.

Finally, things turned upside down in 1791. Priestley's radical positions as a religious minister had created serious opposition within Birmingham's Anglican elite. Moreover, his positive reaction towards the French Revolution further estranged much of Birmingham's elite. In 1791, riots broke out and a violent crowd stormed and burned Priestley's house as well as four dissenting chapels (ibid.). Priestley only survived by fleeing from Birmingham. Priestley then settled for a short time in Hackney, far away from Birmingham, and then decided to emigrate to the United States. He spent the rest of his life in Pennsylvania (ibid.).

The case of Joseph Priestley shows the range of opportunities created within the industrialising regions. It meant that people like Priestley could gain from a demand for applied science. But it also meant that the skills he had acquired within the industrialising regions were equally valued in the South of England and were often the ones that were better remunerated and brought more social capital with them. Priestley's story also gives an extreme example of push forces that actively discouraged people with valuable upper-tail human capital to stay in the North.

A life around coal: James Watt

James Watt was born in Greenock in Scotland in 1736 within the outer periphery of commercial Britain. In his early years his friend Robert Dick, the later chairholder of natural philosophy in Glasgow, convinced him to take on an apprenticeship in instrument making in London where he could learn skills that could not be obtained in Scotland (Tann, 2014). Next, James Watt went to Glasgow, the place of his mother's family and where also many of his friends with an interest in natural philosophy lived (ibid.). In 1764 he was asked to repair a Newcomen steam engine belonging to the natural philosophy class of the University of Glasgow (ibid.). This started a series of experiments with steam engines and an increasing involvement in the construction of steam engines in Scotland (ibid.). Having invented a separate condenser for a steam engine, he formed a partnership with Matthew Boulton who owned a metal-working factory in Soho near Birmingham in 1774. Watt then moved to Birmingham and together with Matthew Boulton produced a large number of a new type of steam engine that was more than 4 times as fuel efficient as Newcomen engines (Mokyr, 1992). After succesfully building the

Boulton & Watts business, he retired to a farmhouse in Doldowlod in Wales, far off from any larger population centre (Tann, 2014). He died there in 1819.

All in all, looking at James Watt, we see a migratory life that led him to half of Britain. Throughout his life we can discern multiple incentives for migration. First, he decided to move to London in order to gain knowledge from the largest agglomeration centre of knowledge in Britain. He then returned to Glasgow, most likely based on family and friendship ties, but also hoping to find a demand for high-quality instruments in the growing university town. Being in Glasgow also meant being in close proximity to the coalfields of the North. This certainly helped his early career in building steam engines that would help him to acquire the necessary practice for his own inventions. At the same time, interacting with the University of Glasgow certainly exposed him to various topics in early science. The University of Glasgow, after various reforms at the beginning of the eighteenth century, was one of the leading Scottish universities that laid a strong focus on the early science of the period. Thus, educational change and industrial demand seem to have created new occupational opportunities for James Watt. By migrating to Birmingham he further increased his opportunities by moving closer to a place that combined immediate access to coal with a pre-existing manufactory. Lastly, his retirement home seems to have been chosen as a place of tranquillity far off in the countryside. Taking this place of death as a proxy for his place of impact would clearly miss the huge role of coal and industry in James Watt's career.

From shambles to riches: Charles Hutton

Charles Hutton was born into the lives of colliers in the not-yet industrialized coal mining in Newcastle in 1737. His father was an overseer and local colliery and Charles Hutton was also supposed to enter work in the mines (Guicciardini, 2004). However, at the age of seven, he injured his right arm in a street fight and was instead sent to school (ibid.). Attending several local schools, he proved quick-witted and talented at classical learning and started to learn mathematics at an evening school. However, after the completion of his education he still had to resort to working in the mines as a coal-cutter. Yet, in 1756 he managed to obtain the place of one of his previous teachers, thereby earning a higher wage than as coal-cutter (ibid.).

In 1760 he opened his own “writing and mathematical school” (ibid.). He also published on practical mathematics. Inspired by an extreme spring tide that destroyed several bridges across the Tyne, he published a book on bridge-building (ibid.) In 1773, he applied for the chair of mathematics at the Royal Military Academy at Woolwich and was chosen for the chair. The move to Woolwich finally removed him from his family roots of Newcastle colliers and brought him into the fashionable circles of London science. In 1774 he was elected into the Royal Society and received its Copley model for his work on ballistics in 1778.[72] He extensively published on practical mathematics and undertook a venture on developing estates in Woolwich (ibid.) In his final years he resigned his professorship at Woolwich and moved to Bedford Row, London, where he died in 1823.

Charles Hutton’s life was deeply shaped by coal and early industrialization in Newcastle. Yet, in contrast to James Watt who migrated towards coal and industrialization, Charles Hutton used the education he had received within the industrialising area of Newcastle to move to the South of England and the old circles of fashionable science. He profited greatly from this move, achieving the status of a learned gentleman and and secured himself a good income. It seems that his early success as a schoolteacher was based on an enlightenment interest in practical mathematics. He then applied his knowledge to applied problems of the early industrialising region, such as the construction of bridges. Based on these publications, he got elected for the chair of mathematics at the Woolwich Academy, close to London. Thus, his career illustrates how experience in applied technical and mathematical problems within the regions of the industrialising North could also become valuable on the national labour market. In this way, the educational chances of and practical experience within early industrialising regions could act as a push-factor for migration as well.

[72] In 1784 he resigned from the Royal Society after a long-standing dispute with Sir Joseph Banks who had plotted to remove him from his role as foreign secretary of the Royal Society (Guicciardini, 2004).

C.2 Data description

C.2.1 Variable definitions

Place of death of notable people. Place of death of notable people taken from a synchronized sample of Wikipedia articles by Laouenan et al. (2022). The author coded the occupation classes according to table 49.

Lifetime places of the Fellows of the Royal Society, 1600–1800. Based on a dataset of Fellows of the Royal Society curated by the Royal Society (Nixon, 1999). The dataset was kindly shared with the author by the Royal Society. Based on short biographies included in the dataset and by reference to external biographies, the author extracted lifetime locations and coded occupations according to table 49. See appendix section C.4 for further details on the construction of the dataset.

Carboniferous strata. Geological location of carboniferous strata. Obtained from Fernihough and O'Rourke (2021).

City size, ca. 1670s. City size estimates from Bennet (2012) based on the work by Law (1967), Robson (1973), and Langton (2000). Cities are counted based on historical city status taken from Clark and Hosking (1993) yielding a total of 1005 cities in England, Wales, Scotland. The majority of the population estimates are based on hearth tax registers from the 1660s and 1670s as well as estimates from the Compton census of 1676. Further historical evidence, especially hearth data was used for the rest of towns, as well as some imputations.

City size, 1801. City size estimates from Bennet (2012) based on the 1801 census.

Location of steam engines, 1706–1804. Count of steam engines from Bogart et al. (2017*a*), accessed January 28, 2021, see also Bogart et al. (2017*b*) for further context.

Hundred boundaries. Based on 1851 shapefile of 1851. parish boundaries from Satchell, Shaw-Taylor and Wrigley (2016) This dataset was created with funding from the ESRC (RES-000-23-1579), the Leverhulme Trust and the British Academy. A description of the dataset can be found in Satchell (2016, 2006): documentation available at: `http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html`.

C.2.2 Summary statistics

Table 46: Summary statistics Royal Society members, aggregate level 1600–1800

	Mean	Std	Min.	Max	Obs
Royal Society members	5.477	(30.862)	0	778	1082
High nobility and military	0.301	(2.409)	0	72	1082
Clergy	0.708	(2.406)	0	31	1082
Merchants	0.167	(1.347)	0	34	1082
Teachers and academics	0.666	(9.685)	0	240	1082
Medical practioners	0.586	(4.554)	0	100	1082
Public office	0.606	(4.393)	0	84	1082
Early technical specialists	0.063	(0.696)	0	19	1082
Craftsmen	0.040	(0.405)	0	7	1082
Independents	0.255	(1.591)	0	31	1082
Artists	0.022	(0.218)	0	4	1082
Observations	1082				

Notes: The unit of analysis is the English and Welsh hundred. Summary statistics are shown for the time period 1600-1800.

C.2.3 Royal Society statistics

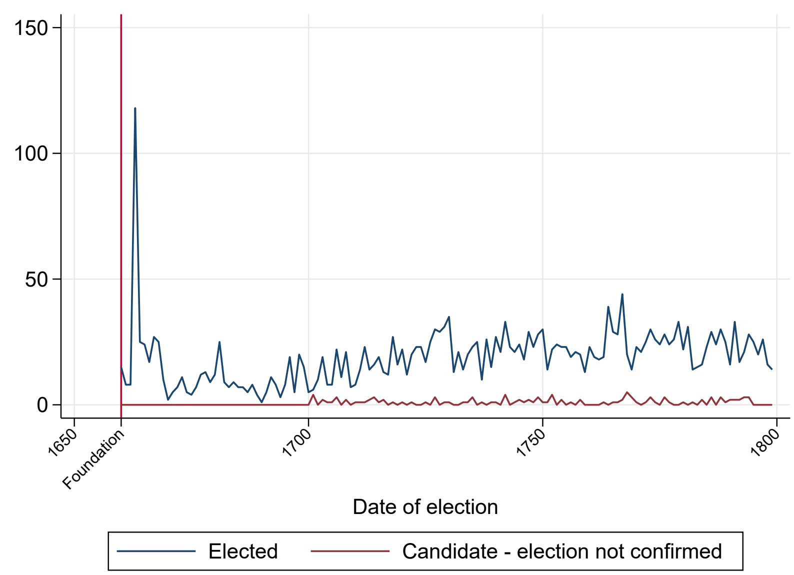


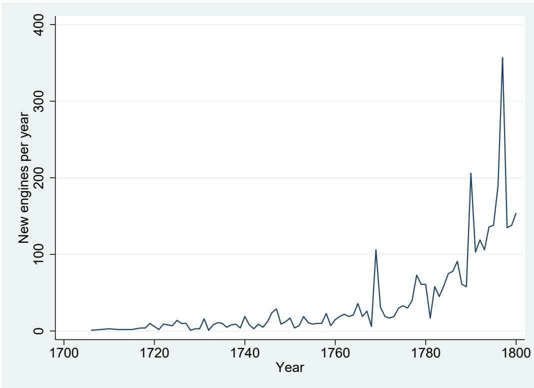
Figure 53: Development of confirmed and non-nonfirmed candidates for election into the royal Society

Table 47: Summary statistics notable people, aggregate level 1600–1840

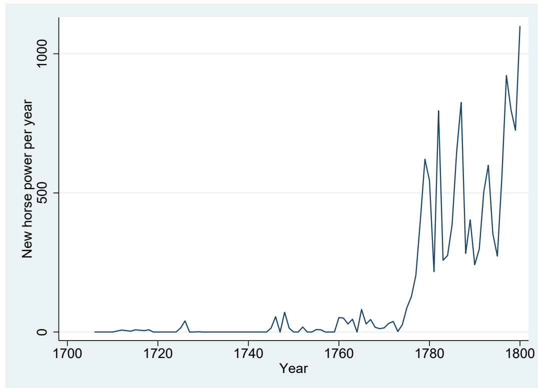
	Mean	Std	Min.	Max	Obs
Notable people	8.795	(71.522)	0	2297	1082
High nobility and military	0.899	(7.612)	0	240	1082
Clergy	0.503	(2.029)	0	55	1082
Merchants	0.230	(2.030)	0	63	1082
Teachers and academics	1.074	(6.736)	0	211	1082
Medical practioners	0.322	(2.372)	0	73	1082
Public office	1.527	(13.028)	0	413	1082
Early technical specialists	0.432	(2.865)	0	87	1082
Craftsmen	0.265	(3.412)	0	110	1082
Independents	0.043	(0.379)	0	10	1082
Artists	1.567	(19.202)	0	624	1082
Observations	1082				

Notes: The unit of analysis is the English and Welsh hundred. Summary statistics are shown for the time period 1600-1840.

C.2.4 Statistics on steam engines



(a) Development of the number of steam engines

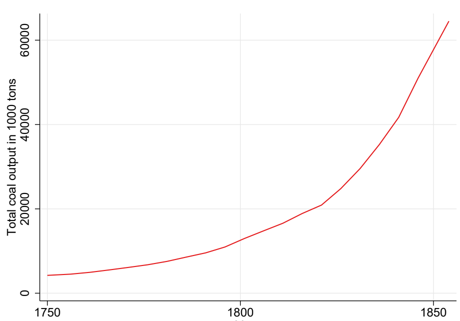


(b) Development of available horse power

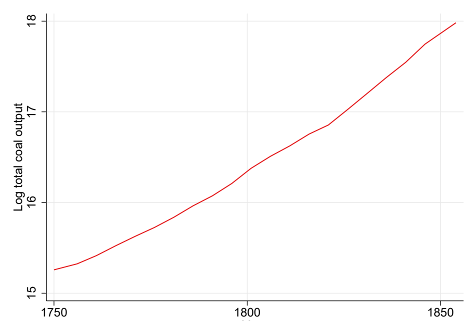
FIGURE 54: Development of steam engines in Britain over time

Data on steam engines is taken from Bogart et al. (2017*b*). In comparing the graph on the number of steam engines and available horse power, it should be noted that approximate horse power is not known for all historically located steam engines. Hence, graph b) forms a subsample of graph a). See Kanefsky and Robey (1980) and Bogart et al. (2017*b*) for further details.

C.2.5 Statistics on coal output



(a) Coal output in levels

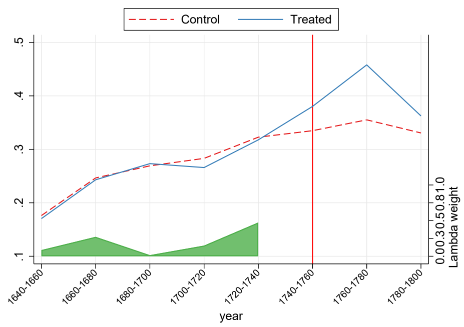


(b) Log coal output

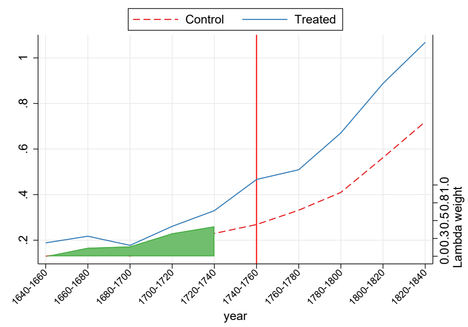
FIGURE 55: British coal output from Pollard (1980)

C.3 Results

C.3.1 Figures



(a) Royal Society members



(b) Notable people

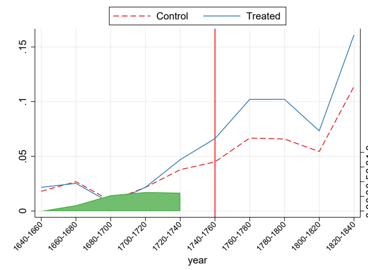
FIGURE 56: SDID trends for carboniferous strata treatment post 1740 for the full sample, including greater London

Notes: Figure shows trends in a synthetic difference-in-differences design (SDID) (Arkhangelsky et al., 2021) of equation 35 for the treatment of activated carboniferous strata post 1760. The figure shows the re-weighted trend of the unexposed control units and the trend of the treatment units. The green area shows the time-specific weights (lambda).

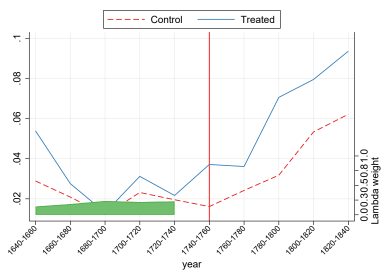
TABLE 48: Synthetic difference-in-differences estimate for carbon activation shock post 1740 for the full sample, including greater London

	Presence of upper-tail human capital	
	(1)	(2)
	R.S. members	Notable people
Carbon activation post 1740	0.0664**	0.181***
	(0.0332)	(0.0346)
Observations	8656	10820

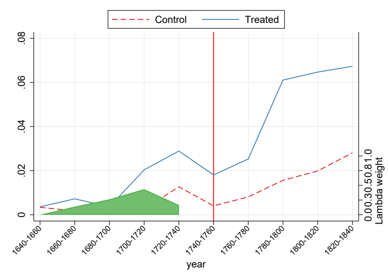
Notes: The table shows results from estimating equation 35 in a synthetic difference-in-differences design (SDID) model (Arkhangelsky et al., 2021). These results are estimated for the full sample, including greater London. Jackknife standard errors in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.



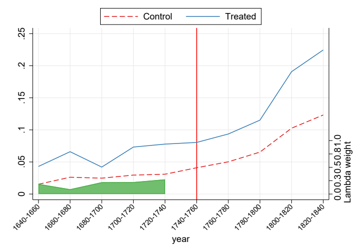
(a) Notable people - occupation class 10: High nobility and military



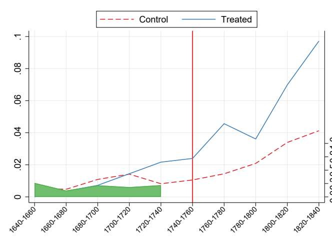
(b) Notable people - occupation class 20: Clergy



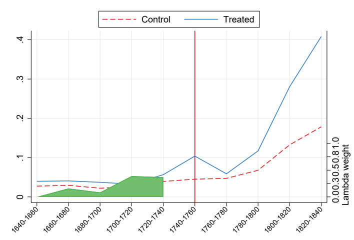
(c) Notable people - occupation class 30: Merchants



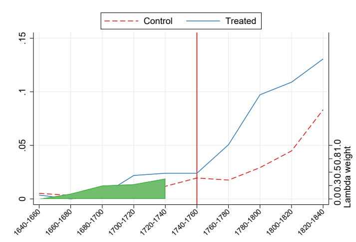
(d) Notable people - occupation class 40: Teachers and academics



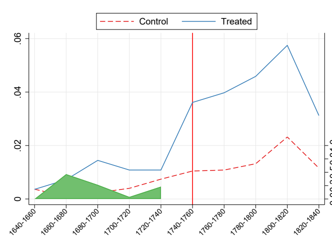
(e) Notable people - occupation class 50: Medical practioners



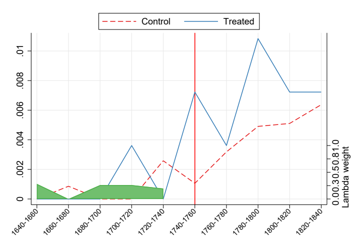
(f) Notable people - occupation class 60: Public office



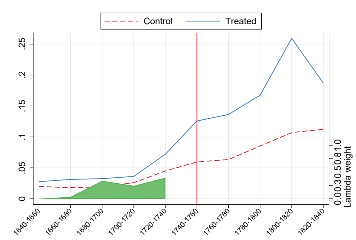
(g) Notable people - occupation class 70: Early technical specialists



(h) Notable people - occupation class 80: Craftsmen



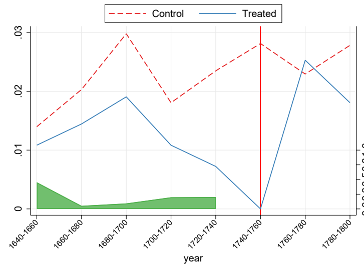
(i) Notable people - occupation class 90: Independents



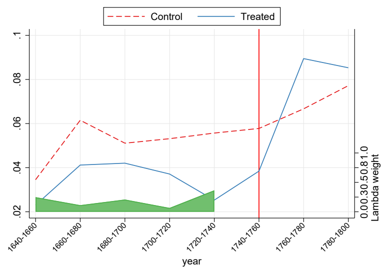
(j) Notable people - occupation class 100: Artists

FIGURE 57: SDID trends for carboniferous strata treatment post 1740 by occupations

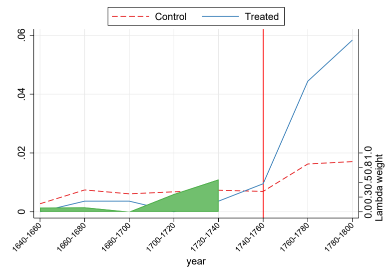
Figure shows trends in a synthetic difference-in-differences design (SDID) for the treatment of activated carboniferous strata post 1740. The figure shows the re-weighted trend of the unexposed control units and the trend of the treatment units.



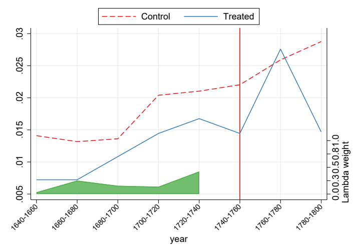
(a) Fellows of the Royal Society - occupation class 10: High nobility and military



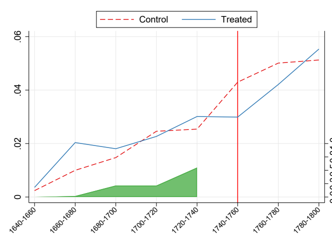
(b) Fellows of the Royal Society - occupation class 20: Clergy



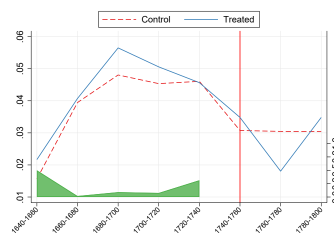
(c) Fellows of the Royal Society - occupation class 30: Merchants



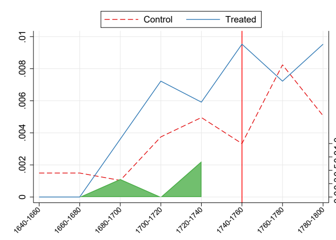
(d) Fellows of the Royal Society - occupation class 40: Teachers and academics



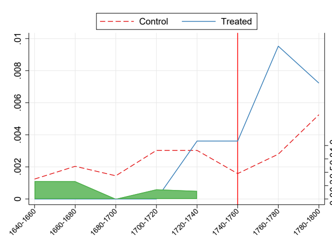
(e) Fellows of the Royal Society - occupation class 50: Medicial practioners



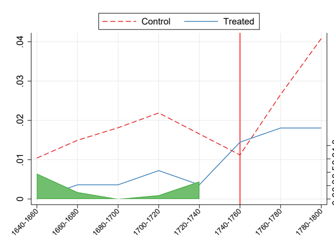
(f) Fellows of the Royal Society - occupation class 60: Public office



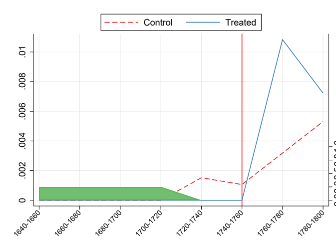
(g) Fellows of the Royal Society - occupation class 70: Early technical specialists



(h) Fellows of the Royal Society - occupation class 80: Craftsmen



(i) Fellows of the Royal Society - occupation class 90: Independents



(j) Fellows of the Royal Society - occupation class 100: Artists

FIGURE 58: SDID trends for carboniferous strata treatment post 1760 by occupations

Figure shows trends in a synthetic difference-in-differences design (SDID) for the treatment of activated carboniferous strata post 1760. The figure shows the reweighted trend of the unexposed control units and the trend of the treatment units.

C.4 Data Coding

C.4.1 A New Coding Scheme for the Occupational Categories of the Knowledge Elites of the Seventeenth and Eighteenth Century

Assigning occupational categories is notoriously difficult for the seventeenth and eighteenth century that witnessed an increasing functional differentiation within the occupations of applied "scientists".[73] Modern occupational categories were only beginning to emerge and often enough turn out to be a poor description of the diversity of activities practised by early members of the Royal Society. For example, John Theophilus Desaguliers (1683–1744) is often considered to be one of the first modern "engineers". Yet, he started his life as a clergyman, later turning to public lecturing on topics of natural philosophy and mechanics, as well as independently experimenting with new technological devices and taking independent assignments in engineering projects. Thus, his range of work clearly supersedes the narrow modern meaning of an "engineer". Indeed, contemporaries would have hardly perceived him as an "engineer", a term that in its non-military sense would only be invented and established a few decades later.[74] In contrast to the opaqueness of early eighteenth century occupations, the picture had turned by the end of the eighteenth century: "Civil engineers" such as Marc Isambard Brunel (1769–1849) or his son Isambard Kingdom Brunel (1806–1859) focused mainly on what we would understand as engineering today and were already recognized as "engineers" in their own time. New occupational titles had emerged and the actual work by these applied technicians and scientists had become more narrow and well-delineated.

Hence, any attempts to classify the members of the Royal Society or e.g. Académie des Sciences should allow for different occupational categories for each single occupational endeavour in an individual's lifespan. Furthermore, occupational categories should be chosen in a way that reflect the employment patterns of the educated elite of the seventeenth and eighteenth century. Standard historical classifications, such as HISCO's (History of Work Information System) HISCLASS, were mainly designed to capture a lower strata of society — thus, it does

[73] The term "scientist" as a product of an ongoing professionalization of science would only have been coined in 1834 by William Whewell (1794–1866) and then broadly adopted in the 1850s (Ross, 1962).

[74] John Smeaton (1724–1792) is usually credited with inventing the term "civil engineer", a reaction to the apparent inapplicability of other occupational titles to his line of work.

not allow for distinctions between university teachers, independent lecturers, or private tutors, nor does it include meaningful categories for the landowning nobility of the day. Furthermore, grouping early eighteenth century scientists under HISCLASS categories such as "biologist" or "chemist" appears problematic at best.

Hence, this paper introduces a new occupational coding scheme especially designed for the European intellectual elite of the seventeenth and eighteenth century. It is meant to capture the broad occupational career paths of the day (ranging from the gentry and military, to the clergy, teachers, and medical men, as well early specialists and craftsmen) and adds further common occupations to each of the broad categories. The resulting coding scheme is aimed at capturing the main occupations of the members of the Royal Society or other members of learned societies, both in Britain and on the continent. It is hoped that this scheme will also be useful for other researchers working with data on the educational elite of the time of the late Scientific Revolution and enlightenment. The occupational coding scheme is presented in table 49.[75]

[75] Other researchers might also use this coding scheme as a starting place for the introduction of further sub-categories needed for their specific research question. Thus, e.g. for a study focussing on France, one could split the category "11 – High nobility" into a "111 – Noblesse d'épée" and "112 – Noblesse de robe".

Table 49: Occupational categories for Royal Society members

General Category	Category Name	Sub-Category	Category Name
1	High nobility and military		
		11	High nobility
		12	Navy
		13	Army
2	Clergy		
		21	Anglican clergy
		22	Dissenting clergy
		23	Roman Catholic clergy
		24	Protestant clergy outside Britain
		25	Presbyterian clergy
		26	Orthodox clergy
3	Merchants		
		31	Merchants
		32	Manufactory owners
		33	Owners of mills, breweries etc.
		34	Book or antiquity traders
		35	Small merchants and shopkeepers
		36	Bankers
		37	Mine owners
		38	Land agents
		39	Farmers
4	Teachers and academics		
		41	University teachers

		42	Teacher at independent schools	
		43	Private teachers	
		44	Independent lecturers	
		45	Librarian	
		46	Position at an Academy / at the Royal Society	
		47	Independent position, e.g. at royal observatories	
		48	Laboratory assistant	
		49	Private patronage	
5	Medical practitioners			
		51	Physicians	
		52	Surgeons	
		53	Apothecaries	
6	Public office			
		61	General public office	
		62	Diplomats	
		63	Jurists	
7	Early technical specialists			
		71	Architects	
		72	Civil engineers	
		73	Army engineers	
		74	Land surveyors / hydrographers	
8	Craftsmen			
		81	Instrument maker	
		82	Goldsmith	
		83(1)	Jewellers and fine works	Jeweller

		832	Jewellers and fine works	Lapidary
		833	Jewellers and fine works	Engraver
		84	Oculist	
		85(1)	Wrights and carpenters	Shipwright
		852	Wrights and carpenters	Millwright
		86	Book printer	
		88	Clock-maker	
		89(1)	Routine craftsmen	Cooper
		892	Routine craftsmen	Stonemason
		893	Routine craftsmen	Dyer
9	Independents			
		91	Independent means	
		92	Rentiers	
		93	Retired	
10	Artists			

The advantage of using this coding scheme over e.g. HISCLASS lies also in its fundamental compatibility to other occupational coding schemes that have been informally created by scholars of the Royal Society and other seventeenth and eighteenth century academies. Thus, Hunter (1994) splits the occupations of all British fellows of the Royal Society between 1660 and 1699 into "aristocrats, courtiers & politicians, gentlemen, lawyers, divines, doctors, scholars & writers, civil servants, merchants and tradesmen" (Hunter, 1994, pp. 126). Here, aristocrats roughly map onto this scheme's category (11), divines onto (2x), merchants and tradesmen onto (3x), scholars and writers onto (4x), doctors onto (5x), and politicians and civil servants unto (6x). Writing on the Académie Royale des Scienes in Paris between 1699 and 1793, McClellan III (1981) splits the member's occupations into the broad categories of "central government, provincial government, education, medicine, military, business & finance, law, technical specialities, and miscellaneous" McClellan III (1981, p. 563). Here, the central and provincial government match onto (6x), education unto (4x), medicine unto (5x), military unto (12) and (13), business and finance unto (3x), law unto (63), and technical specialities unto (7x) and (47).[76] It can further be seen that most of McClellan III's subcategories have a direct correspondence to the subcategories of this paper's coding scheme. Thus, results relying on this paper's coding scheme have the advantage that they are comparable to the earlier historico-statistical literature while at the same allowing for more nuanced sub-categories as well as avoiding vague categories such as "gentlemen" that are more of a rough indicator of social status than an occupational category. This seems to be better captured by explicitly referring to a person's income, e.g. as a rentier (92).

The coding scheme exclusively classifies "occupation", not status or research interest. The different categories are answers to the question of "how did a member of the intellectual elite earn his or her income?" and in order to do so "what professional tasks did a member of the intellectual elite fulfil on daily basis?". Thus, the index is based both on the occupational source of income and a more functional definition.

Yet, the historian of the seventeenth and eighteenth century will find it indispensable to also include the lens of the different estates when answering the question of how "scientific elites" earned their income — however, in a form that still looks at income and functionality. Members of the high nobility derived their income through the rent of their estates — yet, it would appear anachronistic to classify this high nobility merely as rentiers, both with regard to the form of their legal claims to their assets and with regard to the size of the assets themselves. Furthermore, being part of the high nobility usually brought a special functional role as a courtier and often enough as a military leader with it.[77] Thus, offices acquired through courtship or good fortunes during military campaigns could also significantly expand a nobleman's fortunes. Hence, the high nobility consisting of royals, dukes, marquesses, earls, viscounts, and barons, are classified as "high nobility" with regard to their "occupation". However, lesser nobles, i.e. the landed gentry, are classified into the other categories. Similarly

[76] Splitting the categories into a central and provincial government seems well suited to the French central state. However, it appears less attractive as a distinction for Britain or e.g. the German states of the eighteenth century. Furthermore, even in France this category made up only 1.6% of the members of the Académie Royale des Scienes (McClellan III, 1981, p. 563)

[77] The military role of the high nobility diminished over the run of the late seventeenth and eighteenth century — yet, when looking at the Civil War during the seventeenth century, the life-path of many a nobleman was unvaryingly woven into different roles in military campaigns.

members of the clergy are only classified as “clergy” as long as they derived their salaries from the Church. However, if members of the clergy derived their income from e.g. a teaching position, they would be classified as teachers instead.

A further category that should be mentioned is “public office”. It is one of the broader categories within the coding scheme and one that captures a lot of heterogeneity within this group. In contrast to today, eighteenth century civil servants did not follow a clearly cut career path. Often offices could be bought and were dependent on a large system of patronage. There was considerable difference between lower administrative civil servants and “high public office” that combined both an administrative and political role.[78] Furthermore, some public offices only required part-time involvement, thus making it possible for well-connected men to hold several appointments or to fulfil government duties while following their original occupation (e.g. as a merchant, etc.). It would be a worthwhile project to classify all official government positions in eighteenth century England according to these considerations. However, this also would be a project way beyond the scope of this paper. Hence, the coding of this paper follows the simple rule that it excludes any public offices that were not important enough to require an official’s residence at the place of the public office and only codes the “main occupation” of a Royal Society member. It further treats public servants as one category, ignoring differences between the hierarchy of public office. It should be remembered that all of the fellows of the Royal Society considered here had sufficiently high human capital to serve in leading roles within public service (and not as mere clerks etc.).

Given the reflection on the emergence of new occupations, such as “civil engineers”, at the beginning of this chapter, it becomes clear that it is important to code the categories of the early technical specialists, architects, civil engineers, army engineers, land surveyors, and hydrographers in a time consistent way. Thus, for this paper, the coding of technical specialists rather looks at the nature of their work rather than the contemporary occupational name attached to it. Thus, the earliest entry for a “civil engineer” in this dataset are Nicolas Mercator’s (c. 1620–1687) years at Versailles from 1682 to 1687, where he was commissioned

[78]Examples for this broad spectrum of heterogeneity are e.g. Thomas Pelham-Holles (F.R.S. 1749), Prime Minister from 1754–1762 and 1757–1762,

to construct the water fountains of Versailles. In the same manner Domenico Guglielmini's (1655–1720) occupation as a *superintendant of the waters* in Bologna, where he collected much of his experience with hydraulics culminating in his work *Della natura dei fiumi* (1697), is classified as engineering. In contrast William Molyneux's (1656–1698) occupation as *Joint Chief Engineer and Surveyor-General of the King's Buildings and Works in Ireland* is classified as public office, based on the observation that most of the actual activity required by the office was administrative (McParland, 1995). This way the coding scheme is consistent throughout time by looking at whether the work involved mechanical engineering, and not what name was attached to an office. Yet, this also means that we need to be careful in interpreting early entries of "engineering". Having people working in mechanical engineering did not yet mean that these were professionals in an occupation that contemporaries would have recognized as a "civil engineer".

The last category "independents" captures all endeavours that were not built on employment relationships, public office, or independent entrepreneurship. It includes Royal Society members living on their own independent means, e.g. through inheriting a fortune, but also various patronage relationships. It also includes writers and publicists, as their source of income was often mixed between their income from publishing, subscription fees, their own financial fortunes, or patronage (we might think about the mixed means Voltaire used to support himself). The coding scheme further introduces a difference between "independent means" and "rentiers": "Rentiers" would have been able to live off the interest (or substance) of vast fortunes. However, people classified as living on "independent means" would have also relied on other forms of income. However, information on wealth for the eighteenth and seventeenth century proves to be too rare to precisely record the difference between "rentiers" and "independent means". Equally, the category of "retired" was used if there was explicit evidence of Royal Society members retiring from their former occupations (usually due to ill health). However, the category is very likely to under-report the numbers of retirees, especially when looking at a very narrow time frame before a person's death.

C.4.2 Coding Royal Society Members

This section describes the data used to code the fellows of the Royal Society born between 1600 and 1750 according to the occupational scheme presented in the previous sub-chapter. Overall, this paper draws on short biographies from the *Raymond and Beverly Sackler archive resource project* (Nixon, 1999) and then either complemented or added 917 entries from secondary sources, and added information to further 114 entries by drawing on the election certificates of the Royal Society. Thus, the dataset produced by this paper presents to the author's best knowledge the most comprehensive list of the lifetime locations and occupations of Royal Society members up to this date. The section further argues that despite some inevitable survival bias inherent in the study of eighteenth century biographies, and with some caveats, the dataset is broadly representative of the true distribution of past fellows. It is further argued that it is consistently coded over time. Overall this new dataset presents information on 5,180 lifetime addresses and 4,310 life-time occupations for all the 2,269 fellows of the Royal Society born between 1591 and 1750.[79] Out of these 5,180 lifetime addresses, 5,103 could be geocoded.

The coding of Royal Society members according to these classes is mostly based on the short-biographies from the *Raymond and Beverly Sackler archive resource project* (Nixon, 1999) that has kindly been shared by the Royal Society itself. The *Raymond and Beverly Sackler archive project* is based on the Bulloch's Roll compiled in 1941 by William Bulloch and kept at the archives of the Royal Society. It presents a chronological list of all the fellow's lifetime and election dates between 1660 and 1940 drawn from the original register of the Royal Society. It further includes short biographies based on on contemporary volumes of national biography.[80] The *Raymond and Beverly Sackler archive resource project* then digitized these records and updated them with the 1990s versions of the *Dictionary of National Biography* and *Dictionary of Scientific Biography*. Using this compilation of short-biographies has the advantage that it

[79]The lower number of lifetime occupations is mainly due to the fact that addresses for places of birth are not associated with an occupation. For completeness' sake, the data also includes information on all unsuccessful candidates for membership in the Royal Society.

[80]This includes the *Dictionary of National Biography*, George Edward Cokayne's *Complete Peerage* (1887–1898) and *Complete Baronetage* (1887–1898), *The Gentleman's Magazine*, the *Munk's Roll of the Royal College of Physicians*, Frederic Boase's *Modern English Biograph*y (1892–1921), as well as the contemporary volumes of *Who's Who* and *Who Was Who*.

not only draws on secondary literature, but also includes membership information from from the original register of the Royal Society. This information proves to be especially valuable for the earlier times of the Royal Society for which other sources are sometimes markedly scarce. Hence, this resource yields information for broader and less-prominent members of the Royal Society than those included in national biographies. At the same time, the tightness of information from the *Raymond and Beverly Sackler archive resource project* declines for the period post 1700. Therefore, to clear ambiguities and to fill gaps, a broad range of additional secondary resources was consulted: Thus, further information was taken from the *Oxford Dictionary of National Biography* and other national dictionaries.[81]. Furthermore, the *History of Parliament Online*, and the *Munk's Role of the Royal College of Physicians* were consulted. After 1730, the Royal Society furthermore started collecting election certificates that have been used as an additional source for occupations and addresses at the time of election. Finally, for each missing entry a Google search was carried out to look for e.g. information in biographies, or information attached to paintings of these members. Nonetheless, for some members for whom places of residence were recorded, information on occupations is missing.

Table 50: Example of entry from Raymond and Beverly Sackler archive resource project

Category	Entry
Name	Smith; Thomas (1638 - 1710)
Membership	Membership: Fellow Election Date: 6/12/1677 Proposers: Sir John Hoskins
Places	Birth: In the parish of Allhallows, Barking, Essex, England (03 June 1638) Death: Hilkiah Bedford's house, Dean Street, Soho (11 May 1710) Burial: St Anne's church, Soho
Education	Queen's College, Oxford; BA (1661), MA (1663), BD (1674), DD (1683); Magdalen College, Oxford; MA; Incorporated at Cambridge (1673)
Career	Master of Magdalen College School (1664-1666); Fellow of Magdalen (1666-1692); Chaplain to Sir Daniel Harvey, Ambassador to Constantinople (1668-1671); Dean of Magdalen (1674); travelled in France (1676); Chaplain to Sir Joseph Williamson (FRS 1663) (1678-1679); Vice-President of Magdalen (1682); Rector of Standlake, Oxfordshire (1684-1687); Bursar of Magdalen (1686); Non-juror, ejected from Magdalen (1692); resided in the household of Sir John Cotton and his eldest son and had charge of the Cottonian manuscripts; advised collectors on their libraries

[81] Among other national dictionaries, such as the *Nieuw Nederlandsch Biografisch Woordenboek*, the use of the *Deutsche Biographie* (https://www.deutsche-biographie.de/home), combining the *Alte Deutsche Biographie* and *Neue Deutsche Biographie*, should be highlighted as a source that was consulted relatively often. Other dictionaries of national biography that were consulted include the *Hessische Biographie*.

Table 51: Coding of the example entry

Entry	Birth	Death	Name	University of education	Time	Address	Occupation	Nun-Juror
1	1	0	Smith; Thomas (1638 - 1710)	Oxford	1638	In the parish of Allhallows, Barking, Essex, England	—	0
2	0	0	Smith; Thomas (1638 - 1710)	Oxford	1664	Oxford	Teacher at school (42)	0
3	0	0	Smith; Thomas (1638 - 1710)	Oxford	1666	Oxford	University teacher (41)	0
4	0	0	Smith; Thomas (1638 - 1710)	Oxford	1668	Constantinople (Istanbul, Turkey)	Anglican clergy (21)	0
5	0	0	Smith; Thomas (1638 - 1710)	Oxford	1671	Oxford	University teacher (41)	0
6	0	0	Smith; Thomas (1638 - 1710)	Oxford	1678	London	Anglican clergy (21)	0
7	0	0	Smith; Thomas (1638 - 1710)	Oxford	1679	Oxford	University teacher (41)	0
8	0	0	Smith; Thomas (1638 - 1710)	Oxford	1692	Dean Street, Soho, London	Independent means (91)	1
9	0	1	Smith; Thomas (1638 - 1710)	Oxford	1710	Dean Street, Soho, London	Independent means (91)	1

The entry of Thomas Smith (1638–1710) illustrates the data structure as well as a few coding issues at the hand of a relatively less known fellow of the Royal Society. Table 50 shows the original entry from the *Raymond and Beverly Sackler archive resource project* and table 51 shows the way this information was coded while simultaneously relying on on additional information from the *Oxford Dictionary of National Biography.* The original entry from the *Raymond and Beverly Sackler archive resource project* draws on the Bulloch's Roll, the *Dictionary of National Biography*, the *Alumni Oxonienses* (Foster, 1891), the *Alumni Cantabrigienses* (Venn and Litt, 1952), and Hunter (1994). Comparing it to the entry for Thomas Smith (1638–1710) in the *Oxford Dictionary of National Biography* by Harmsen (2004) confirms that the short biography has captured all information relating to lifetime movements and occupations.

With Thomas Smith, we see a not untypical career of a seventeenth century Oxford graduate. He originally taught at Magdalen College School after having graduated with an M.A. from Magdalen College at Oxford.[82] In 1666 he became a fellow of the same college, an appointment he held until 1692 when he was expelled as a non-juror.[83] Yet despite this stable position, we see that he also accepted three other positions in the meantime, two positions as a chaplain and one one as a rector. Holding such overlapping offices is not untypical for the seventeenth and eighteenth century and poses a challenge to the coding of these offices. The paper has adopted the rule to only use occupations for addresses where a person actually lived. If a person fulfilled two offices at the same place, the paper uses the one that was most likely a person's main source of income. Hence, for Thomas Smith, the data coding in figure 51 includes an entry of him being a chaplain at the embassy at Constantinople from 1668 to 1671. It further includes his appointment to Sir Joeseph Williamson, secretary of state, and a short stay as rector of Standlake, Oxfordshire.[84] Yet, it excludes his travels in France that apparently only lasted for a year and that cannot be pinpointed to one address.

Furthermore, looking at Smith's occupation after 1688, the short-biography is insufficiently vague, only stating that he "had charge of the Cottonian manuscripts". This makes it necessary to consult the *Oxford Dictionary of National Biography* that states the he became the "unofficial librarian of the Cotton Library (...) [but] had never been paid for his services as librarian but had lived from his scholarly production and the financial support of friends" (Harmsen, 2004).[85] As the occupational scheme presented in this paper primarily asks after a person's source of income, and only secondly after their "functional" activity, his occupation after 1692 is coded as being of "independent means". A further implication of this way of coding occupations is shown by the future of Thomas Smith's stay in London. In 1702 Sir

[82]The university of education is coded as Oxford. Thus the coding intentionally excludes incorporations of degrees – i.e. the official recognition of another university's degree at a university where a student did not graduate.

[83]Non-jurors were a dissenting fraction fraction *within* the Church of England that refused to swear allegiance to the newly crowned William III after the Glorious Revolution of 1688. As non-jurors still remained part of the Church of England they are not coded as dissenters.

[84]Harmsen (2004) states the resigned this additional appointment himself.

[85]The ODNB further increases the level of accuracy regarding his address after 1689 as it gives us the information that Smith lived at "lodgings in Dean Street, Soho, in the house of his nonjuror friend Hilkiah Bedford".

John Cotton died and the library was locked up (ibid.). Yet, although, according to Harmsen (2004), the "grievous disappointment of no longer being able to act as unofficial librarian of his beloved library embittered Smith" (ibid.), Smith continued his scholarly work without interruption between 1692 and his death in 1710: Coding by the source of income seems to be a more stable category than coding after functional activities and hence does not necessitate a new entry in 1702.

However, sometimes marking the exact time of career changes can be inherently imprecise. While official appointments, such as professorships or official offices are directly connected to a starting date, some occupation shifts are more subtle. This issue can be illustrated by looking at one of the craftsmen members of the Royal Society, John Whitehurst (1713–1788 and F.R.S. 1779), who originally practised as a clockmaker, but later on expanded his business into different kinds of scientific instruments as well. Thus, drawing on additional information from the *Oxford Dictionary of National Biography* (Vaughan, 2004), the paper adopts the following assignment of occupations: During his mature years in Derby from 1735–1771 he is recorded as a "clock-maker", while for his later years in Derby (1772-1778) and London (1779-1788), he is recorded as an "instrument maker". Yet, the timing in the shift in his occupation is only based on Vaughan (2004)'s observation that "By this time [1772] Whitehurst had extended his range of products to include scientific instruments". Thus, the following problems arise: First, shifts between occupations can be (inherently) imprecise. Second, often such members would have continued their original trade, in the case of John Whitehurst clock-making, in the background. Hence, when using this data for statistical purposes it is important to use large enough time periods (e.g. of 10 or 25 years) that allow for measurement error in the coding of the times of each occupation. Furthermore, any model that studies individual-level effects should explicitly allow for the effect of lagged values of occupations. The last point is also valid independently of measurement problems: Any previous occupations in t_{-1} would add to the skill set, human capital, and social capital of a person in in t_0. Careers are path-dependent and often cumulative processes build on a person's professional career in the past. Furthermore, using known addresses with a date as the basic unit of analysis means that some occupations that were not linked to one address, such as the army or the navy, might be under-represented.

Table 52: Success Ratio of Occupational Coding

	All R.S. Members				
Election date	Members	Occ. info	Share	No lifetime dates	Shares
1660–1675	400	344	0.86	31	0.94
1675–1700	229	194	0.85	22	0.94
1690–1705	288	238	0.83	19	0.89
1705–1720	456	351	0.77	35	0.85
1720–1735	539	291	0.54	78	0.68
1735–1750	532	240	0.45	103	0.64
1750–1775	558	345	0.62	99	0.80

Table 53: Success Ratio of Occupational Coding

Members from Britain			Members from Britain with lifetime info		
Election date	Members	Occ. info	Share	No lifetime dates	Shares
1660–1675	320	301	0.94	8	0.97
1675–1690	158	148	0.94	3	0.96
1690–1705	197	177	0.90	0	0.90
1705–1720	293	253	0.86	3	0.87
1720–1735	255	192	0.75	9	0.79
1735–1750	199	147	0.74	8	0.78
1750–1775	266	242	0.91	1	0.91

Next, table 52 and 53 show the success rate of assigning occupational categories to Royal Society members. Table 52 shows the overall numbers of members assigned to occupational categories within this project. However, this also includes the considerable number of corresponding foreign members of the Royal Society. As these generally have less information in their entries from the *Raymond and Beverly Sackler archive resource project* and as time-constraints have not yet allowed full additional research on these members within this project, data for these fellows is less representative. However, for the empirical analysis, this paper only draws on the British members of the Royal Society. These are defined as all members for who we know that they lived in Britain during at least one point in their life.[86]

Table 53 shows the success rate of matching all British fellows. We see that success rates ranged from 74% to 94% depending on each decade. Generally, the availability of information for early fellows elected between 1660 and 1700 is usually comprehensive leading to success rates of over 90%. Similarly, the period after 1750 also yields a success ratio of 91%, reflecting

[86]There is some additional survival bias on fellows for whom we lack information to assign a nationality. I will be able to present better statistics on this once I have completed my research on the occupations and locations of all foreign members.

the higher number of extant source material and biographical information for the second half of the eighteenth century. However, there is a dip for members elected during the first half of the eighteenth century. Therefore, the next paragraphs will reflect on the survival bias on member biographies inherent in this data. One additional measure that should be considered is the numbers of fellows for whom the Bulloch's Roll only includes their date of election, but not their date of birth or date of death. It is thus unlikely that most of these names could ever be matched to other sources. Therefore, the right side of table 53 presents the share of all matched members with lifetime information that can be interpreted as the success rate of matching possible candidates for to occupations. As we see, these cases usually do not make up for more than 5% of all members. Therefore, the main source of survival bias seems to come from fellows with known lifetime dates for whom this study could not find information on their occupations in life. What drives this survival bias?

First of all, such missing information on a fellow results from a lack of biographical scholarship within the secondary sources. Thus, who is included in the *Oxford Dictionary of National Biography* is shaped by contemporary judgements as well as the question whether there are extent sources on a given person. Furthermore, additional biographical information from the secondary literature is usually more comprehensive for the nobility, members of parliament, physicians, or university men due to the availability of additonal biographical lists and compilations for these professions. Therefore, it is important to compensate for bias resulting from drawing exclusively on the secondary literature. Therefore, the coding process also draws on the original election certificates of the Royal Society. Yet, the practise of compiling election certificates was only started in the 1730s, making the period 1720–1730 a less representative period than others, and never became entirely consistent, so that we have some members for whom election certificates were never compiled (or lost). Besides this more general survival bias of election certificates, it is also the case that not all election certificates included a candidate's profession. Instead, they sometimes simply described a candidate as e.g. a "Gentleman particularly studious in various branches of Science which are the peculiar objects of the attention of the Royal Society (. . .)" (Royal Society, 1791). Here it is likely that these descriptions often referred to men with independent and a private interest in scientific topics. Hence, the lack of a profession on an election certificate might not be an omission, but an accurate description of the lives of rentiers. However, there is no way to ascertain this impression — therefore, such members could not be assigned to occupational categories.

Hence, it appears that there is some inherent survival bias in the data. Given the previous discussion, we would expect the bias to point towards an overweighting of the nobility, members of parliament, physicians, and university men as well as an underweighting of settled "gentlemen" of independent means that is strongest for the first half of the eighteenth century. Hence, we might see an artificial compression of the relative share of e.g. rentiers, independent means, merchants, and craftsmen for the period of 1700 to 1750. Furthermore, comparisons of the composition between potentially overweighted and underweighted groups between the periods of pre 1700, 1700-1750, and post 1750 should be taken with care. However, any broader trends going back to 1660 that remains consistent after 1750 are not likely to be affected by survival bias. Likewise, adding interactions between period dummies and occupational classes might be a sensible method to account for this potential survival bias in the empirical framework.

C.4.3 Manual Coding Rulebook

Locations of Society Members:

- Explicit addresses and plausible inferences from job occupations (e.g. "surgeon at St Thomas's Hospital" ⇒ Southwark, London) are used for members' addresses
- Short-term stays (<= 1 year) as well as travels are excluded
- Addresses are only included when they are sufficiently specific, that is at least allowing identification on a town-level ("born in Cornwall" is excluded, "lived in Soho near Birmingham" is included)
- Only addresses with a date are included. Otherwise, the construction of a dynamic panel becomes impossible.
- This coding scheme does not allow for multiple residences at the same time. Usually the short biographies allow for distinguishing between e.g. a summer residence (excluded) and a permanent home (included). Also, some offices, especially church offices in different places were often held at the same time. In this case, excluding clearly honorary positions and looking at the time the positions were held and drawing on further secondary sources help identifying the primary position. If this is not possibly, addresses in doubt are excluded.
- The "address field" from the *Raymond and Beverly Sackler archive resource project* recording addresses from the Bulloch's roll or other archival records from the Royal Society is used as additional information.
- If a member is recorded as a member of parliament, then the member is supposed to have had a permanent address in London — although MPs often did not have permanent residence in London.[87]

[87] This assumption is admittedly nothing but a rough proxy for a member's true permanent address. Yet, it appears a more reasonable assumption than uncritically drawing on an MP's constituency as an approximation of the MP's place of residence. Constituencies often enough did not correspond to an MPs actual local interest. Instead, patronage, as well as the infamous rotten boroughs were important elements in 17th and 18th century elections — see Kishlansky (1986).

- Education is not an occupation (e.g. studying at a university) and therefore treated separately. However, occupations in teaching, e.g. fellowships are an occupation.
- “Imprisoned in Tower” is not a place of residence

C.4.4 Entry barriers into the Royal Society and scope of its membership

Founded in 1660, the Royal Society was Britain's first scientific society and remained its only one until the foundation of foundation of the Lunar Society in Birmingham in 1765. Its members featured the familiar names of the English Scientific Revolution, such as Robert Boyle, Robert Hooke, Isaac Barrow, Isaac Newton, or John Wilkins and it would become Britain's most eminent scientific society and "the very embodiment of the ideal of the free dissemination of useful knowledge" (Mokyr, 2002, p. 43). Entry into the society depended on being proposed by at least three members (formalized in 1730) and a favourable ballot vote of the council. This mechanism was designed to ensure a minimum of scientific proficiency and prestige. Furthermore, with membership also came the duty of membership fees. Hence, it is important to quickly discuss the extant of the exclusivity of the Royal Society to understand its representativeness for the broader Brititish scientific elite.

First, it is important to point out that the Royal Society was more open than the state funded academies of the continent. However, images of the Royal Society with respect to its openness differ within popular history. This paragraph will seek to clarify some confusion. On the one hand, the exclusiveness of the Royal Society in the nineteenth century is often projected on its past in the early seventeenth and eighteenth century. On the other hand, an image of absolute openness of the Royal Society to anyone seeking entry has been popularized by Voltaire:

> "A seat in the Academy at Paris is a small but secure fortune to a geometrician or a chemist; but this is so far from being the case at London, that the several members of the Royal Society are at a continual, though indeed small expense. Any man in England who declares himself a lover of the mathematics and natural philosophy, and expresses an inclination to be a member of the Royal Society, is immediately elected into it" (Voltaire, 1733).

However, we should take the Voltairian description with a grain of salt, pointed more at the shortcomings of the French Academy than an accurate description of the Royal Society itself.

Still it contains some truth if only comparatively. To understand how a person could enter the Royal Society, the next paragraphs will describe the election process in detail:

Entry into the Royal Society was always dependent on being suggested by existing members. The minimum requirement for membership can be inferred from the official election certificates that usually highlighted that a person was, in the language of the certificates, "well versed in natural philosophy".[88] However, scientific achievement appears to have been helpful for entry, but not necessary. *[work in progress, statistics on members publishing]* Miller (1989, p. 156) for example, describes the entry criteria of the Royal Society in the eighteenth century as "lax" and the Royal Society as an "open institution". Another indicator for the relative openness of the Royal Society is the rejection rate at election. Appendix figure 53 shows the number ratio of elected fellows and those elected as candidates but not confirmed. The non-confirmed cases consist of rejections, but also sudden deaths before election or ambiguous source materials. Hence, the number of non- elected fellows represents an upper-bound estimate of the true number of rejected fellows. Figure 53 shows that rejections only started to become significant after 1700, but even then the mean acceptance rate between 1700–1800 remained at a high level of 95%. Surely, being suggested by at least three members was the most significant barrier even before a candidate was put to ballot. Yet, the low rejection rates at least show that membership proposals were not competitive within the Royal Society itself. Also, as shown by (Dowey, 2017, p. 85), the average age of the fellows of the Royal Society at the time of election was around their mid-thirties throughout the eighteenth century, in contrast to their late 40s to early 50s during the second half of the nineteenth century or even their mid-70s in the first decade of the 2000s. Thus, membership was an active part of a scientific career, not only an honour received late in life. The evidence thus indicates that membership of the Royal Society was conferred upon successfully practising members of the scientific elite (and its patrons). Entry to the institution was guarded by eminent scientists themselves. However, it seems that although high knowledge and an engagement with the natural philosophy of the day was expected, special accomplishments were not necessary for entry.

[88] Compare to e.g. Ralph Knight (elected 1741) described as a "Gentn of Learning, distinguisht Merit, well versed in Natural and Philosophical knowledg" (Royal Society, 1741).

How strongly the Royal Society overlapped with the dimension of "eminent or notable scientists" can by seen by Hans's (1951) analysis of the educational and social background of all entries in the *National Dictionary of Biography* (D.N.B.) for men born between 1685 and 1785 who are known to have received any formal education. Of these, Hans identified 689 entries as "scientists".[89] Out of these 689 entries, 539 were also fellows of the Royal Society. All in all, the Royal Society seems to have adopted the role of an institution that organized the early research discipline of the areas of the Scientific Revolution under its umbrella. It seems to have been inclusive for the members of that academic research program and exclusive to outsiders. Thus, the fellows of the Royal Society seem to be a good proxy for the rank and file of the British scientific elite as conceived by contemporaries and modern writers of biographical dictionaries. However, it excludes the many improving artisans or practising schoolteachers who came to neither wide recognition nor fame, but also plaid a crucial role in the dissemination of useful knowledge (see e.g. Kelly, Mokyr and Ó Gráda, 2023).

Lastly, it is important to consider the arrival of provincial scientific societies after the second half of the eighteenth century as a potential substitute for membership in the Royal Society. Yet, it appears that many of these societies had a significant overlap in membership with the Royal Society. Often it even were Royal Society members that founded these societies. One major foundation of the eighteenth century was the Society for the Encouragement of Arts, Manufactures and Commerce in 1754 that primarily focused on practical improvements, rather than "scientific" discourse (see Howes, 2020). Yet, in its beginning 60% of the founding members were also Royal Society members (Dowey, 2017, p. 42). Later, the Lunar Society in Birmingham, the prototype of many later provincial "scientific" societies, was founded in 1765 (see Schofield, 1957, 1963). Yet, Erasmus Darwin as one of its most decisive founding members had already been elected as a member of the Royal Society in 1761. Thus, the input from and connection to the Royal Society itself seems to have inspired the creation of the Lunar Society as the Royal Society's unofficial provincial offspring. After his involvement in the Lunar Society, Erasmus Darwin further ventured to co-found the Derby Philosophical Society in 1783.

[89] In this number, Hans (1951) further included 130 men "who attained eminence through apprenticeship and practical work without receiving any formal education as" (Hans, 1951, p. 34) as well as 186 additional entries for men born in the seventeenth century.

Furthermore, membership numbers of the early provincial societies were relatively small. For example, the much studied Lunar Society only featured 14 active members. Thus it appears, that at least until the very end of the eighteenth century, chances to substitute membership in the Royal Society with membership in provincial scientific societies were low and if they existed still correlated with the presence of some fellows of the Royal Society. Often, it seems membership in provincial societies was a complement to membership in the Royal Society and not a substitute. Thus, possible bias through such a substitution mechanism appears small. Overall, the Royal Society seems to be as useful and consistent a proxy than we could expect to find for capturing the British scientific elite throughout the late seventeenth and eighteenth century.

5 Science and patenting: An analysis of English patents, 1700–1820

Abstract

How much did technical innovations during the English Industrial Revolution rely on advances in science? This paper adopts a new way to answer this old question by creating a new index of patent proximity to science. The index is based on applying natural language processing techniques to the universe of English patents and scientific texts during eighteenth century. The paper finds that a higher degree of proximity to science is linked to increased innovativeness in patents, particularly in the fields of applied physics, instruments, mathematics, and chemistry. The major industries that profited from patent proximity to science were textiles, chemistry, and instrument making. Altogether, the paper shows that there was already a solid interaction between scientific ideas and practical inventions as early as the First British Industrial Revolution.[90]

Keywords: Knowledge Diffusion, Innovation, Human Capital, Natural Language Processing

JEL Classification: N33, I23, O33, O31, O43, O14

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5.1 Introduction

There is a long-standing debate on the impact of science on technical innovations during the first British Industrial Revolution. On the one hand, there is a tradition in the literature arguing that eighteenth century science was a direct driver of technical innovations (Schofield, 1957, 1963; Musson and Robinson, 1969; Jacob, 2014). Other accounts (Mokyr, 2002, 2016; Stewart, 1992; Stewart and Weindling, 1995; Stewart, 2007) have argued for a more indirect role of scientific and enlightenments ideas on technical innovations that culminated in an "industrial enlightenment" (Mokyr, 2009). On the other hand, other scholars have argued that eighteenth century science did not yield right predictions, was of questionable use, and if anything, only played a secondary role in fostering innovations (Mathias, 1972; Hall, 1974; Ó Gráda, 2016).

Empirical evidence on this question is rare. One important contribution is Hanlon (2023) who studies the number of patentees who also published in the scientific journals of the Royal Society for the time period 1800–1869. He finds that the number of patentees who also published in scientific journals was relevant and constantly rising throughout the time period. He further finds that patentees who also published in scientific journals also had higher quality patents. The innovation of this paper is to move beyond co-authorship as a proxy of knowledge spillovers and to introduce a new text-as-data based measure of *patent proximity to science* that captures the use of common concepts and ideas in both science and technology.

To measure whether the technology of the First Industrial Revolution also incorporated concepts from science, the paper exploits information stored in the text data of eighteenth and early-nineteenth century patents and eighteenth century scientific books. Using natural language processing (NLP), the paper maps the content of patent descriptions and the titles of scientific books into a multidimensional content space. Then, calculating average proximity to scientific titles within the content space, we derive a measure of patent *proximity to the concepts and ideas* from science. The new index makes it possible to use variation from within the space of ideas to explain economic phenomena.

Drawing on this new index, the paper investigates the research question of whether patents that were more *similar to science* were also more innovative during the First English Industrial

Revolution. It finds that patents within the industries of *textiles, chemistry, and instrument making* were more innovative if they also had a higher proximity to a select number of scientific fields. These fields are *applied physics, chemistry, mathematics, and scientific instruments.* However, the paper does not find an association between proximity to science and patent innovativeness for the industries of *metallurgy, engines, and ships.* Yet, these broad findings do not rule out that some positive effects existed for sub-groups within industries. Taking engine industries as a case study, the paper finds that there was a positive association between engine patents that were directed at fuel efficiency and proximity to applied physics. Yet, we do not find an association between patents for new engine designs and proximity to applied physics. Overall, these results provide new insights into the role of science for the early Industrial Revolution and its role on different industries. The results appear compatible with early science having a modest, but significant impact on a select number of industries during the First Industrial Revolution.

To construct the new index *patent proximity to science*, the paper uses a) patent descriptions from Woodcroft (1854*a*) and b) the universe of all scientific texts from the English Short Title Catalogue, 1600–1800. It then uses a large-language model to create a representation of the concepts and ideas within the text data in a geometrical space. Next, it defines an index of average patent cosine proximity to titles within scientific fields. The index performs well when tested against narrative descriptions from the literature and an intuitive assessment of the most "scientific patents" according to the index. The paper then uses the new measure of *proximity to scientific fields*, to estimate the association between a patent's proximity to science and a patent's innovativeness. To assess a patent's innovativeness, the paper draws on bibliographic patent citations from Nuvolari, Tartari and Tranchero (2021).

The estimation strategy faces the challenge of separating effects that are solely due to *proximity to science* from confounders that correlate with *proximity to science* such as e.g. writing style. If these confounders also correlate with patent innovativeness, this would lead to severe bias. In the case of writing style, this appears easily plausible. We would expect writing style to vary by a patentee's educational background which could either reflect a patentee's skills or a patentee's choice of technology class. Furthermore, we would expect that different technology classes are likely to have had different potential for innovation based on e.g. the presence of low-hanging fruits or the limitations of eighteenth century technology. Hence, it is easily imaginable that *proximity to science* correlates with an educated writing style and this writing style correlates with other factors associated with patent innovativeness.

To address these concerns, the paper follows a twofold strategy: First, it employs a wide range of controls for individual patentee characteristics including patentee's HISCLASS status from Nuvolari, Tartari and Tranchero (2021). It further employs time and technology class fixed effects from Billington and Hanna (2020). Second, the paper employs a placebo approach where for each scientific field we define a list of industries that could have been plausibly affected by the particular scientific field and another list of industries that should not have been affected. For example, for the scientific field of *Chemistry*, we would expect a plausible effect on *chemical industries.* However, we would not expect a plausible effect on industries such as *carriages, construction, furniture, hardware, etc.* Hence, the latter group is used as a placebo group. The placebo group tests whether the proximity to scientific fields index picks up any spurious associations with proximity to science, such as e.g. writing style, and therefore serves as an important validation of the results.

The paper finds that there was a relevant and significant association between the scientific fields of *applied physics, chemistry, mathematics, and scientific instruments* and a select number of industries. These industries are *textiles*, *instrument making*, and *chemical industries.* The industry-placebo approach confirms that we do not find associations between proximity to a scientific field an unrelated industries. For textile industries, the fastest growing industry of the British Industrial Revolution, the paper finds that a one standard deviation increase in *proximity to applied physics* was associated with a 4.8% increase in patent innovativeness. Likewise, increasing *proximity to mathematics*, and *proximity to scientific instruments* by one standard deviation is associated with an increase in patent innovativeness of respectively 5.6% and 5.1%. Hence, the findings show that even during the early British Industrial Revolution science meaningfully interacted with technological innovations at core industries of the Industrial Revolution, such as textiles.

Yet, the results that science mattered for textile industries might appear surprising, since innovations in textiles have often been viewed as the product of simple tinkering rather than high-science (Mokyr, 1992; Cardwell, 1994). To shed light on this apparent paradox, the paper goes into some length to capture the *content* of the scientific concepts that drove higher patent inoperativeness. The paper introduces an approach that it calls *stipulative proximities* to key terms. Effectively, it calculates proximity to representations of key-words, such as *precise measurement*, within the content space. These new stipulative proximities are then added to the regression in a horse race approach. The approach is similar to Ash, Chen and Naidu (2022) who use similarity of judges' rulings to word embeddings of key terms in law-and-economics.

Concretely, the paper follows two accounts from economic history that have argued that scientific ideas and methods had a bearing on textile industries. First, Kelly and Ó Gráda (2022) argue that systematic quantification and precise measurement taken from science had a positive impact on textile industries. Second, Jacob (2014) has argued that Newtonian mechanics were at the core of engineering progress during the British Industrial Revolution and even affected innovations in textile industries. In a horse race specification with stipulative distances, the paper finds that the precise measurement view can account for half of the effect size of *applied physics*. Although Newtonian mechanics seem to have had a small effect as well, it appears that precise measurements and systematic quantification lay at the heart of textile innovation. Hence, the findings of this paper, in accordance with Kelly and Ó Gráda (2022), stress the importance of spillovers from scientific practise and scientific spirit for innovations during the early British Industrial Revolution.

These results raise the question of why, for engines, we do not find a positive association between proximity to applied physics and patent innovativeness. Afterall, improvements in e.g. steam engines also fundamentally relied on precision engineering for e.g. cylinders and condensers that had to bear the full force of the heated steam. A potential solution to this puzzle is that the design of new engines was very different from the process of improving engines. To test this hypothesis, the paper splits the sample by patents for engines that were efficiency improving and all other innovations, mainly the design of new engines. It finds that only patents aimed at improving efficiency showed a positive association between proximity to applied physics. The results fit well with the widely held notion in the history of science and technology that early thermodynamics owed more to steam engines than steam engines to early thermodynamics (Mokyr, 1992). At the same time, the practical methodology of early-science, in the form of precise measurements, seems to have been a key element in the precision engineering to make steam engines workable and more fuel efficient.

Lastly, the paper investigates the role of patentees in the innovation process. First, it shows that patentees who published scientific books were also more likely to produce patents with a higher proximity to scientific fields. Next, the paper follows the question of how many patentees, often from a humble background and distant to the social circles of high science, could have accessed ideas from science. The paper suggests that textbooks summarizing the state of science and technology could have been an important mechanism in the knowledge transmission. The paper uses natural language processing to calculate patent proximities to two contemporary textbooks, John Bank's *A Treatise on Mills* (1795), and his subsequent *On the Power of Machines* (1803). Then, in a horse race specification it shows that these two books can account for half of the effect size of *proximity to applied physics.* This is strong evidence that textbooks would have carried enough information to drive the prior results for patent innovativeness and *proximity to applied physics.*

The paper speaks to a large literature on the economic impact of scientific innovations. There is a wide consensus on the modern impact of scientific innovations on technical innovations. For example, Mansfield (1991) analysed survey data from business executives on whether their product new products would have been possible in the absence of academic research within the last 15 years. He finds that 11% of firm's new products and 9% of new processes would not have been developed in the absence of science. Furthermore, the impact of modern universities on patenting and economic growth been widely documented Kantor and Whalley (2014); Valero and Van Reenen (2019); Andrews (2023). Yet, it is not clear how much science mattered during the early Western take-off towards modern economic growth.

Most of the evidence on the early impact on science focuses on the second-half of the nineteenth century. However, there are a few important contributions that have shed light on the beginning of science's positive impact on technological innovations. First, Hanlon (2023) has shown that scientific patentees, proxied through publications in scientific journals, also produced more innovative patents for the time period 1800–1869. He also shows that scientists in modern scientific fields such as mechanics, chemistry, sound, scientific equipment, electricity, and engineering were most likely to also register patents. Second, Dittmar and Meisenzahl (2021) argues that scientific innovations at German research universities led to large spurts in technological innovations and economic growth after 1800. They show that distance to German research universities was a strong predictor of manufacturing and exhibits at the Crystal Palace exhibition. This study contributes to the literature by adding evidence to the role of science on technological innovations before 1800. Furthermore, it introduces a novel way of capturing proximity to science within patent innovations by applying natural language processing to the text of patents and eighteenth century science.

The paper further speaks to the importance of upper-tail human capital that have been highlighted by a large literature, including Squicciarini and Voigtländer (2015), Hanlon (2022), and Kelly, Mokyr and Ó Gráda (2023). It demonstrates how one element of how upper-tail human capital, knowledge about science, could have fostered economic growth. By showing that scientific insights from systematic quantification and precise measurement were an important input into patent innovations, this paper also highlights specific groups of upper-tail human capital that would have been important for accessing insights from practical science, such as watchmakers, instrument makers, as well as applied mathematicians (see Kelly and Ó Gráda, 2022).

5.2 Data

5.2.1 Patent data

The paper combines the current state of research on British patents by combining patent data from Nuvolari, Tartari and Tranchero (2021), Billington and Hanna (2020), and Billington (2021). This combined dataset includes data on patentees, year of patenting, technology classes, industry and the social background of patentees. The paper then matches this stock of patent data to patent descriptions from Woodcroft (1854*a*) that will be used to construct an index of patent proximity to science. Appendix section D.1.1 describes the construction of each variable in detail.

Patent descriptions from Woodcroft (1854*a*) list the original descriptions of the original patents granted. These are overall short descriptions of the patents with an average length of 186 words. Table 54 lists an example entry. It is a patent registered by Thomas Cochrane, a Royal Navy officer born from a scientific inventor's family, and notably the historical inspiration for Patrick O'Brian's Jack Aubrey. The patent itself refers to various scientific concepts such as *atmospheric pressure* or *combustible matter*. The example shows that the patent descriptions usually contain some information on the patentee, some legal text on the confirmation of the patent as well as information on the patent itself: Usually they take a form where they convey information on the object of invention as well as its purpose. Furthermore, they provide a short summary of the method with which this aim is achieved. These descriptions are usually brief and were often supplied by full technical drawings of the invention. As a basic pre-processing, the paper uses regular expressions to separate the legal text from the actual description of the patents. The yellow background in table 54 illustrates the process.

TABLE 54: Example of a patent description from Woodcroft (1854*a*)

Patentee	Year	Patent description
Thomas Cochrane	1813	A grant unto Sir Thomas Cochrane, knt, for his invented method and methods of regulating atmospheric pressure in lamps, globes, and other transparent cases; of supplying combustible matter to flames, and preserving uniform intensity of light; to hold to him, his exors, admors, and assigns, within that part of our united kingdom of Great Britain and Ireland called England, our dominion of Wales, and town of Berwick-upon-Tweed for the term of fourteen years pursuant to the statute; with a clause to inroll the same within six calendar months from the date thereof By writ, & c

Using patent data, it is important to be aware that patenting rates differed widely across different industries. As shown by e.g. MacLeod (1988) and Moser, Voena and Waldinger (2014), patenting rates were high in industries where reverse engineering was easy, while patenting rates were smaller in industries that could effectively rely on secrecy. Hence, the following analysis will apply industry-fixed effects or conduct the analysis on an industry-by-industry basis. Furthermore, it is possibly that patenting rates varied between industries based on the nature of invention. Other incentives, like e.g. medals or a culture of open-science might have motivated inventors not to patent high-quality observations which are therefore lost in this dataset.

5.2.2 Constructing an index of patent proximity

Is it possible to use the information contained in the patent data to construct an index of proximity to eighteenth century science? Such an approach should overcome the following challenges:

1. The index should be based on a representative sample of eighteenth century science
2. Given that the influence between e.g. applied physics and chemistry is likely to have been very different on patenting, the index should be able to distinguish between different scientific fields
3. The index should identify the use of similar concepts, object, and ideas as in scientific texts. This can be challenging as the language used in patent titles might differ from the language in scientific texts, even when referring to the same concepts.
4. The index should not capture spurious similarities in language (e.g. how often do texts mention the word "abstract")

The paper addresses the first two challenges by creating a text-corpus of eighteenth century science based on the titles from the universe of British scientific publishing based on the English Short Title Catalogue (ESTC). Scientific titles are split into the fields of *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*. The ESTC data and methods used to construct these scientific fields are described in the previous papers of the thesis.

Next, the paper addresses the last two challenges, by introducing a new approach of measuring a historical patent's proximity to science based on state-of-the-art large-language models (LLM) based on a transformer architecture. These models capture semantic and contextual information in textual data, allowing for a deeper understanding that is able to capture the use of concepts, objects, and ideas. The paper uses a BERT model (Bidirectional Encoder Representations from Transformers) to process the texts from both patents and scientific subjects from the ESTC. This approach yields text-embeddings for both the patent and ESTC data. Texts embeddings are a dense vector representation of the meaning of text in a multi-dimensional space. Proximities between these embeddings of patents, and eighteenth century science can then be calculated using cosine similarities. For patent p_i proximity to science, Ω, is defined as the average cosine similarity to a scientific field:

$$sim(p_i) = \frac{1}{N} \sum_{\tau_j \in \Omega}^{N} cos(p_i, \tau_j) \tag{36}$$

It is important to recognize what this index can and cannot capture. First of all, it is limited by the content of patent descriptions. If the invention underlying a patent relied on ideas from science in the construction of one of its components, but this is not mentioned in the patent description, then the index cannot capture this. Likewise, if a patentee was lying about the concepts used in the construction of a patent, then the index will be biased. Overall, given the relative brevity of the patent descriptions it is likely that this index misses many connections between patented inventions and science, especially so if the connection between patented inventions and science only concerns sub-components or technical details. On the other, this also means that the index is likely to only capture the relevant ideas and concepts that were considered important enough to be mentioned in the patent descriptions. Hence, the index is well suited to study patents that relied on science at the core of their invention.

Additionally, it is important to keep in mind that the index is only supposed to capture the intensity of the use of scientific ideas, concepts, and objects. It does not test how central the concepts are to the underlying invention, nor whether they are applied correctly. There are many examples of s

The following section will conduct some intuitive quality checks on the index. It will test whether the index is able to replicate well known patterns on the connection between science and patenting. Furthermore, this exercise will provide some intuition on the nature of scientific concepts, objects, and ideas. The section will argue that proximity to science was often driven by basic concepts like precise measurement and experimentation, instead of the "high science" of complex theories.

5.2.3 Quality checks

This section exposes the new patent proximity to science index to a few basic and intuitive quality checks. First, this section presents a basic comparison between patents that are the most and the elast similar to applied physics to judge whether this captures our basic intuition about the use of scientific concepts. The underlying patterns of ideas, concepts, and objects, within these patents are further illustrated using word clouds. Second, the paper lists a few famous patents, both that are known for incorporating scientific concepts and those that are the product of basic tinkering and compares their proximity to applied physics. Finally, the paper investigates whether descriptions from the historical literature of scientific concepts that were incorporated into inventions during the Industrial Revolution fit with the patterns found in this index. Altogether, these different approaches seek to test whether the new index adheres with our intuitive understanding of patent's "scientificness" and aims to illustrate what concepts are driving the variation of the index.

First, table 55 lists the 10 patents that are most similar to applied physics and the 10 patents least similar to applied physics. At the top of the list we find patents explicitly referring to scientific concepts such as "the specific gravity of fluids and metals", "concentrating by evaporation various sorts of liquid", "communicating motion in or unto bodies", or "atmospheric pressure". We further find reference to scientific objects or instruments such as a "gasometer", a "quadrant", or a "selenographia", an astronomical model of the moon.[91] Overall, the 10 patents include a mix of scientific or technical instruments and chemical processes. In contrast, table 56 list the 10 patents at the bottom of the proximity to applied physics index. Reassuringly, they feature purely practical processes such as "improved methods of splitting hides and shaving or splitting leather", a new "belt or girdle", or a new "health restoring pill". Altogether, the titles from table 55 and 56 capture our intuition that these patents with a high

[91] John Russel's (1745-1806) original *Selenographia* is kept at the Royal Maritime Museum in Greenwich.

proximity to applied physics index do incorporate ideas, concepts, and objects from physics, while patents at the bottom of the index do not.

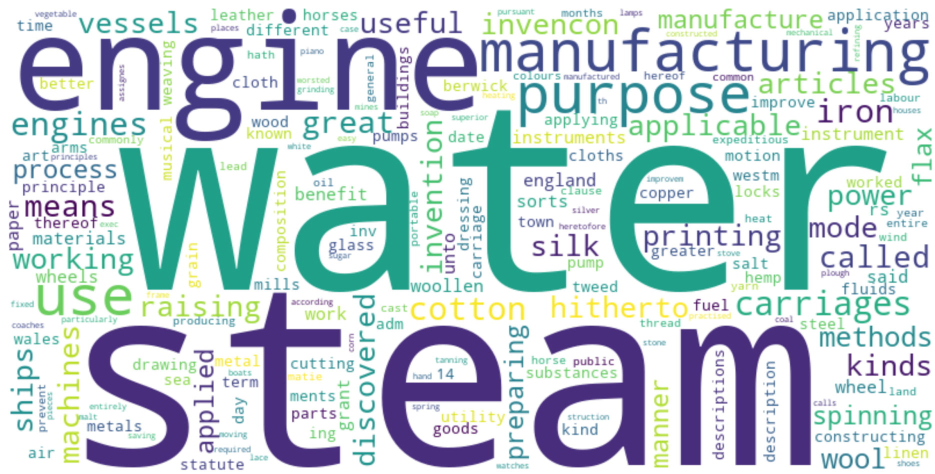
Yet, these 10 top and bottom patents with respect to their proximity to science should not be seen as representative for the sample. Instead, they convey useful information about the nature of patents within the extreme ends of the proximity to science distribution. In order to have a more representative overview of the content of patents close to science and distant to science is to use word clouds. Word clouds give a visual representation of the most frequent words within a corpus of text, by scaling words according to their frequency. To capture the use of *relevant* words within the corpus, the paper uses a tf-idf approach (term frequency–inverse document frequency approach). Here, *relevant* words are defined as words that appear frequently in an individual document in comparison to its frequency in the whole corpus. Figure 59 plots word cloud representations for the tf-idf frequences of all patents ($n = 4,063$) and the top 2% of patents ($n = 82$) that are most similar to applied physics.

Table 55: Patent Details and Proximity to Applied Physics

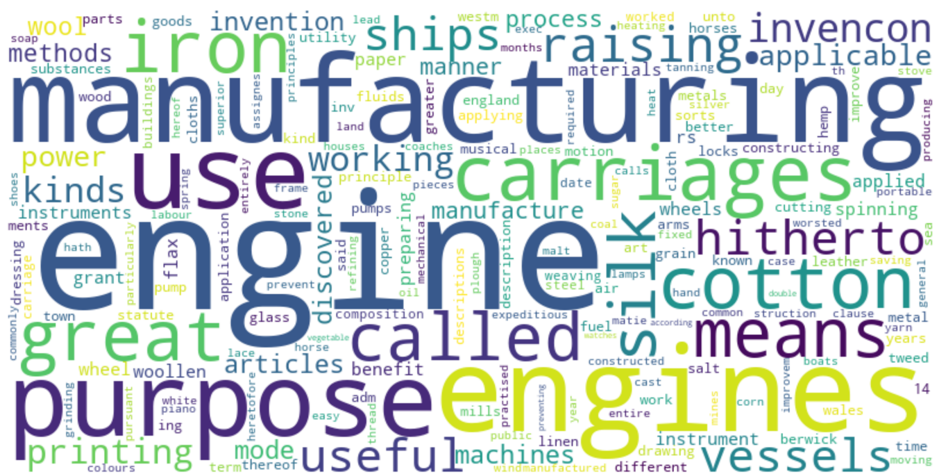
Patentee	Year	Patent description	Proximity to applied physics
John Ashton	1818	invented " Certain improvements in 732 CHRONOLOGICAL INDEX OF or on instruments and apparatus for ascertaining the strength of spirituous liquors, and also the specific gravity of fluids and metals "	0.264
James Atkinson West	1817	invented " Certain improvements in or on lustres, chandeliers, lan thorns, and lamps of various descriptions, and in the manner of conveying the gas to the same "	0.259
William Robert Wale King	1813	invented certain improvements in the application of heat to the purposes of boiling water and other fluids, and to other useful purposes, and of the apparatus of perform? the same	0.253
Anthony Perrier	1822	invented " Certain improvements in the apparatus for distilling, boiling, and concentrating by evaporation various sorts of liquids and fluids	0.248
William Caslon the younger	1823	invt d "Certain improvements in the construction of gasometers "	0.248
John Hadley	1734	of the sole lycence and privi- ledge of making and vending his new invented instrument or quadrant for taking at sea the altitude of the sun, moon, or Starrs, as also any other angles, and also his new invented level to be fixed to a quadrant for taking me- ridional altitudes at sea, therein more particularly described	0.246
John Russell	1796	new invented apparatus named the selenographia, to exhibit the phenomena of the moon, consisting of a globe, on which are deliniated the spots on the moons surface, affixed to an instrument which is contrived to give it such motions as will describe the effects produced on the face of the moon under all circumstances; with certain appendages thereto belonging, illustrative of the same	0.245
Philip Taylor	1818	invented " New method of applying heat in certain processes to which the same method hath not been applied ; likewise for im- provements in refrigerators "	0.243
James Dawson	1814	invented certain means of producing or communicating motion in or unto bodies either wholly or in part surrounded by water or air, or either of them, by the reaction of suitable apparatus upon the said water or air, or upon both of them	0.243
Thomas Cochrane	1813	invented method and methods of regulating atmospheric pressure in lamps, globes, and other transparent cases ; of supplying combustible matter to flames, and preserving uniform intensity of light	0.242

Table 56: Patent Details and Proximity to Applied Physics

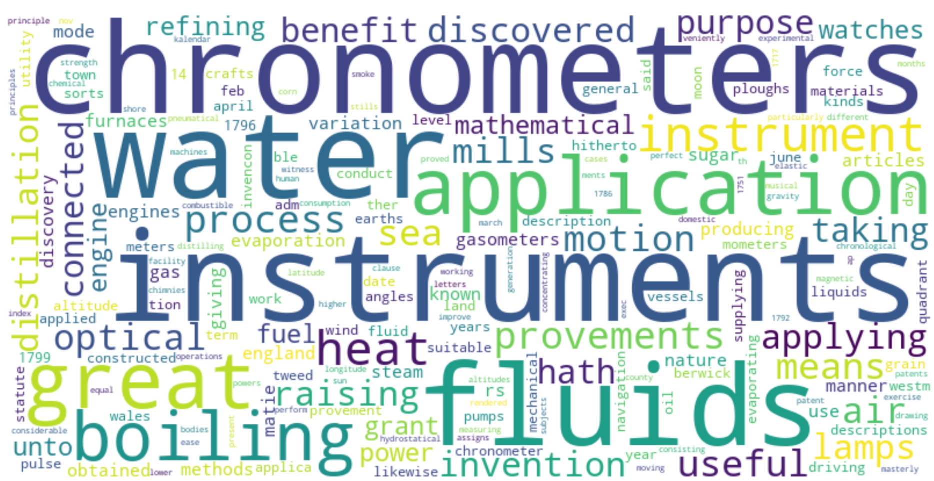
Patentee	**Year**	**Patent description**	**Proximity to applied physics**
Ferdinand Smyth Stuart	1809	discovered substitute, the produce of this country, for Peruvian bark	-0.011
Joseph C. Dyer	1811	new and improved methods of splitting hides and shaving or splitting leather	-0.004
William Leedham	1791	improvement for preventing the splinter bars of wheel carriages from being out of order	0.004
George Bolton	1795	new improved gun lock for muskets, pistols, and other fire arms	0.012
Robert Barber	1805	new and improved modes of making and shaping stockings and pieces, and also some new and improved kinds of stocking stitch and warp work	0.013
Thomas Watson	1783	new invented purging paste for horses & dogs, being a primary medicine for all diseases incident to each, & calculated for all ages & sizes of both the animals	0.015
Joseph Bramah	1784	new invented lock for doors, cabinets, and other things on which locks are used, which is more simple, effectual, and durable, & totally differs from any other sort of lock, being constructed without wheels or wards; and the same is also much cheaper, and cannot possibly be picked or opened by any of the means practised for picking locks, or by any other key than the key which belongs to the lock	0.017
George White	1812	improved method of preventing accidents from carriages	0.018
Walter Leake	1753	new invented pill, called pilula salutaria or health restoring pill	0.019
James Edgell	1762	new invented belt or girdle, called a shooting belt	0.019



(a) All patents



(b) All patents — without the terms of "steam" and "water"



(c) Patents within top 2% of proximity to applied physics

FIGURE 59: Word clouds of patent descriptions

Notes: Word clouds based on the text of patent descriptions excluding a basic list of stop words.

First, plotting all patents reveals the large importance of energy sources, with the terms *water* and *steam* featuring as the two most frequent terms. In order to make the interpretation of the other terms easier, sub-figure 59b removes *water* and *steam* from word cloud for all patents. It reveals wide usage of technical terms, such as "manufacturing", "engine", "carriages", and "cotton". In contrast, the word-cloud 59c for the top 2% of patents that are most similar to applied physics reveals a different pattern. These patents feature a wide usage of precision instruments such as *chronometers*, and *instruments*. Furthermore, the word cloud does not only prominently feature *water*, but also the physical term of *fluid*. Furthermore, the word-cloud refers to features concepts and processes such as *boiling, distillation, evaporation, motion, optical, or mathematical*.

These simple patterns already suggest that the proximity to science index does not only capture the incorporation of concepts from high-science such as mechanics, models, and predictions, but also captures the usage of precision-instruments, measurement, and applied processes from the scientific work-floor such as distillation or evaporation.

Lastly, we can draw on the literature on the scientific enlightenment in Britain to judge which kind of scientific concepts we would expect to see integrated into technical inventions and revealed in patent descriptions. As an example, Margaret Jacob argues that "Newtonian mechanics (as well as chemistry) (...) were applied (...) to the weight, friction, and velocity of wheels, to the gravity, elasticity, and combustibility of atmospheric air" (Jacob, 2014, pp. 111 f.) By counting the relative likelihood of these words, W, appearing in patents with a high score of proximity to applied physics, P, in comparison to all other texts, we can judge whether the proximity to science measure captures similar trends as the historical literature.

Table 57 shows the relative probabilities of the appearance of "Margaret Jacob words" within the top 5%, 2%, and 1% of patents that are most similar to the field of applied physics in comparison to all patents. We see that all of the words of *weight, velocity, gravity, atmospheric, and air* are more likely to appear within the top 1% of patents most similar to applied physics than in the full corpus. Furthermore, the difference between titles close to applied physics and the full corpus is very pronounced: For instance, the term "gravity" is 115 times more likely to appear in the top 1% of such patents, followed by *atmospheric* (14.49 times), *velocity* (9.66

times), *air* (4.8 times), and *weight* (1.66 times).[92] We further see that this difference is less pronounced for the top 2% and top 5% of titles (although even for the top 5% the term of *gravity* is 5.84 times as likely to be used). This shows that the description of scientific concepts used in inventions and patents described in the literature on the scientific enlightenment seems to correspond well to this paper's measure of proximity to applied physics. The strong results for the top 1% indicate that the literature seems to have highlighted the absolute top-tier of patents incorporating highly complex and theoretical concepts from physics. However, this does not necessarily mean that patents beyond the 1% or 2% threshold did not incorporate ideas from applied physics. Instead, the word cloud in figure 59 shows that this paper's measure of distance to applied physics might also capture the use of scientific ideas that are less complex, e.g. from a focus of measurement and processes from the scientific work-floor.

Table 57: Relative likelihood of "Margaret Jacob" terms appearing in patents similar to science in comparison to all titles

Term	Proximity to applied physics		
	Top 5% proximity	Top 2% proximity	Top 1% proximity
Weight	1.0	0.5	1.66
Friction	0.56	1.12	0.0
Velocity	0.97	2.94	9.66
Wheels	0.64	0.0	0.0
Gravity	5.84	35.33	115.90
Elasticity	—	—	—
Combustibility	—	—-	—
Atmospheric	1.46	4.42	14.49
Air	0.93	2.5	4.80

Notes: The table shows the relative likelihood of "Margaret Jacob words" appearing in texts similar to physics in comparison to all texts. Concretely, the paper calculates the relative probability of the words *weight, friction, velocity, wheels, gravity, elasticity, combustibility, atmospheric, and air*, W, appearing in texts with a high score of proximity to applied physics, P, in comparison to all other texts A, $RL(W) = \frac{P(W|P)}{P(W)=P(W|A)}$.

Finally, it should be highlighted that this explorative exercise does not allow for distinguishing whether these broad trends are due to industry- or technology class-effects or capture something unique to proximity to science. Hence, the following sections will introduce a for-

[92]We can further note that elasticity and combustibility do not appear within the whole corpus. Furthermore, the term of wheels does not appear in the top 2% of patents most similar to applied physics.

mal regression based approach that investigates the impact of proximity to science on patent quality by industry.

5.3 Empirical analysis

5.3.1 Framework

The paper investigates whether patents that were similar to science were also more innovative. The paper proxies patent quality using a bibliographic citation index from Nuvolari, Tartari and Tranchero (2021). To capture proximity to scientific fields, the paper uses semantic proximity between patents and titles within different scientific fields (see data section 5.2). The paper focuses on the fields of *applied physics, chemistry, mathematics, and scientific instruments* that are most likely to have been related to technical progress during the Industrial Revolution. The relationship between proximity to science and patent innovativeness is estimated in the following model:

$$\text{Patent quality}_{ict} = \beta_1 \text{Proximity to scientific field } (j)_{it} + \boldsymbol{X'_{it}}\beta_2 + \gamma_c + \alpha_t + \varepsilon_{ict} \qquad (37)$$

where the outcome Patent quality$_{ict}$ captures patent i's quality as measured through the bibliographic citation index from Nuvolari, Tartari and Tranchero (2021) in 10-year period t, and technology class c. To address overdispersion, the patent quality index is transformed using the inverse hyperbolic sine transformation. The main explanatory variable is a measure of proximity to scientific fields. The analysis concentrates on the scientific fields of *applied physics, chemistry, mathematics, and scientific instruments* that are most likely to have had an impact on mechanical industries during the Industrial Revolution. To ease interpretation, the variable is z-score transformed, with a mean of 0 and a standard deviation of one.

To disentangle the relationship between patent quality and patent proximity to scientific fields from inventor-specific effects, the equations adds a vector of patentee characteristics, $\boldsymbol{X'_{it}}$ based on Nuvolari, Tartari and Tranchero (2021) and Billington (2021). They include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Lastly, the paper adds a control for the (log) length of a patent to rule out bias in the proximity to science index due to short titles with insufficient information on the content of a title. Furthermore, to avoid bias from time or technology specific effects, the model further includes time fixed effects, α_t, and technology class fixed effects, γ_c, based on Billington and Hanna (2020).

In this exercise, it is important to highlight the limitations that are intrinsic to the measure of *proximity to scientific fields*. Mainly, the indicator captures the use of scientific ideas, concepts, and objects as they were mentioned in the patent descriptions. However, the patent descriptions from Woodcroft (1854*a*) only provide self-reported overviews of the invention without specifying all technical details. Hence, the index is more likely to capture a patent's core ideas behind the invention than its technical details. Hence, especially for complex inventions drawing on a wide range of inputs, the index is likely to miss core connections between a patent and science. Furthermore, the regression model does not allow for identifying the exact mechanism that links new scientific ideas to patent innovativeness. Instead, the paper mainly aims to establish a basic association between patent innovativeness and patent proximity to science while ruling out obvious confounders, such as field or industry specific effects. This association might reflect multiple mechanism during the process of invention such as implementing concrete predictions from science, a higher reliance on experimentation, or a stronger focus on exact measurements. Still, while remaining agnostic on the concrete channel, the results from this regression model speak to the importance of the interaction between science and technology for technological progress.

There are still several sources of bias that should be carefully considered. First, the use of scientific language in patents might reflect a patentee's educational background rather than the actual invention underlying the patent. For this reason, the paper introduces a set of indicator variables for patentees' HISCLASS status. In the eighteenth century, occupational class should have been strongly correlated with educational background and might even be a better measure to capture outside influences requiring the use of a sophisticated "scientific language".

Furthermore, the paper uses a placebo-group approach to test whether the association between patent innovativeness and proximity to science is driven by non-scientific field related confounders. The placebo group is constructed by restricting the sample to patents from industries that were likely unrelated to a given scientific field.[93] Hence, for these placebo groups we would expect to find a zero effect of distance to a scientific field on patent innovativeness. However, if the association between patent innovativeness and proximity to a scientific field were driven by confounders that are unrelated to specific scientific fields (such as e.g. a patentee's educational background or social status), then we would expect to find a positive coefficient for proximity to science for the placebo group.

Additionally, it is also important to consider field-specific bias that arises if the likelihood of patenting an invention (instead of e.g. keeping it secret) were related to its expected usefulness. If it was a better strategy to keep high-value innovation secret, and if high value innovations were based on scientific concepts, then these inventions would drop out of the sample and create a downward bias in the estimation results (see Horstmann, MacDonald and Slivinski, 1985; Anton and Yao, 2004).

While, there is no direct way to account for this bias, we can draw on the literature to assess the size of the potential bias. Generally, the effect is likely to be of less relevance for some industries, such as textiles, where most inventors patented. Meisenzahl and Mokyr (2011, p. 460) show that out of a large sample of innovators in textiles, only 19% did not patent. Hence, the bias is likely to be less relevant for textiles than for other industries.[94] Furthermore, research from Moser (2006, 2013) shows that patent rates were relatively constant across different levels of patent quality. Using data from the 1854 Crystal Palace exhibiton, Moser (2006, 2013) documents that the main determinant of the decision whether to patent was the difficulty of reverse-engineering, while patent quality only played a secondary role. If anything, high-quality patents were slightly more likely to be patented. Hence, it appears that the the size of the bias might be relatively small.

[93] For example the paper assumes that proximity to science should only affect chemical industries. All other industries are then grouped together as a placebo-group. A list of all industries is shown in appendix table 62.

[94] For example, Meisenzahl and Mokyr (2011, p. 460) show that 65% of innovators in instruments and ca. 50% of innovators working with engines never patented.

5.3.2 Empirical results

In the following, the paper presents the results from estimating equation 37 starting with *proximity to chemistry*, and continuing with *proximity to applied physics*, *proximity to mathematics*, and *proximity to scientific instruments*. The effects are shown separately for different industries, capturing the intuition that treatment effects of specific fields might have been heterogeneous across industries. The paper assumes that only a subset of industries would have been likely to be affected by proximity to each scientific field. Therefore, all other fields are collected in one group of unrelated industries to serve as a placebo test. A list of all industries is shown in appendix table 62.

Results are presented in figure 60–63. Coefficients are shown for three different specifications. First, it shows baseline results using only period fixed effects. Then, in the second specification, the paper adds technology-class fixed effects. Lastly, controls for patentee characteristics, including indicator variables for patentee's HISCLASS status are added. The last specification is the paper's preferred specification and the following interpretation of coefficients will always refer to this specification.

First, figure 60 presents the results for *proximity to chemistry*. In this setting, it is assumed that only industries classified as *chemical industries* would be plausibly affected by *proximity to chemistry*. The graph shows that for patents within chemical industries an increase of *proximity to chemistry* by one standard deviation is associated with a 3.5% increase in a patent's innovativeness. In contrast, for the placebo group of all other industries, the coefficient for *proximity to chemistry* is precisely estimated at zero.

Next, figure 66-63 present the results for *applied physics*, *mathematics*, and *scientific instruments*. The paper assumes that these fields could have affected a wider array of industries. Concretely, the paper tests the effects on textiles, instruments, ships, engines, and metallurgy as well as all other fields. First, figure 66 presents the results for *proximity to applied physics*. Across all fields, we only find a significant effect for textile industries. Here, a one standard deviation increase in *proximity to applied physics* is associated with a 4.8% increase in patent innovativeness. Notably, in the baseline specification the effect for engines is negative

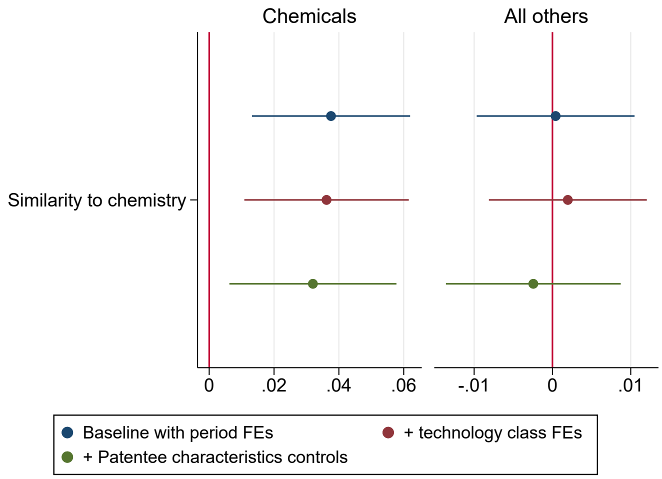


FIGURE 60: Does patent proximity to Chemistry increase patent quality? By industries

Notes: Results are estimated using the model from equation 37. The graph shows results for three separate specifications: a) a baseline only using (log) patent length as a control, b) added technology class fixed effects, and c) added controls for patentee characteristics. Patentee characteristics include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Results are estimated by different industries. Standard errors are multi-way clustered at the technology class and period level. The graph reports 90% confidence intervals.

- however, the effect becomes smaller and insignificant when adding technology fixed effects. Reassuringly, the placebo test of all other industries is precisely estimated at zero.

Lastly, figure 62 and 63 show results for the association between patent innovativeness and *proximity to scientific instruments* and *proximity to mathematics*. The graph shows that *proximity to scientific instruments* affects patent innovativeness in both instrument industries and textile industries. Here, increasing patent *proximity to scientific instruments* by one standard deviation leads to a 5.1% increase in a patent's innovativeness. Likewise *proximity to mathematics* leads to an increase in patent innovativeness in instrument industries and textile industries. For textile industries, increasing patent *proximity to scientific instruments* by one standard deviation leads to a 5.6% increase in a patent's innovativeness. Reassuringly, the placebo groups are both precisely estimated at zero. It is likely that mathematics ans scientific instruments are closely related in the practise of exact measurement.

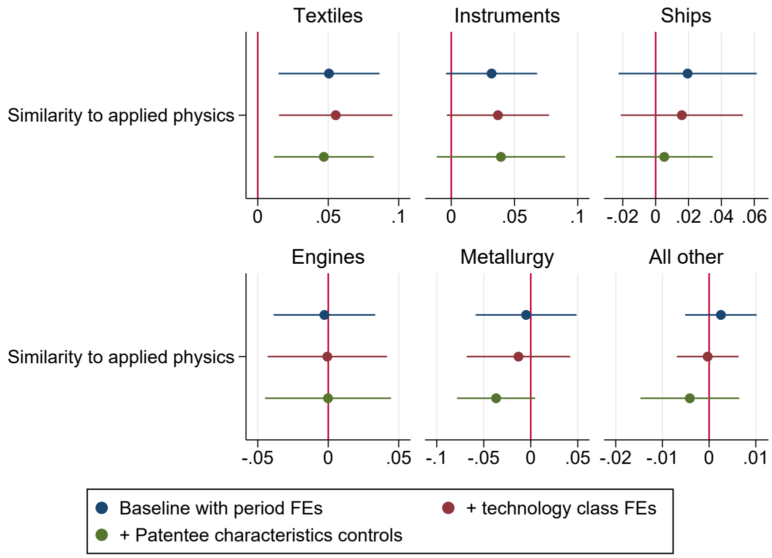


FIGURE 61: Does patent proximity to applied physics increase patent quality? By industries

Notes: Results are estimated using the model from equation 37. The graph shows results for three separate specifications: a) a baseline only using (log) patent length as a control, b) added technology class fixed effects, and c) added controls for patentee characteristics. Patentee characteristics include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Results are estimated by different industries. Standard errors are multi-way clustered at the technology class and period level. The graph reports 90% confidence intervals.

Overall, the findings show that chemical industries, textile industries, and instrument industries show the strongest association between science and patent innovativeness. Yet, the paper does not find an association between science and patent innovativeness for ships, engines, and metallurgy. Within these, it might appear surprising that the results do not indicate an association between engines and applied physics. Afterall, the steam engine is well known to have been impossible without Toricelli's and von Guericke's discovery of the vacuum (Allen, 2011).

Yet, by the eighteenth century the existence of the vacuum was well known and would have all steam engines - hence it is unlikely to be identified within this framework. It is also broadly agreed that the physics of atmospheric pressure were only developed decades after the steam engine. The first seminal work on thermodynamics was done by Sadi Carnot in France in 1824 wondering why high-pressure steam engines were superior to low-pressure steam engines

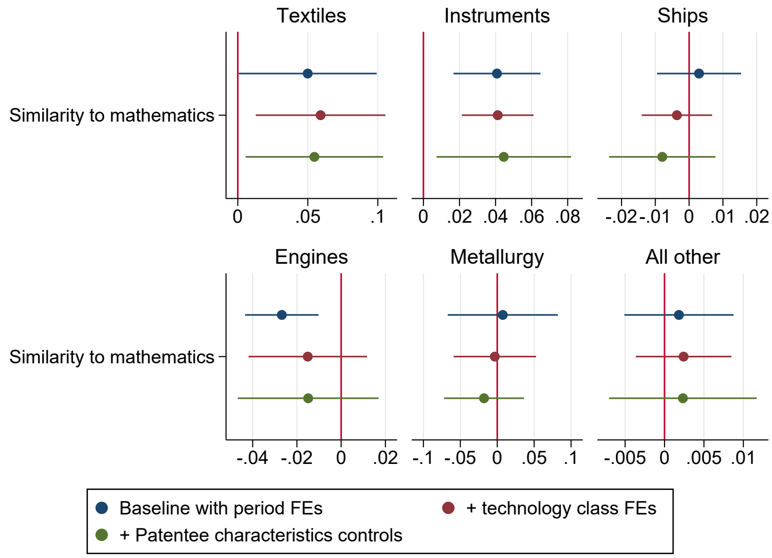


FIGURE 62: Does patent proximity to mathematics increase patent quality? By industries

Notes: Results are estimated using the model from equation 37. The graph shows results for three separate specifications: a) a baseline only using (log) patent length as a control, b) added technology class fixed effects, and c) added controls for patentee characteristics. Patentee characteristics include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Results are estimated by different industries. Standard errors are multi-way clustered at the technology class and period level. The graph reports 90% confidence intervals.

(Mokyr, 1999). Hence, theoretical physics owed more to the practical workings of the steam engine than vice versa. Yet, there it is also possible that more applied physical concepts like quantitative measurements and precise instruments might have had a bearing on steam engines. This will be further discussed in section 5.3.4.

Next, we consider the three industries that are found to have been associated with science, chemical industries, textile industries, and instrument industries. Out of these three, textile industries was the largest and fastest growing industry within the First Industrial Revolution. Especially cotton industries had an average annual growth rate of ca. 6% percent and accounted for up to 40% of total industrial output (Harley, 1982; Crafts, 1983; Crafts and Harley, 1992). The paper shows that patent innovativeness in textile industries was associated with proximity to *applied physics*, *scientific instruments*, and *mathematics*. Hence, it appears that were was a

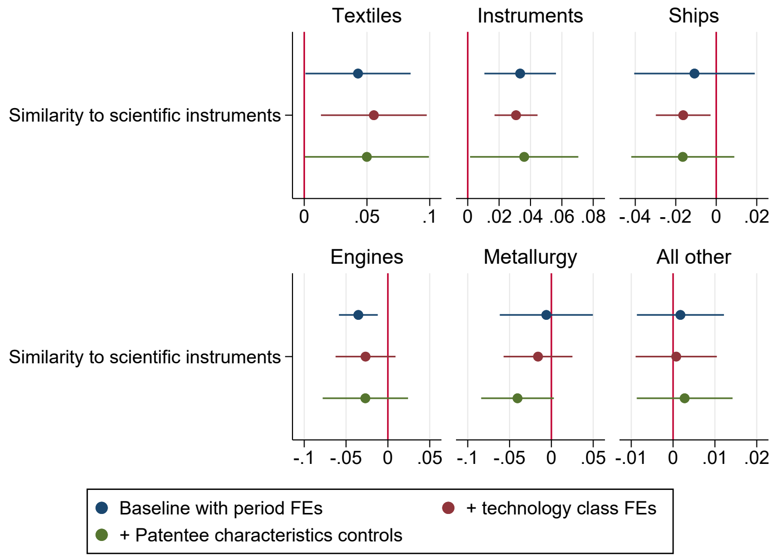


FIGURE 63: Does patent proximity to scientific instruments increase patent quality? By industries

Notes: Results are estimated using the model from equation 37. The graph shows results for three separate specifications: a) a baseline only using (log) patent length as a control, b) added technology class fixed effects, and c) added controls for patentee characteristics. Patentee characteristics include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Results are estimated by different industries. Standard errors are multi-way clustered at the technology class and period level. The graph reports 90% confidence intervals.

solid interaction between scientific ideas and practical inventions in the largest industry during the First Industrial Revolution.

This finding that there was a strong association between science and patent innovativeness might appear surprising as well, since traditionally early textile innovations have been seen as a product of simple tinkering rather than high-science (Mokyr, 1992; Cardwell, 1994). Furthermore, inventors within textile industries seem to have a been in a relatively bad position to incorporate complex scientific knowledge. In a prosopographical study of the inventors of the British Industrial Revolution, Meisenzahl and Mokyr (2011) document that textile inventors had received the least formal education and were most likely to have been apprenticed. In a similar study, Allen (2009) documents that textile industries had the highest share of inventors without an enlightenment connection. Furthermore, Allen (2009) argues that most of the existing enlightenment links in textiles were established after the original inventions. Hence, the findings from figure 63 seem to stand in direct contradiction to this traditional perspective of textile innovations being a simple product of tinkering.[95]

However, recently Kelly and Ó Gráda (2022) have highlighted the importance of high precision instruments in the construction of the ever-more complex machinery of the Industrial Revolution. Most importantly, Kelly and Ó Gráda (2022) stress that early textile machinery quickly reached a high level of complexity. In order to construct these machines, there was an early demand for skilled watchmakers, and instrument makers, a group that had been in close interaction with applied science throughout the century (Allen, 2009, 2011; Kelly and Ó Gráda, 2022; Kelly, Mokyr and Ó Gráda, 2023). Additionally, Kelly and Ó Gráda (2022) argue that precision instruments became crucial for the making of interchangeable machine tools. Although the main development in interchangable machine tools happened between 1820–1840, early innovators like Marc Isambard Brunel, Henry Maudslay, or Joseph Clement, were already laying the foundations for their precision engineering in the early 1800s. Likewise their work was built on the innovations in precision engineering of an earlier generation of inventors. For example, John Wilkinson's (1728-1808) boring machine was a stepping stone towards making interchangeable parts from iron.

Hence, it appears plausible that the link between patent innovativeness and science in textile industries was driven by a focus on exact measurement and precision instruments that were taken from science. Alternatively, it remains possible that concepts from high-science, such as Newtonian physics (see Jacob, 2014), would have been successfully integrated into inventions in textile industries. The following section will investigate these two mechanisms by creating patent proximities to the BERT embeddings of stipulated concepts such as *precise measurement*, *precise instruments*, *mathematical*, *Newtonian physics*, or *laws of motion*.

[95] This stands in in contrast to chemical industries where the impact of early science has been more widely recognized (Landes, 1969).

5.3.3 Textile innovation and science: Mechanism

This section investigates which concepts in *applied physics* were most important for driving the association between patent innovativeness and proximity to *applied physics*. The paper focuses on two plausible mechanisms. First, based on Kelly and Ó Gráda (2022), we might expect that precision instruments and applied mathematics might have been key for the construction of key textile industries. Second, following Jacob (2014), we might expect that Newtonian physics played a key role in engineering and mechanics.[96]

In order to test the role of these concepts within the association between patent innovativeness and proximity to *applied physics*, the paper uses a key-feature of sentence embeddings in BERT models. In Bert models, the embedding of even a single word captures the full context of the underlying text data. Thus, simple technical terms like *precise measurement*, capture the full context of all mentions of *precise measurement* within the underlying text-data the BERT model was trained on. Hence, by creating proximities between patents and short terms that describe the mechanism at hand, we capture the full contextual meaning of *precise measurement* as captured in the embedding space. We call this approach, as adding *stipulative terms*. To the best of the author's knowledge, this paper is the first one within the innovation literature using a *stipulative term* approach — although the logic follows straight from "zero-shot classification" exercises that have become common within data science. All in all, adding patent proximity to stipulative terms to the model from equation 37 should control for the full meaning-space associated with the term and should therefore be a good method to see whether the stipulative concept captures parts of the original effect of proximity to *applied physics*.

A disadvantage of this approach is that using embeddings for short stipulative concepts mainly relies on information from a model trained on modern data. In contrast, proximity to every published work in applied physics between 1600 and 1800 should capture a historically more accurate measure of historical science. Hence, the approach introduces some bias. In this context, the bias is most likely to be downward bias, since using a modern meaning of a spipulative term is less likely to be associated with the meaning of eighteenth century and

[96] Although, Jacob (2014)'s account focuses more on classical engineering outside textiles, it still remains a plausible mechanism for textile innovations that should be tested empirically.

early nineteenth century patents. Hence, given the presence of downward bias, finding positive effects of these stipulative effects should be relevant and meaningful.

First, the paper introduces three stipulative terms for capturing the Kelly et al. (2021) account of precision measurement and applied mathematics: *precise measurement*, *precise instruments*, and *mathematical*. Additionally, it introduces three stipulative terms for capturing the Jacob (2014) account of Newtonian physics: *Newtonian physics*, and *laws of motion*.

TABLE 58: Can precision measurement or Newtonian physics account for the mechanism?

	Exact measurement					Newtonian physics		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Innov.	Innov.	Innov.	Innov.	Innov.	Innov.	Innov.	Innov.
Similarity to applied physics	0.0469**	0.0339**	0.0316**	0.0303*	0.0247	0.0444*	0.0363*	0.0415
	(0.0197)	(0.0152)	(0.0133)	(0.0144)	(0.0180)	(0.0240)	(0.0198)	(0.0237)
Similarities to “Precise Measurement”		0.0475			0.0158			
		(0.0471)			(0.0402)			
Similarities to “Precise Instruments”			0.0510		0.0367			
			(0.0530)		(0.0507)			
Similarities to “Mathematical”				0.0317	0.0132			
				(0.0390)	(0.0282)			
Similarities to “Newtonian physics”						0.00450		-0.0160
						(0.0182)		(0.0235)
Similarities to “Laws of Motion”							0.0278	0.0372
							(0.0358)	(0.0423)
Period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Technological class fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Patentee characteristics controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	397	397	397	397	397	397	397	397
R-squared	0.23	0.24	0.24	0.24	0.24	0.23	0.24	0.24

Notes: The table shows results from estimating equation 37. Standard errors are multi-way clustered at the technology class and period level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 58 presents the results. Column 1 shows the baseline result from equation 37 for the subsample of textile industries. Then, column 2–4 introduce stipulative terms on exact measurement. It can be seen that none of the stipulative terms are significant. Yet, all of the three terms decrease the effect size of *proximity to applied physics* by about a third. Combing all terms in a horse race in column 5, the coefficient for *proximity to applied physics* is decreased by half and becomes insignificant. This is strong evidence that a relevant part of the effect found for *proximity to applied physics* runs through the concepts of precise measurement, precise instruments, and mathematics.

Next, column 5–8 introduce the stipulative terms for Newtonian physics. In contrast, these terms decrease the coefficient by proximity to applied physics by a much smaller amount. In a horse race in column 8, *proximity to applied physics* is only decreased by 10%. Yet, the coefficient for *proximity to applied physics* also becomes insignificant. Hence, this is evidence that Newtonian physics capture some part of the effect of *proximity to applied physics.* Yet, it is also clear that this effect is significantly smaller than the one for exact measurement.

Furthermore, appendix section D.2 illustrates the actual word content behind the mechanism by plotting word clouds for innovative patents in textiles that are either close or distant to scientific fields. The exercise shows that words related to precision instruments and precision engineering make up for most of the difference between the word clouds for innovative patents close to science and word clouds for innovative patents that are distant to science.

Altogether, this exercise indicates that the channel of exact measurement as proposed by Kelly et al. (2021) seems to account for most of the association between patent innovativeness and *proximity to applied physics* for textile industries. In contrast, the Newtonian physics that are at the core of Jacob (2014)'s seem to capture a smaller part of the variation. The results are further supported by a comparison of word-clouds that offer an intuitive access to the content of the titles.

5.3.4 Engine innovation and science: Mechanism

The previous discussion opens a crucial question. If measurement and precise instruments were important for innovations in textile industries, then why do we not find an association between applied physics and engines? Afterall, the design of steam engines had always crucially depended on making precision parts that could withstand the atmospheric pressure within the engines. Boulton and Watt crucially depended on engineers like John Wilkinson to produce their cylinders and condensers (Mokyr, 1999) and the importance of the engineering of precision parts only increased with Trevithick's high-pressure steam engine. So, why do we find a zero result for the association between applied physics and engines?

One plausible explanation is that precise engineering mattered for the refinement and building of engines, but not for original design ideas. Original designs still drew on physics, but the previous results would suggest that theoretical predictions did not always contribute to the quality of the invention. Given that there are still patents on the likes of "perpetual motion machines" within the dataset, this might not appear too surprising.

One way to distinguish between the refinement of engines and original designs is to split the sample by patents that focused on improving an engine's efficiency. Thus, the paper defines all patents that mentioned either *consumption* or *fuel* as efficiency increasing patents. Table 59 shows that for efficiency increasing patents for engines, we find a positive association between applied physics and patent innovativeness. For all other patents we do not find a significant association.

TABLE 59: Can precision measurement or Newtonian physics account for the mechanism?

	Efficiency increasing engines		All other engines	
	(1)	(2)	(3)	(4)
	Innov.	Innov.	Innov.	Innov.
Proximity to applied physics	0.0991**	0.0296	-0.00667	-0.0205
	(0.0366)	(0.0293)	(0.0270)	(0.0326)
Proximity to Precise Measurement		0.197**		0.0303
		(0.0568)		(0.0416)
Period fixed effects	Yes	Yes	Yes	Yes
Technological class fixed effects	Yes	Yes	Yes	Yes
Patentee characteristics controls	Yes	Yes	Yes	Yes
Observations	94	94	429	429
R-squared	0.53	0.59	0.18	0.18

Notes: The table shows results from estimating equation 37. Standard errors are multi-way clustered at the technology class and period level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

To further test, whether this effect is indeed due to precision engineering, the paper follows the approach from the previous section by adding the stipulative terms of *precise measurement* to the regression. The results show that *precise measurement* can partly account for the positive association between applied physics and patent innovativeness within efficiency increasing patents: In a horse race regression in column (3), *precise measurement* remains positive and insignificant, while *applied physics* becomes significance. In contrast, *precise measurement* does not add explanatory power to engine patents that were not efficiency increasing.

Altogether, this exercise finds similar to patterns to the previous section on textile innovation that had shown that the scientific methods with its reliance on precise measurement was a key channel for patent innovativeness and proximity to applied physics within textile industries. It appears that for those patents that were concerned with efficiency improvements, hence patents that relied on small improvements and precision engineering, we find that a) applied physics was positively associated with patent innovativeness and b) that this channel can be explained by the inclusion of stipulative terms for *precise measurement.* These results further show that the Kelly et al. (2021) channel was present within different industries.

5.4 Patentees' access to scientific ideas

So far the analysis has abstracted away from the level of the patentee. It has been shown that patents that were more similar to science were, for a special set of industries, also more innovative. However, it is not clear what drove the scientificness of patents. Was there a strong relationship between patentees' interest in science and the scientificness of their patents? Furthermore, where could patentees have gained access through science, given that most of them were not academics taking part in the current scientific debates of the time?

To answer these questions, the paper first sets out to test whether patentees interest in science, as captured through patentees' publication ins science, correlated with the scientificness of their patents. Then, the paper explores whether the channel of scientific textbooks can account for access to science that could have driven the relationship between patent proximity to science and patent innovativeness.

5.4.1 Does patentees' knowledge about scientific ideas influence their patents?

First this section investigates whether patentees who had an interest in science would have incorporated concepts from science into their patents. The paper proxies patentees' interest in science and knowledge about science by classifying publications by patentees. The paper then creates a measure of the direction of patentees publishing with respect to science (Ω)

by calculating the shares of patentees' publications within science: $v(\Omega) = (b_\Omega/n)$ In accordance with the other papers in this thesis, fields in science are defined as *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments.* However, many of these fields, like medicine, are unlikely to be related to patents in the core-industries of the Industrial Revolution. Hence, in accordance with the previous analysis, the paper also separately defines applied physical sciences as *applied physics, mathematics, chemistry and scientific instruments.*

Using these proxies, the paper tests whether patentees who published in science also had more scientific patents:

$$\text{Proximity to scientific field } (j)_{it} = \beta_1 \cdot v(\Omega)_{ict} + \beta_2 \cdot b_{ict} + \boldsymbol{X'_{ict}}\beta_4 + \alpha_t + \gamma_c + \varepsilon_{ict} \qquad (38)$$

where the dependent variable $sim(p_{ict}, \Omega)$ captures patent, p_{ict},'s proximity to science, Ω, in period t, technology class c, and time period t. To ease interpretation, the variable is z-score transformed, with a mean of 0 and a standard deviation of one. The main explanatory variable $v(\Omega)_{it}$ captures a patentee's share of publications within science and hence a patentee's direction of patenting towards science. The share of patentee's publications within science is further log-transformed to address overdispersion and to assure symmetry in the fixed-effects estimation (Gerdes, 2010).[97] In order to capture the extensive margin of publishing, the paper further adds the regressor of b_{ict} defined as an indicator variable taking the value of zero if a patentee never published and one if a patentee ever published in any discipline.

The model further adds a set of control variables, $\boldsymbol{X'_{ict}}$, capturing patentees' individual level characteristics, similar to the model in equation 37, including the number of patentees registering the patent, the patentee's HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, or whether they were from England, Scotland, Ireland or a foreign country.[98] These patentee-level control variables are taken from Nuvolari, Tartari and Tranchero (2021) and Billington (2021). Lastly, the model adds patent

[97] Because the logarithmic transformation is not defined at zero, the paper follows the conventional approach of adding a small number to the variables before applying the logarithmic transformation.

[98] A patentee's HISCLASS status is defined using a set of indicator variables for each HISCLASS category.

technology class and period fixed effects, α_t and γ_c. Patent technology classes are taken from Billington and Hanna (2020).

Table 60: Did patentees publishing in science also have patents that were more similar to science?

	Patent proximity to all scientific fields			Patent proximity to physical sciences		
	(1)	(2)	(3)	(4)	(5)	(6)
	Pat. sim.	Pat. sim.	Pat. sim.	Pat. sim.	Pat. sim.	Pat. sim.
Log patentee share of publications in all scientific fields	0.247**	0.234**	0.215*			
	(0.0994)	(0.103)	(0.0995)			
Log patentee share of publications in physical sciences				0.242***	0.238***	0.239***
				(0.0755)	(0.0741)	(0.0776)
Patentee published at least once	-0.0308	-0.0183	-0.0254	0.0464	0.0366	0.0422
	(0.0858)	(0.0844)	(0.102)	(0.0848)	(0.0708)	(0.0887)
Period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Technological class fixed effects	No	Yes	Yes	No	Yes	Yes
Patentee characteristics controls	No	No	Yes	No	No	Yes
Observations	4006	4006	4006	4006	4006	4006
R-squared	0.05	0.10	0.10	0.05	0.14	0.14

Notes: The table shows results from estimating equation 38. It estimates the effects of patentee's share of publications in science on their patents' proximity to science. Scientific fields are defined as astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments. The fields of the physical sciences are defined as applied physics, mathematics, chemistry, and scientific instruments. Patent proximity measures are z-score transformed to ease interpretation. Publication shares are transformed using a $log(0.01 + x)$ transformation. Standard errors are multi-way clustered at the technology class and period level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 60 shows the results. First, it shows results from regressing patentees' share of publications in all scientific fields on their patent proximity to all scientific fields. Column 1 shows baseline results only using period fixed effects. Column 2 adds technology class fixed effects and column 3 adds controls for patentee characteristics. For the most demanding model in column 3, we see that increasing patentee's share of publications in all scientific fields by 100% is associated with an increase by $\sim 1/4$th of a standard deviation in patent proximity to scientific fields. Furthermore, since the coefficient for *Patentee published at least once* is insignificant, the results suggest that the findings are not driven by a quality effect of publishing anything, but by the direction of patenting towards science.

Yet, since the fields of the Scientific Revolution also contain fields like medicine that might not be associated with innovations in mechanical industry, the next part of the table restricts results to publications in and patent proximity to *applied physical sciences* consisting of *applied physics, mathematics, chemistry and scientific instruments*. The size of the coefficient is similar to the previous specification looking at all fields of the Scientific Revolution.

Overall, this exercise shows a strong relationship between the scientific interests of patentees and the actual content of their works. The results are pure associations and it is not claimed that the connection causally runs from a patentee's scientific interest to their patenting activity. For example, an interest in improving and patenting more efficient steam engines might well have led to an interest in atmospheric physics. Instead, the results simply document the strong overlap between scientific interests and scientific patenting. It further is strong evidence that patents' proximity to science not only reflected superficial reference to scientific terms but was associated with a deep engagement with scientific studies (even leading to publications on the subject).

5.4.2 How did patentees access scientific knowledge? The channel of applied textbooks

A final open question is whether patentees would have been likely to access concepts from the scientific literature given the cost of books and the high barriers to understanding these texts. Following the scientific debates would surely have come with prohibitive access costs. This includes the necessity to read books in several languages to read into long-standing debates to get a full overview of the theories in swing. Yet, we do not have to assume that inventors followed the scientific debates directly. Instead it is much more likely that they would have borrowed concepts and ideas from applied textbooks or the publications from the *Society of Arts*.

To test whether applied textbooks would have been sufficient to convey useful concepts and ideas, the paper further processes the full content of two important contemporary textbooks in a BERT model. These are John Bank's *A Treatise on Mills* (1795), and John Bank's subsequent *On the Power of Machines* (1803) that have been highlighted by (Cookson, 1994, p. 147) as readily available text-books for practical inventors. Cookson argues that the "(...) the connection of these books to science were slender, their contents generally limited to the most basic mathematics and mechanics, practical calculations for the use of millwrights, and specific though simple diagrams of various machines" (Cookson, 1994, p. 148). So, the question

Table 61: Can applied textbooks on science account for the mechanism?

	Applied texbooks on science			
	(1)	(2)	(3)	(4)
	Innov.	Innov.	Innov.	Innov.
Similarity to applied physics	0.0469**	0.0377*	0.0214	0.0206
	(0.0197)	(0.0181)	(0.0203)	(0.0203)
Similarity to On the Power of Machines		0.0240		-0.0184
		(0.0229)		(0.0159)
Similarity to A Treatise on Mills			0.0481	0.0626
			(0.0337)	(0.0366)
Period fixed effects	Yes	Yes	Yes	Yes
Technological class fixed effects	Yes	Yes	Yes	Yes
Patentee characteristics controls	Yes	Yes	Yes	Yes
Observations	397	397	397	397
R-squared	0.23	0.24	0.24	0.24

Notes: The table shows results from estimating equation 37. Standard errors are multi-way clustered at the technology class and period level and included in parenthesis. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

remains whether these contents were sufficient to account for the association between patent proximity to applied physics and higher patent innovativeness.

Table 61 shows the results of including proximities to the *A Treatise on Mills* and *On the Power of Machines* to the model from equation 37. We see that including each of the two books individually significantly decreases the coefficient of applied physics. The largest effect seems to be due to *A Treatise on Mills*. Adding both books as controls in column 3, shrinks the coefficient for applied physics by more than half. The results appear to be convincing evidence that the results found in the previous section can be sufficiently accounted by knowledge about concepts from applied physics that were relatively easily accessible for applied inventors with a basic secondary education.[99]

5.5 Conclusion

The paper has shown that eighteenth century science and patented innovations had already started to meaningfully interact during the early British Industrial Revolution. The findings

[99] It is possible that these early textbooks also cover material that was disseminated to oral channels, especially public scientific lectures (Stewart, 1986*b*, 1992). As it was often the same lecturers that also published scientific and technical textbooks the paper views both public lectures and textbooks as part of the same channel, distilled and simplified compilations of knowledge that were accessible to the common inventor.

stand in support of a long literature that has argued for the importance of scientific innovations for the onset of modern economic growth (Musson and Robinson, 1969; Stewart, 1992; Jacob, 2014; Mokyr, 2016). It further contributes to our understanding of the role of upper-tail human capital during the First Industrial Revolution by illuminating potential channels through which upper-tail human capital could have mattered for growth: Upper-tail human capital would have formed both the basis for a) creating science and b) translating scientific insights to a broader audience (including inventors). Furthermore, the paper shows that new innovations drawing on scientific insights seem to have relied on precision measurements. Hence, c) upper-tail human capital would also have been necessary to build the more scientific inventions.

The paper has shown that proximity to the scientific fields of *applied physics, chemistry, mathematics, and scientific instruments* had a bearing on the three main industries of *textiles, chemicals, and instrument making.* Here, textile industries stand out as the largest and fastest growing industry of the British Industrial Revolution. The paper finds that increasing patent proximity to applied physics was associated with a 4.8% increase in patent innovativeness. The finding might appear surprising, since textile innovations have been often described as a product of simple tinkering rather than high-science (Mokyr, 1992; Cardwell, 1994).

To solve this puzzle, the paper has further investigated which *content* was the driving force behind the association between patent innovativeness and patent proximity to science. The paper has followed two main predictions from the literature, Kelly and Ó Gráda (2022) and Jacob (2014). First, Kelly and Ó Gráda (2022) has argued that textile innovations mainly profited from systematic measurement and precision instruments. Second, Jacob (2014) has argued that Newtonian mechanics were a driving force behind most industries in early industrializing Britain. To test these two predictions, the paper has introduced a new approach of creating stipulative patent proximities to the embeddings of simple technical expressions. These were then added to horse race specification to see how much they account for the original effect of *proximity to applied physics.* The results have shown that the channel of systematic measurement and precision instruments accounted for most of the association between patent innovativeness and patent proximity to science. Overall, the results indicate that early eighteenth century science improved textile innovations more through its scientific method and scientific spirit than through predictions and high-brow mechanics.

Lastly, the paper has investigated the question of where patentees got their scientific knowledge from. The paper has shown that some of patentees seem to have been deeply engaged in scientific studies themselves. This is shown by the positive association between a patent's proximity to science and the own patentee's publications in science. However, this effect only holds for a minority of patentees. Most patentees would have lacked the time, resources, and education to engage into the academic debates of science. To answer where patentees got their knowledge of science from, if not from academic publications, the paper proposes that applied textbooks could have played an important role. Applied textbooks summarized scientific knowledge in relation to technical problems and are likely to have been widely available to most patentees. To quantify this channel, the paper has calculated patent proximities to two applied textbooks. It has shown that this measure can account for much of the original effect between proximity to applied physics and patent innovativeness. Hence, this serves as strong evidence that applied textbooks could have served as an important role in the transmission of scientific ideas to the doors of practical inventors.

Overall, the paper has shed new evidence on the role of science as an input for innovation during the First British Industrial Revolution. It has shown that there was a positive association between patent proximity to science and patent innovativeness for key industries such as textiles. It has shed new evidence on the components of science important for textile innovations. Here, the paper has shown that it was systematic quantification and precision instruments, products of scientific practise and scientific spirit, that mattered more than theories and predictions. Furthermore, the paper has shed some light on potential mechanisms of knowledge diffusion towards inventors and has highlighted the role of applied textbooks as a channel between high-science and simple inventors.

Appendices

D Appendix for paper 4

D.1 Data description

D.1.1 Variable definitions

Patent proximity to science

Patent proximity to scientific field. Average text proximity of a patent's short description to all titles of a scientific field from the English Short Title Catalogue. Scientific fields are defined as: *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments*. Refer to section 5.2.2 for the construction of the proximity measure. Patent short descriptions are taken from Woodcroft (1854*a*).

Patents

Bibliographic Composite Index of patent quality (BCI). A patent's innovativeness or quality based on a composite index of three sources of patent quality as introduced by Nuvolari, Tartari and Tranchero (2021). The first source is *Woodcroft's Reference Index of Patents of Invention* (WRI) introduced by Nuvolari and Tartari (2011). The WRI captures a patent's visibility within the contemporary engineering and legal literature. The second source is the number of times a patent was mentioned within a comprehensive list of works within the literature on the history of technology. The third source is the number of times a patent was mentioned in biographical dictionaries. The three sources of patent quality are combined using the methodology from Lanjouw and Schankerman (2004). Data obtained from Nuvolari, Tartari and Tranchero (2021).

Patent technology class. A patent's technology class constructed through the machine-learning approach developed by Billington and Hanna (2020). For each patent, the paper uses the highest-scoring technology topic ("Topic-One"). Data obtained from Billington and Hanna (2020) and Billington (2021).

Patent industry. The industry for a patent's usage assigned by Nuvolari and Tartari (2011) based on Woodcroft (1854*b*). The classification system is similar to Moser (2011). Data obtained from Nuvolari, Tartari and Tranchero (2021).

Patent year. Year a patent was registered from Woodcroft (1854*a*).

Patent length. Number of characters in a patent text from Woodcroft (1854*a*).

Patentees

Patentee share of publications in the Scientific Revolution. A patentee's share of publications within the fields of *astronomy, almanacs, applied physics, mathematics, chemistry, biology, geography, medicine, and scientific instruments* out of all his or her publications. The publication data is based on the English Short Title Catalogue (ESTC) with subject classes assigned using machine-learning (see the first paper of this thesis). Matching between patentees and ESTC authors are based on phonetic NYSIIS unique name matches. The whole ESTC-patantee name-space consists of 84% unique matches. Non-unique matches are dropped from the sample.

Number of inventors. The number of patentees who registered a patent based on Woodcroft (1854*b*). Data obtained from Billington (2021).

Patentee's HISCLASS status. A patentee's occupation within Woodcroft (1854*b*) assigned to the HISCLASS system by Woodcroft (1854*b*). The HISCLASS indicator variables are defined consecutively for the first, second, third and fourth patentee of multi-authored patents. Data obtained from Billington (2021).

Gentleman. A patentee's occupation listed as gentleman instead of an actual occupation within Woodcroft (1854*b*). Data obtained from Billington (2021).

Engineer. A patentee's occupation listed as engineer. Data obtained from Billington (2021).

Patent agent. A patent with at least one patentee whose occupation lists *patent agent*. Data obtained from Billington (2021).

Metropolitan. A patent with at least one patentee living in a town with a population greater than 50,000. Data obtained from Billington (2021).

English. A patent with at least one patentee living in England. Based on the listed residence of Woodcroft (1854*b*). Data obtained from Billington (2021).

Scottish. A patent with at least one patentee living in Scotland. Based on the listed residence of Woodcroft (1854*b*). Data obtained from Billington (2021).

Irish. A patent with at least one patentee living in Ireland. Based on the listed residence of Woodcroft (1854*b*). Data obtained from Billington (2021).

Foreign. A patent that was communicated from abroad as listed in Woodcroft (1854*b*). Data obtained from Billington (2021).

D.1.2 Descriptive data statistics

Table 62: Patent distribution by *Industry*

Category	Number of Observations
Agriculture	151
Carriages	220
Chemicals	288
Clothing	105
Construction	167
Engines	465
Food	220
Furniture	233
Glass	45
Hardware	323
Instruments	237
Leather	79
Manufacturing	232
Medicines	171
Metallurgy	174
Military	116
Mining	25
Paper	114
Pottery	81
Ships	160
Textiles	400
Total	4006

Notes: .

Table 63: Summary statistics

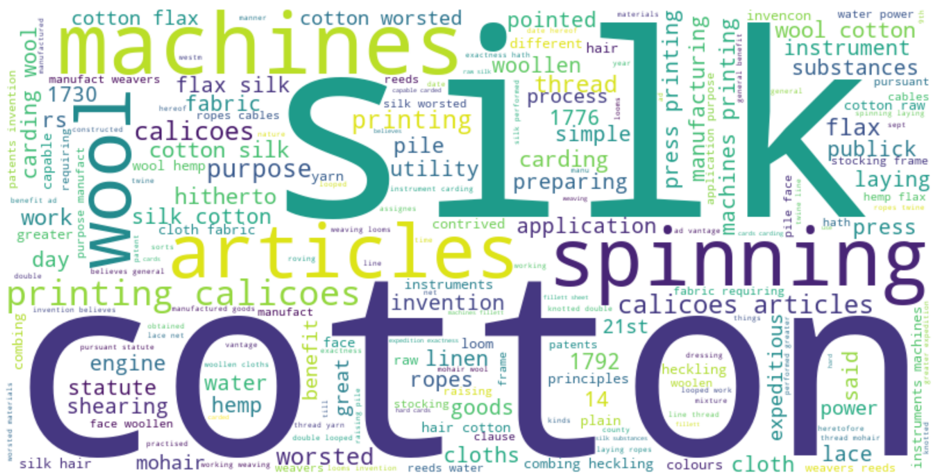
	Mean	Std	Min.	Max	Obs
BCI	-0.000	(0.397)	-0.455	5.462	4006
Similarity to chemistry	-0.000	(1.000)	-2.978	3.754	4006
Patent similarity to applied physics	0.129	(0.039)	-0.011	0.264	4006
Patent similarity to mathematics	0.134	(0.043)	-0.018	0.307	4006
Patent similarity to scientific instruments	0.153	(0.047)	-0.024	0.377	4006
Patent length in characters	477.264	(2222.611)	9.000	30512.000	4006
Hisclass rank of first patentee	3.834	(3.036)	0.000	12.000	4006
Hisclass rank of second patentee	0.325	(1.418)	0.000	11.000	4006
Hisclass rank of third patentee	0.040	(0.510)	0.000	9.000	4006
Hisclass rank of fourth patentee	0.010	(0.270)	0.000	9.000	4006
Number of inventors per patent	1.097	(0.342)	1.000	4.000	4006
At least one patentee is an engineer	0.109	(0.312)	0.000	1.000	4006
Patentee(s) have a patent agent	0.001	(0.035)	0.000	1.000	4006
At least one patentee is characterized as a gentleman	0.210	(0.407)	0.000	1.000	4006
At least one patentee is living in a metropolitan area	0.533	(0.499)	0.000	1.000	4006
At least one patentee is English	0.915	(0.279)	0.000	1.000	4006
At least one patentee is Scottish	0.032	(0.177)	0.000	1.000	4006
At least one patentee is Irish	0.013	(0.114)	0.000	1.000	4006
At least one patentee is foreign	0.042	(0.200)	0.000	1.000	4006
Patentee published	0.080	(0.272)	0.000	1.000	4006
Patentee share of publications in the Scientific Revolution	0.002	(0.012)	0.000	0.111	4006
Patentee share of publications in physics, chemistry, mathematics, and instrumen	0.006	(0.077)	0.000	1.000	4006
Patent similarity to the Scientific Revolution	0.109	(0.034)	0.007	0.252	4006
Patent similarity to physics, chemistry, mathematics, and instruments	0.098	(0.270)	-0.923	1.351	4006
Observations	4006				

Notes: .

D.2 Word clouds for innovative patents close to science in textile industries

A good way to illustrate the concepts driving the association between proximity to science an patent innovativeness is to create word clouds for innovative patents in textile industries that are either close or distant to *applied physics* and *instruments*. Innovative patents are defined as patents above median innovativeness. The word clouds are shown in figures 64–65.

Reassuringly, both innovative patents that are close and distant from *scientific instruments* and *applied physics* broadly refer to the same objects and concepts in textile industries. This shows that the proximity index did not select on an unusual group of patents. Going into the details of the word-cloud for innovative patents close to *scientific instruments*, we can read that the patents refer to objects and processes such as *exactness, instrument, and instruments, application, and* as well as relatively specific technical tasks such as *press printing, spinning laying, instrument carding, laying ropes, cards carding.* Likewise, going into the details of innovative patents close to *applied physics*, we can read that the patents refer to objects and processes such as *instruments machines, carding engines, and instrument carding* and specific technical tasks such as *roving spinning, cylinders carding, and weaving winding.* Overall, the word clouds indicate that innovative textiles in patents, both close to *scientific instruments* and *applied physics*, were similar to other innovative patents, but came with an overall increase in precision engineering and the use of exact measurements.

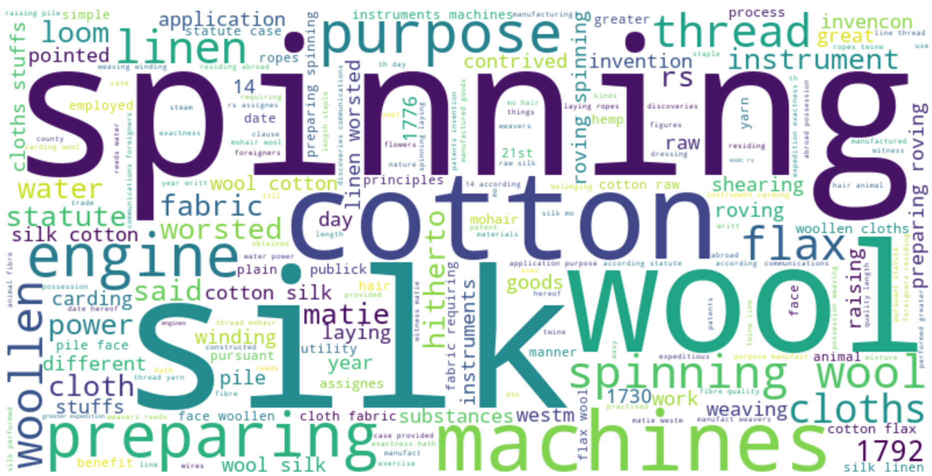


(a) Innovative patents close to scientific instruments

(b) Innovative patents distant to scientific instruments

FIGURE 64: Word clouds comparing innovative patents within textile industries based on their proximity to scientific instruments

Notes: Word clouds based on the text of patent descriptions excluding a basic list of stop words. Innovative patents are defined as the top 50% of the Nuvolari, Tartari and Tranchero (2021) innovation index. Patents close to scientific instruments are defined as patents above $\frac{1}{2}$ of a standard deviation above the mean of the proximity to scientific instruments index.



(a) Innovative patents close to applied physics

(b) Innovative patents distant to applied physics

FIGURE 65: Word clouds comparing innovative patents within textile industries based on their proximity to applied physics

Notes: Word clouds based on the text of patent descriptions excluding a basic list of stop words. Innovative patents are defined as the top 50% of the Nuvolari, Tartari and Tranchero (2021) innovation index. Patents close to scientific instruments are defined as patents above $\frac{1}{2}$ of a standard deviation above the mean of the proximity to applied physics index.

D.2.1 Robustness tests

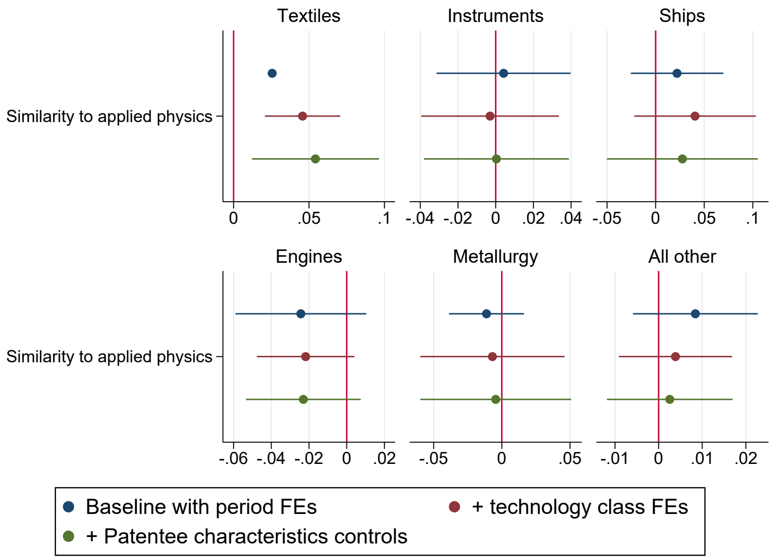


FIGURE 66: Using the Woodcroft Reference Indicator: Does patent proximity to applied physics increase patent quality? By industries

Notes: Results are estimated using the model from equation 37. Instead of the Bibliographic Composite Index (BCI), the paper uses the Woodcroft Reference Index as the outcome variable. The graph shows results for three separate specifications: a) a baseline only using (log) patent length as a control, b) added technology class fixed effects, and c) added controls for patentee characteristics. Patentee characteristics include the number of patentees registering a patent, indicator variables for patentees' HISCLASS status, and indicator variables capturing whether a patentee was an engineer, had a patent agent, and his country of origin. Results are estimated by different industries. Standard errors are multi-way clustered at the technology class and period level. The graph reports 90% confidence intervals.

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