The Economic Origins of Modern Science: Technology, Institutions, and Markets

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Abstract

I study how the introduction of Gutenberg's printing press shocked the market for ideas and the labor market, increasing the returns to and quantity of science. Professor salaries increased significantly relative to skilled wages after printing diffused. Science professors enjoyed the largest salary increases, the share of university courses on scientific subjects increased, and graduates shifted towards scientific careers. Scientific activity and invention began to grow across cities, particularly where printing interacted with universities and political competition, which previously delivered limited support to science. These changes are not explained by prior economic or cultural trends and predate the Protestant Reformation.

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1 Introduction

The emergence of modern science in Europe is one of the most consequential changes in knowledge production in history (Shapin 1996; Bernal 1969; Needham 1964). Until the 1400s, knowledge growth was slow; universities were committed to non-empirical knowledge programs; and intellectual secrecy was typical in the private sector. The European economy shifted into a regime of unprecedented knowledge growth between 1400 and 1600, in a process known as the scientific revolution.[1] Scientific methods developed, radical breakthroughs were made in multiple fields, and knowledge began to be shared as a public good (Hall 1983; Eamon 1984; Mokyr 2005). A large literature argues that this transformation in knowledge production was a fundamental precondition for modern growth (Mokyr 2016; Easterlin 2009; David 2008; Rostow 1975; Lewis 1955). Mokyr (2005; p. 1132) observes: "The scientific revolution was in many ways the prelude to the intellectual developments at the base of the Industrial Revolution." However, no quantitative research characterizes the rise of early modern science, or examines the underlying causal factors, to the best of my knowledge.

This paper investigates how the diffusion of Gutenberg's printing press increased the returns to and quantity of scientific activity, and transformed knowledge production in Europe. I propose an economic explanation, grounded in historical evidence, that generates predictions on labor markets, the supply of education, and scientific activity. I test and verify the predictions in novel microdata on: the price of books; professors' salaries, teaching, and publications; university graduates' careers; and scientific activity and invention across cities. I find that introduction of printing led to a large increase in the relative incomes of the most highly educated people in historic Europe. University professors' salaries rose, professors of scientific subjects enjoyed the largest increases, and salaries rose the most for professors who published scientific works. These changes in incomes reflected the direct effect of printing on the labor market and endogenous responses in human capital accumulation and knowledge.

The economic process involved the interaction between two markets: the market for ideas and the labor market. Printing impacted the market for ideas, understood broadly to comprise exchanges between producers and consumers of ideas (Mokyr 2016; Coase 1974). Printing reduced prices for consumers and increased the size of the market facing idea producers, starting in the 1450s. The shock to the market for ideas was transmitted to the labor market, in which universities and states competed over talent and employed scientists. The transmission of the shock to the labor market matters because the direct pecuniary returns to scientific activity remained limited in the private sector: the market for scientific books was small if growing and authors' intellectual property rights were weak, as piracy

[1] The term "Scientific Revolution" encompasses changes that varied across space, time, and research fields. I document aspects of this variation and discuss the historiography of the Scientific Revolution below.

was endemic. However, by changing how ideas were produced, assessed, and acquired, and how reputations were made, printing increased the returns to science in the labor market.

The pre-existing institutional environment shaped the process of economic change. Three features of this environment stand out. First, the presence universities, which employed scholars and produced human capital. Second, the political institutions of late medieval Europe, which employed highly trained staff and shaped political competition. Third, cities with legal autonomy, which provided the setting for the printing industry and for interactions between public and private sector science. These institutions were established in the middle ages, centuries before the introduction of printing (Huff 2017; Cobban 1975; Weber 1958).

Narrative evidence suggests that the returns to human capital shifted following the introduction of printing. Medieval universities competed over professors and students, and rulers competed to employ highly trained elites (Denley 2013). Printing promoted new ideas and intellectual celebrity (Wootton 2015). The status of scientists rose (Lines 2006). Significantly, there was mobility between university and non-university positions: Galileo left his professorship at Padua to become court mathematician to the rulers of Florence. The history broadly suggests that printing influenced how students choose universities and courses, the academic job market, and role of political competition in the market for science.

Printing had supply and demand effects that specifically promoted the development of science, according to historical research. On the supply side, printing's impact on the variety and price of ideas as *inputs* into knowledge production promoted science (Burke 2000; Pettegree 2010). Thus, in her classic study of printing, Eisenstein (1980) argues that the ability to compare and recombine ideas was especially important for science.[2] Printing also led to increased demand for science. The lower price of ideas promoted "thicker" markets and new scholarly communities (Wootton 2015). This activated the reward structure described by Merton (1957; 1973), in which recognition awarded by the scientific community for being first to develop an idea or make a discovery brings returns in the labor market; it more generally lowered the costs of assessing science, which previously had limited the demand for science (David 2008). Printing also directly promoted values favorable to scientific inquiry (Rossi 2001; Eamon 1985) and a larger process of pro-science cultural change (Mokyr 2016). To be clear, historical "science" comprised a range of activities including teaching and research in anatomy, astronomy, botany, mathematics, medicine, and natural philosophy (Park and Daston 2003). Moreover, "men of science" often worked at the intersection of science and technology, contributing to the development of applied techniques (Shapin 2006).[3]

[2] Eisenstein (1980) offers an historical argument that anticipates Weitzman (1998) on "recombinant growth" and Mokyr (2005) on the importance of changes in the "access cost" (price) of ideas.

[3] Wootton (2015; p. 29) notes that "scientist" was simply a new word for a type of person long in existence.

Economic analysis of the narrative evidence generates predictions that can be tested in microdata. First, we expect that printing led to a large scale decline in the price of books and to shifts in the circulation of scientific ideas. Second, we expect that printing led to increases in the returns to upper tail human capital and, especially, to scientific activity. Given the role of publishing in establishing reputation, we expect professors' salaries to respond to their own publications. Third, we expect to observe supply side responses in scientific training: the number and share of scientific courses at universities should increase. Fourth, we expect to find highly trained individuals differentially achieving success in scientific careers after printing. Fifth, we expect that shifts in scientific and technological activity should reflect how printing interacted with universities and political competition, and thus to vary spatially with the presence of universities and with geographic variation in political competition. To test and verify these predictions, this paper proceeds as follows.

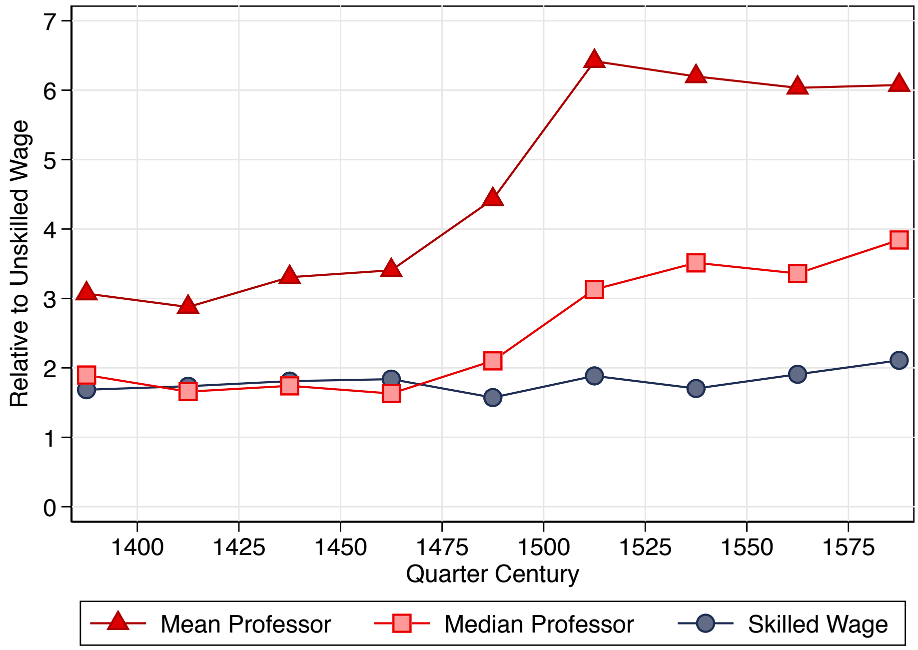
First, I construct novel data on the price of books to document the shock to the market for ideas. The price of books is a summary statistic capturing the cost of accessing ideas (Cipolla 1956), but has not been systematically documented (Nuovo 2013). Book prices fell 1.7 percent per year between the 1460s and the early 1600s, accounting for differences in book characteristics, and 2.4 percent per year in absolute terms. In 1460, books frequently cost a year's worth of wages. By the mid-1500s, books cost less than one day's wages. The share of scientific books published in non-Latin vernaculars increased from 1 to 60 percent.

Second, I investigate data on professor salaries and teaching from university records. Figure 1 shows the evolution of professor salaries at Italian universities, drawn from university payroll documents that record salaries at the professor-year level and provide unique evidence on incomes for educated elites.[4] Professor salaries were stable relative to workers' wages before printing and increased sharply after printing diffused in the late 1460s. The median professor went from earning the same as a skilled worker to twice as much; effects at the mean were greater. The relative increase in professors' salaries contrasts with the stable wage premium received by skilled workers, indicating the importance of the returns to "upper tail human capital" in the process I study. In the analysis below, I show that printing led to significantly larger salary increases for professors in scientific fields. Professors of anatomy, astronomy, botany, mathematics, and natural philosophy, whom I classify as "scientific," enjoyed larger pay increases than professors of "non-scientific" subjects such as law, theology, rhetoric, grammar, poetry, and Greek.[5] There was no underlying trend in salaries towards

[4]Printing was adopted in Rome in the late 1460s and in other Italian cities in the 1470s. Ornato (1985; p. 70) observes that the impact of printing on book markets became evident from the early 1470s. I discuss non-Italian universities, and potential regional heterogeneity in the response to printing, below.

[5]Details on teaching, and on the classification of professors in terms of the courses they taught, are provided below. The nature and definition of historic science are discussed in Section 2.

Figure 1: The Evolution of Professor Salaries



This graph shows the distribution of professor salaries at the universities of Bologna, Florence, Padua, Pavia, Perugia, Pisa, and Rome. The professor salary data comprise 8,357 observations at the professor-year level. Salaries are indexed to unskilled wages in the same year, with daily wages multiplied by 250 to obtain a "year of unskilled wages." The median and mean salaries are calculated across observations in a quarter century. The "Skilled Wage" series is the mean of the annual ratio of skilled to unskilled wages by quarter century. Annual data on skilled and unskilled wages are from Goldthwaite (1980). Details on the data are provided below. Printing was established in Rome in the late 1460s and in the 1470s in other Italian cities.

science before printing, and the differential increase in pay for science professors holds when we study variation within universities. Salaries rose across the distribution, including for the majority of professors who did not become published authors. However, for a given professor, we observe large salary increases following scientific publications. Changes in the returns to human capital were accompanied by changes in the supply of training: the share of university teaching on scientific courses was stable or falling before printing and increased afterward. These baseline findings reflect evidence from Italian universities, which provide uniquely comprehensive data on salaries and teaching assignments. However, I find professor salaries similarly increased following scientific publications for German professors. Microdata on the careers of graduates from German universities provide corroborating evidence: the probability of a graduate pursuing a scientific career was not increasing before printing and began to increase after the introduction of printing and before the Protestant Reformation.[6]

Third, several considerations indicate that the shift in salaries reflected the impact of

[6]For German universities, data on graduates are preserved, but systematic evidence on pay and teaching do not exist before printing. For Italian universities, data on students do not survive. I discuss the surviving evidence across universities, including at Oxford, Paris, Salamanca, and Louvain, below.

printing. Professor salaries were stable, and exhibited no trends toward science, before printing. The shifts in salaries occurred before the Protestant Reformation and before European contact with the Americas. Evidence on social changes that preceded printing strongly indicates that rise of science was an unintended consequence of the diffusion of printing. Printing diffused in world characterized by economic and cultural change, notably the cultural developments of the Renaissance, including the spread of "humanism" (Burke 1972; Lopez 1976; Denley 2013).[7] Humanism involved the recovery of classical texts; the diffusion of innovations in rhetoric and philosophy; and the formation of elites for academic and civil service careers (Kristeller 1955). In the early 1470s, printers rushed to publish humanistic books and flooded this segment of the market: competition created incentives for them to diversify output (Bühler 1960). In the data on salaries, the relative pay of professors teaching humanistic subjects was growing before printing. Afterwards, the trend in pay shifted away from humanism and towards science. The shifts in the returns to human capital thus suggest that the impact of printing on science may have been an unintended consequence of technological diffusion that reflected non-scientific demand-side factors.

Fourth, to investigate how printing interacted with existing institutions and cultural factors, this paper constructs novel microdata from the history of science literature on individual scientists and inventions across all European cities. In the data, cities with universities emerge as centers of science and invention in the print era, including for activities conducted by people who were not themselves professors. Local exposure to political competition and state patronage also explain scientific and inventive activity, as suggested by prior research (Jones 2003; Mokyr 2016), but only after the introduction of printing.

This analysis contributes to the literature on technological change, and specifically printing. Prior research compares cities that did and did not adopt printing in the 1400s, and uses distance from Gutenberg as an instrumental variable to study city growth and the spread of Protestantism as outcomes (Dittmar 2011; Rubin 2014). The development of science was of similarly fundamental importance but unfolded differently: the impact of printing on science was concentrated in cities that were always going to adopt the technology in the 1400s, irrespective of geography.[8] To trace the impact of printing on science, I therefore construct novel evidence on the labor market, education, and invention. In these data, I find support for the view that, "a major technological breakthrough really signals the *beginning* of a series of developments of great importance," and that we might "*define* a major innovation

[7] I discuss the role of political events, including for example the fall of Constantinople, and the diffusion of humanism and cultural changes both in Italy and in other parts of Europe, in detail below.

[8] University towns drew, and were characterized by, competition among multiple printers. Thus, while Dittmar and Seabold (2019) provide complementary evidence showing that city-level competition among printers shaped the diffusion of religious ideas and business practices in the 1500s, the implications of printing for *science* were not principally driven by variation in competition among printers in a given city.

as precisely one that provides an entirely new framework... [that] will often shape subsequent research for decades" (Rosenberg 1982; p. 156 – emphasis in original).

The analysis also contributes to a larger literature examining the development of science in European history. Perhaps closest to this study is Mokyr (2016), which provides narrative evidence on the role of knowledge elites and cultural change in promoting science in historic Europe. Related, classic arguments in the history of science and in economics suggest that economic development drove the emergence of modern science. Needham (1964) and Zilsel (1942) argued that private sector activity developed the skills and environment in which science emerged. Schumpeter (1976) argued that the "economic rationality" developed by capitalist enterprise reshaped the sciences.[9] Marx suggested that private sector demand provided key incentives for the development of science, but that science also influenced economic activity (Rosenberg 1974). This paper provides quantitative evidence and a new synthesis. I confirm the importance of the private sector and culture, but show that the shift in knowledge production occurred as the shock associated with for-profit printing was transmitted to labor markets in which states and universities were key employers.

The paper also offers new evidence on labor markets and human capital. In recent decades, technological change has favored skill and led to increased inequality, whereas in the 19th century technological changes favored the unskilled (Acemoglu 2002). Prior research on incomes before the industrial revolution rests almost entirely on wage data and finds that the premia for skilled labor were stable from the early 1400s through the 1600s.[10] A related literature indicates the historical importance of educated elites in transforming European society (e.g. Mokyr 2016; Squicciarini and Voigtländer 2015), and narrative evidence indeed suggests that printing led to a major expansion in the activities and influence of such groups (Verger 2000; Eisenstein 1980; Eamon 1984). However, no prior research has studied the returns to upper tail human capital in early modern Europe, to the best of my knowledge.[11] I find that printing led to large scale skill-biased technological change.

The findings also have implications for how we interpret the role of culture and potentially deep-rooted factors in the development of science. Prior research points to features of European society that date from the middle ages as important factors in the development of

[9] Schumpeter (1976; p. 124) argued that "economic rationality" and the "profit-loss calculus" first developed by business activity were extended to, "subjugating – rationalizing – man's tools and philosophies, his medical practice, his picture of the cosmos, his outlook on life, everything in fact..."

[10] The literature focuses on skilled and unskilled wages in construction trades. See Phelps Brown and Hopkins (1955) and Clark (2005) on England, Van Der Wee (1975) on the Low Countries, Malanima (2013a) on Italy, Allen (2001) on 15 European cities, and Van Zanden (2009) for a synthetic review across regions.

[11] Related research studies shifts in the sectoral allocation of labor away from religious and towards administrative employment during the Reformation (Cantoni et al. 2018), and towards administrative and private sector employment, where political change expanded public goods (Dittmar and Meisenzahl 2019).

science, in particular the university (Huff 2017; Chaney 2018).[12] Indeed, research on science and technology in the middle ages suggests a process with deep roots (Crombie 1963; Duhem 1913-1915), possibly tied to Christianity (White 1972) or even a "peculiarly European joy in discovery" (Landes 2006; p. 9). Another strand of literature points to the role cultural *changes* over the early modern period as key factors in the development of science, including religious changes tied to the emergence of Protestantism.[13] This paper provides evidence that universities indeed promoted science, but shows that the introduction of printing shifted university activity towards science. The timing of the shifts in salaries, teaching, and graduates' careers, qualifies arguments linking the development of science to religious factors. The positive shift in the returns to and quantity of science is observed following the introduction of printing, before the Reformation, and in areas that remained Catholic. In Germany, differences across universities in the shift towards scientific achievement foreshadow which universities later became Protestant.[14] While these findings place important limits on the possible role of religion as a causal factor, it is important to note that I consider evidence running into the early 1600s, and that patterns in later periods may certainly differ.

Finally, this research relates to the literature on politics and the development of science. David (2008) observes that political competition among rulers who employed human capital elites increased support for science in historic Europe. Jones (2003) and Mokyr (2016) observe that political fragmentation in Europe limited the ability of anti-science rulers to restrict the development of science. I find that scientific activity was positively related to measures of political competition, but that this positive relationship appears clearly only after the introduction of printing.

In what follows, Section 2 provides historical evidence on early modern science, the role of printing, and the predictions I take to the data. Section 3 describes the data. Section 4 examines evidence on scientific activity in universities, including professor pay, teaching, and publications. Section 5 examines evidence on invention and scientific activity across cities.

[12] Chaney (2018; 2008) assembles evidence on historic manuscripts to measure scientific activity, and finds that scientific activity in Europe rose during the middle ages with the foundation of universities, and that Europe overtook the Islamic world in science the 1100s and 1200s. Chaney (2018) indicates that European science, as measured by surviving manuscripts, was approximately stable between the mid 1300s and the mid-1400s, consistent with the evidence I present on salaries, teaching, and scientific activity before printing. I discuss the transmission of science from the Islamic world in Section 2 below.

[13] The role of Protestants and Protestantism has been emphasized by Merton (1938), Hill (1964), and Landes (2006). However, Rabb (1965) points to the fact that the association between Protestantism and science appears in early to mid-1600s, a century after the Reformation. Heilbron (1989) emphasizes the significance of Catholic contributions to science, including by the Jesuits.

[14] Chaney (2008) finds that religious competition promoted scientific activity in the Islamic world. In the data, there is limited evidence of religious competition effects in our particular time period. However, the evidence that political competition promoted science in Europe is very much in line with Chaney's findings and analysis, in which religion fundamentally operates as a dimension of political economy.

2 The Development of Science and Role of Printing

Debate on Origins of Science

There is debate among historians over the process leading to the development of science. Several interrelated questions stand out. First, was there a sharp shift in scientific activity worthy of the designation "the Scientific Revolution" and, if so, when? Second, how can we measure or assess scientific activity? Given that the criteria and objects of knowledge were changing, what defines "science" or "modern science"? Third, what factors drove or explain the underlying social process?

The predominant view is that early modern Europe experienced a profound shift in knowledge production known as the Scientific Revolution some time between the 1400s and 1600s (e.g. Hall 1983; Bernal 1969; Butterfield 1957). This view has influenced economics. Lewis (1955) argues that the theory of economic growth should consider knowledge before and after science; Rostow (1975) that the application of science defined the transition to modern growth; Mokyr (2005) that the scientific revolution was a prelude to the industrial revolution. The European Commission (2009) argues that intellectual changes in the "European Renaissance of the 15th and 16th centuries" provided the foundation for growth:

> "The very notion of scientific method emerged... led by Copernicus, Keppler, Galileo, Vesalius and others... what we today recognize as scientific disciplines started to form in astronomy, anatomy, botany and mechanics... These new insights and skills shook the established order and laid the groundwork for the prosperity brought by the Industrial Revolution, and our own age of the Knowledge Economy."

A range of arguments point to large scale transformations in scientific activity in early modern Europe. Eisenstein (1980) argues that the printing press drove the development of science by promoting new forms of intellectual exchange, competition, and production, starting in the later 1400s (see also Wootton 2015). Other scholars emphasize the importance of specific discoveries for scientific thinking and cultural change: Neddermeyer (1998) and Bergdolt (2006) point to the publication of Copernicus' astronomy and Vesalius' anatomy in 1543; Hall (1983) suggests that publication of Kepler's heliocentric theory in 1560 marks the beginning of modern science; Westfall (1985) indicates that Galileo's astronomical findings of the early 1600s were key. While emphasizing that the early modern era was characterized by a large increase in intellectual innovation, Park and Daston (2003) question whether the term "Scientific Revolution" is an adequate description for patterns of change in intellectual activity which varied across time, space, and fields.[15]

A contrasting body of scholarship suggests that science developed relatively gradually and emphasizes the role of factors established by the high Middle Ages. Huff (2017) argues that the "foundation" of European science was the legal and institutional change of the 1200s, which established universities and innovations in law and governance. Duhem (1913-1915) argues that medieval science provided the key intellectual foundation for later developments, and that the development of science was a gradual process. White (1972) suggests that pre-Reformation Christianity promoted core cultural beliefs supporting the investigation of nature and invention. Other scholars point to the importance of exchanges with and the transmission of knowledge from non-European societies, including the spread of Arabic numbers, the adoption of paper, and the "rediscovery" of Greek science preserved in Arabic sources, diffusion processes were largely concluded by the mid-1300s (Boas 1962).

The Nature of Historical Science

Prior research on the development of early modern science has been largely non-quantitative and embodies debate over how to measure or assess scientific activity.

This research classifies specific activities as scientific. To examine variation in professor salaries, and in the structure of education, this paper classifies as "scientific" university teaching of anatomy, astronomy, botany, mathematics, medicine, natural philosophy, and surgery. Teaching in courses on canon and civil law, classical languages (Greek, Hebrew, and Latin), moral philosophy, poetry, theology, and related subjects is classified as "non-scientific'. It is important to be clear, however, that the concept of science was itself only incipient over the period of study. This paper uses "science" and "scientist" as a shorthand: historically, researchers and intellectuals we classify as scientists were more likely to be described as "men of science" and "natural philosophers" (Park and Daston 2003). While the classification of activities as scientific and non-scientific helps us to interpret shifts in the returns to human capital, it is important to note that, "during the centuries of the Renaissance, the classical dichotomy between thinkers and makers all but disappeared in Europe, whereas the distinction between scientist and engineer had not yet appeared" (Mokyr 2013; p. 46). Scientific and technological activity became closely linked (Hall 1983).

The nature of scientific activities varied over time. Famously, the astronomy of the late 1500s was not the same as the astronomy of the 1400s, indicating that what counts as science and as evidence is subject to change (Kuhn 1970).[16] More generally, a protracted process

[15] In his monograph, *The Scientific Revolution*, Steven Shapin (1996; p. 1) wryly notes: "There was no such thing as the Scientific Revolution, and this is a book about it." I use the term here in a similar spirit.

[16] Kuhn's (1970) argument about the "structure of scientific revolutions" is frequently invoked in discussions

unfolded in which scientific ideas tied to the Aristotelian tradition were supplanted and new forms of knowledge became ascendant.[17] The fact that the salaries of science professors rose after the introduction of printing thus may reflect both shifts in the demand for a given body of knowledge and training and improvements in knowledge and training.

The Role of Printing

Printing was established in Mainz, Germany around 1450 and was from its inception a for-profit industry (Dittmar 2011; Dittmar and Seabold 2019). Printing spread first to select German cities in the 1460s. In Italy, a printing press was established in Rome 1467; in Venice in 1469; in Florence, Milan, and Bologna in 1471; in Padua in 1472 (Pettegree 2010). In university cities that became centers of scientific thinking there was thus very little variation in the timing of adoption.

Narrative evidence indicates that printing contributed to the development of science in several interrelated ways. First, printing had a supply-side effect on the production of scientific knowledge. Printing dramatically lowering the cost of accessing existing knowledge which was an *input* into knowledge production: Eisenstein (1980) argues that this radically expanded the combinations of existing knowledge that were possible and thereby transformed science. Eisenstein (1980) argues that printing advanced science both by enabling scholars to critically compare evidence and theories from multiple sources at low cost and by increasing interactions between university-based and non-university researchers.[18]

Second, printing changed the "market for ideas," raising the return to scientific activity directly and through the effects of endogenous innovation. Printing promoted the emergence of larger communities of scholars, changed how ideas and scholars were evaluated, and altered the nature of competition. The review of evidence and theoretical arguments improved and the modern reward structure of science emerged, whereby researchers establish priority claims on innovations and discoveries and receive rewards in the labor market (Stephan 1996). Priority claims date from the era of printing (Wootton 2015). Galileo's 1610 letter to Cosimo II de Medici's secretary captures how printing changed the competitive landscape:

> "I did not want to prolong the publication lest I run the risk that perhaps someone else might have discovered the same and preceded me. And therefore I have published it in the form of an *avviso* [newsletter]. . . with the intent of reprinting as

of break-thoughs in astronomy. However, Kuhn explicitly states that his framework applies to paradigm shifts across fields and subfields in the sciences, including those that appear as "local" or modest to non-specialists.

[17] For example, Vesalius' (1543) anatomy text listed errors in the previously canonical work of Galen.

[18] Drake (1970) argues that printing led to the emergence of innovative, evidence based science *outside* universities. Eamon (1984; 1985) emphasizes the role of printing in disseminating previously non-circulating technical information to craftsmen, technologists, and "tinkerers" outside universities.

soon as possible with many additions of other observations." (cited in Gingerich and van Helden 2003; p. 261)

To be clear, Galileo developed the telescope for astronomical investigation and explicitly rushed his work to press to ensure that it would appear in the 1610 Frankfurt book fair. More generally, printing promoted a shift in intellectual competition which *induced* a sequence of intellectual innovations. Wootton (2015) observes, "The printing press fostered a sort of intellectual arms race, where new weapons (the astronomical sextant…the telescope…the pendulum clock…) were constantly being brought up to the front line."

Third, printing contributed to a process of pro-science cultural change. Ornato (1985) observes that economic competition in printing drove printers to pioneer an "ideology of progress" in order to foster demand for new content.[19] Hall (1983; p. 13) confirms that, "the fifteenth and sixteenth centuries were the first in which there had been any self-conscious literary interest in crafts and technology…producing a host of books perfused by the belief that innovation and improvement in techniques is both possible and necessary."

Fourth, narrative evidence strongly suggests printing interacted with the labor market, including through its impact on employment and teaching at universities. Burke (2000) observes that the opportunities available to highly educated elites expanded following the introduction of printing. Lines (2006) notes that the status of scientific activity rose within Italian universities in the later 1400s.[20] I discuss the university and the labor market below.

Science developed as an *unintended* outcome of technological change (Wootton 2015).[21] The unintended consequences reflected the economics of the printing industry. Printing was a high fixed cost industry characterized by intense price competition; this created strong incentives for product differentiation and the introduction of new content (Ornato 1985; Dittmar and Seabold 2019). These dynamics date from the first years of printing: Italian printers flooded the market for humanistic books and experienced a crisis of overproduction in 1472 (Bühler 1960). Narrative evidence indicates that printing shifted the direction of knowledge production and cultural change in an already dynamic European economy; in fact, before the mid-1400s humanists had shown little enthusiasm and some considerable resistance to science (Bergdolt 2006; p. 112). Grafton (1980; p. 267) observes, "It changed the directions of existing cultural movements as suddenly and completely as a prism bends and transforms a beam of light. If printing did not create the Renaissance, for example, it

[19] This dynamic was very much in keeping with Schumpeter's (1976) argument that *typically* capitalist producers innovate in advance of and then shape consumer preferences.

[20] To be clear, Lines (2006) does not argue that this change was directly or uniquely due to printing.

[21] Wootton (2015) provides evidence indicating that a defining characteristic of the scientific revolution was that it was a process of unintended and unanticipated changes.

nonetheless made it undergo a sea change."

The economic process also reflected the weakness of intellectual property rights for historic authors. Piracy, plagiarism, and borrowing were pervasive (Pettegree 2010). Authors were typically unable to claim revenues generated by the publication of their work in other cities: "In an era before effective enforcement of copyrights and licenses, printers freely pirated texts produced by others" (Creasman 2016; p. 72). Intellectual property was insecure even within a city. For example, testimony offered to the Venetian authorities in 1496 indicates that competing printers, "use every cunning device to steal the proofs of [a competitor's] new work from the hands of the pressmen, and set to, with many men and many presses, to print the book before the original designer of the book can finish his edition, which, when it is ready for issue, finds the market spoiled by the pirated edition" (Brown 1891; cited on pp. 55-56). While new intellectual property rights were developed to respond to these dynamics, notably the local "privilege" which promised exclusive publication rights within a city, authors' ability to secure the income generated by their works was limited (Nuovo 2013). A few authors became superstars, including Erasmus and Martin Luther, but book sales did not generally generate high incomes for authors in the 1500s.[22] However, "with the advent of printing, an author, even without formal copyright, could be assured that his discoveries would be publicly acknowledged" (Eamon 1996; p. 90).

Universities and the Labor Market

Until relatively recently, the dominant view has been that universities did little to promote the Scientific Revolution. Several of the most important historical scientists chose to leave their university positions. Galileo quit his chair at Padua to enter the employ of the Medici Dukes; Tycho Brahe established an observatory with support from King Frederick II of Denmark, before becoming imperial astronomer to Rudolf II in Prague. In the early 1600s, Francis Bacon argued that in universities and colleges, "everything is found adverse to the progress of science" (cited in Porter 1996; p. 532). This led many to conclude that, "The history of the Scientific Revolution lies almost completely outside the universities" (Ashby 1966; see also Bernal 1964). However, a revisionist literature observes that most historical scientists were educated and employed at universities (Schmitt 1975) and that of the approximately three hundred historic scientists listed in the *Dictionary of Scientific Biography* only a few were not educated at universities (Porter 1996). Narrative evidence suggests that university libraries, research collections, operating theatres, and botanical gardens provided important support to scientific knowledge.

[22] Venice was one of the few cities in which we observe writers able to support themselves on book sales, but these so-called *poligrafi* only emerged in the later 1500s, a century after printing (Richardson 1999).

Universities provided elite education and employed scholars who were the most highly trained individuals in historic Europe. Universities emerged to serve professional, governmental, ecclesiastical needs in medieval European society, starting in the 11th century (Rashdall 1936; Cobban 1975; Verger 2000). The four faculties in European universities were arts, law, medicine, and theology.[23] Undergraduate courses in the arts faculty provided a path to higher degrees, while law and medicine were the two advanced, professional faculties. Courses in the medical faculty included anatomy, medical theory, medical practice, and surgery; these are all classified as scientific in the analysis below. The arts faculty provided teaching in scientific subjects – such as astronomy, arithmetic, mathematics, and natural philosophy – and non-scientific subjects – such as poetry, rhetoric, dialectics, Greek, and Hebrew. Italian universities provided extremely limited instruction in theology. Less than two percent of courses are in theology in the data on Italian universities presented below.[24]

Universities were supported by secular state authorities. Public funding by city and regional governments was the principal component in university budgets by the mid-1300s (Grendler 2002; Zucchini 2008).[25] State authorities supported universities for several reasons. Rulers had an interest in the formation of educated elites who would serve in public and ecclesiastical offices, and professors were often expected to expertise and services to local political authorities. For example, Grendler (2002; p. 223*) notes that professors of civil law and of medicine could be asked to provide their expert services to rulers; mathematicians and skilled scientists provided services related to irrigation and hydrology and to ballistics and fortification.[26] Universities also provided symbolic and ideological support to rulers. In addition, universities provided, or had the potential to provide, economic benefits: student populations were large relative to city populations, rented accommodations, and broadly consumed goods and services.[27]

Universities competed over students and professors. Students were motivated by "the prospect of monetary gain and an established position in the social order" (Cobban 1975; p. 17). In the 1200s, John of Salisbury remarked, "The lucrative arts, such as law and medicine, are now in vogue, and only those things are pursued which have a cash value" (Paetow 1927; p. 155). Students were mobile: Italian universities drew students not only

[23] In Italian universities, the medicine and arts faculties were formally grouped together as a combined "medicine and arts" faculty.

[24] Canon law courses were prominent in the law faculties; several popes had degrees in canon law.

[25] In Italy, universities were strictly funded by the state, and "Like other communal employees, professors received periodic payments" (Grendler 2002; pp. 160-1). At non-Italian universities, including for example Louvain, some professors were paid with cash flows on Church endowments called *prebends* (Paquet 1958).

[26] States in Northern Italy were involved in large scale irrigation works. The first mathematics professor at Heidelberg also served as a ballistics expert to the local ruler.

[27] After the Black Death, the Florentine authorities used their university to promote economic recovery, explicitly raising professor salaries so as to hire famous faculty and thereby attract more students.

from Italy, but from England and Germany, especially for post-graduate courses degrees. Universities competed for student enrollments: a 1413 statement of the Venetian senate indicates, "Students follow famous teachers, and if provisions for this are not made, our *studium* [university] will be ruined" (cited in Grendler 2002; p. 23). Competition over professors was frequently intense, particularly for intellectual celebrities (Denley 2013). Universities had incentives to innovate and did: during the Protestant Reformation, Italian universities introduced degree granting ceremonies outside Catholic Church jurisdiction so as to stay in the market for German Protestants students (Hammerstein 1996).

While professor salaries and the composition of university teaching were relatively stable and then shifted sharply following the introduction of printing, as shown below, universities were never static. For example, a community of scholars pursuing the philosophical and scientific ideas of the Islamic scholar Averroes (Ibn Rushd) developed at the university of Paris in the 1200s and shifted to Padua in the 1300s (Randall 1940; p. 180). There were also important changes in university structure and governance. The Italian universities originally developed as relatively loose corporate bodies in which students hired professors (Rashdall 1936). However, by the mid-1300s secular governments took control of university administration, budgets, and professor salaries in Italy; and competition over faculty led to the development of formal stipends (Post 1932; p. 194). These changes were arguably fundamental and shaped the context in which the introduction of printing played out.[28]

Other Factors in the Development of Science

A range of additional factors have been suggested as explanations for the rise of science. Some of these were effectively fixed before printing, while others reflected social changes occurring before, after, and alongside the impact of printing.

The role of political factors has been emphasized, in particular by authors who have contrasted European institutions with those in other regions such as China (Jones 2003; Mokyr 2016; Needham 1964). The fragmentation of Europe into many states limited the power of anti-scientific authorities who otherwise might have suppressed scientific activity (Jones 2003; Mokyr 2016) and, more positively, transmitted political competition into the markets in which scholars offered their labor and ideas (Eamon 1996). Rulers supported science to serve practical ends related to governance, defense, and economic development. For example, in Italy rulers supported scientists investigating hydrology and irrigation. Rulers also supported science as a prestige activity designed to reinforce dynastic claims: a classic example of patronage designed to reinforce dynastic claims is the Medici support for Galileo

[28] This change was also fundamental in producing evidence: it is only once state authorities assumed control of budgets and salaries that large scale, consistent records on teaching and salaries exist.

(Westfall 1985). While political fragmentation predates printing and the shift in the returns to science that I document, David (2008) and Biagioli (1989) argue that political competition shifted the demand for mathematics in Italy in the 1500s, as conflict increased the value to rulers of knowledge with applications in ballistics and fortification design.

The role of religion in the development of European science is subject to debate. Merton (1938) provided evidence on a correlation between dissident Protestantism and scientific activity *within* 17th century England. In the 1500s, new restrictions on publishing, including on some scientific topics, were established in parts of Catholic Europe. A classic view is that Catholicism and the counter-Reformation reduced scientific activity (Landes 1998). However, a considerable body of research documents scientific and experimental innovation by Catholic scholars, the role of the Jesuits in developing scientific knowledge (e.g. Heilbron 1989), and the fact that any Protestant advantage does not appear clearly before the 1600s (Rabb 1965).

It is also natural to wonder about role of underlying cultural developments that were transforming intellectual life in Europe before and as printing was introduced. The key movement here was humanism. Bergdolt (2006; p. 112) observes that it is surprising how vehemently resistant humanists were to medical and scientific research until at least 1450.

Finally, two further events deserve mention as potential shocks that influenced the development of scientific thinking. The first is the European "discovery" of the Americas (1492), which led to increased knowledge and increased demand for scientific knowledge, including relating to astronomy and navigation (Burke 2000). It is important to note that the impact of the encounter with the Americas was itself significantly shaped by printing: Wootton (2015; pp. 106-7) notes that, "the technical prerequisties for the discovery game were only just coming into existence in 1492, for it was the printing press (invented c. 1450) which carried news of the discoveries. . . It was the printing press that established a common knowledge base against which these discoveries could be measured."[29] The second is the fall of Constantinople to the Ottomans in 1453. While the fall of Constantinople was a major event, it is important to note that the migration of Greek scholars to Italy predates the fall of Constantinople, most of the arrivals were not scholars in the sciences, and it is likely that the collapse of Byzantium was a net *negative* for Western scholarship (Burke 1972).[30]

[29] Wootton (2015; p. 59) observes that printing shaped and amplified the cultural impact of the new world encounter: for example, the use of words relating to "discovery" spread after the 1504 publication of a letter by Amerigo Vespucci describing his exploratory journeys.

[30] An interesting example is the Greek humanist Theodorus Gaza. Gaza fled to Italy in 1430, and edited and arranged the first-ever printing of Pliny's classical *Natural History* in Rome in 1469 (Zilsel 2003; p. 51).

3 Predictions

The historical evidence generates four key predictions that motivate the analysis below. First, we expect the real price of books to fall following the introduction of printing, and to see the composition of content shifting with prices towards science. Second, we expect the salaries of professors to rise across the distribution, especially for professors of scientific subjects, and that professor salaries should rise following in response to publications. Third, we expect to see university teaching, and the occupational achievements of graduates, shift towards science. Fourth, we expect scientific activity and invention to increase most in the printing era in cities that had universities and were more exposed to political competition, reflecting the way printing interacted with prior institutions. As a corollary, we expect that universities and political competition had limited implications for science before printing.

The historical literature on the rise of modern science implies additional predictions that can help us interpret the role of printing and other factors. A first set of further predictions relates to factors set and quasi-fixed by the Middle Ages. If modern science emerged out of a relatively continuous process driven by aspects of European institutions or culture that were formed by the Middle Ages, we would expect growth in the returns to and quantity of science to pre-date printing. Thus if the introduction of paper or Greek science preserved by Arabic sources were by themselves critical, we would expect to see science growing after these innovations diffused in the 1100s and 1200s.[31] In contrast, if printing acted on a static or low growth initial equilibrium, we would expect professor salaries, the composition of university teaching, scientific activity, and invention to be stable or exhibit low growth before printing.

An additional set of predictions relates to changes in European society. Historical research suggests three dimensions of cultural and institutional change may have been particularly consequential in reshaping the intellectual landscape. First, are cultural changes in the Renaissance, including humanism, that began in 1300s. Second, are changes in religion which developed with the Protestant Reformation after 1517 and thus postdate and partly reflect the impact of printing. Third, are changes in cultural values promoting science and the associated development of scholarly societies and networks. These largely date from or after the introduction of printing.[32] If modern science responded to these changes, we would expect to see corresponding patterns in the data. Similarly, if the encounter with the

[31] Greek science was transmitted in the high middle ages: Ptolemy's 2nd century treatise on mathematics and astronomy, the *Almagest*, was translated from Greek into Arabic in the 900s and from Arabic into Latin c. 1175. Arabic numerals were known to Europeans since the 900s; Pope Sylvester II studied Arabic numerals in the late 900s. Paper mill technology arrived in Europe from the Arabic world by the 1100s.

[32] While these are the leading candidate explanations, I discuss below David's (2008) suggestion that the rise of science reflected a shift in demand for mathematics driven by the French invasion of Italy in the 1500s.

Americas was key, we would expect a response in science after 1492, or perhaps after the 1520s as news of the wealth of Mexico and Peru spread (Schmitt 1975).

4 Data

Book Prices – I construct evidence on prices and physical characteristics for printed books for over 1,600 market transactions observed between 1460 and 1625. For each printed book with price data, I record physical and content characteristics. These include book format (folio, quarto, ocatavo, or other); the presence of printing in multicolor ink; the presence of illustrations; printing on parchment (as opposed to paper). Content is classified in 37 content categories following the Universal Short Title Catalogue (USTC 2012).[33]

Prices for printed books are from the following sources. The records of Christopher Columbus' son, Hernando Colón, record over 800 purchases made in 41 European cities between 1512 and 1539 (Martínez et al. 1993; de Huelva 2012). The data include purchase prices in local currencies and the current exchange rate. A typical example is: "Este libro costó 8 negmit en Anvers a 29 de julio de 1531 y el ducado de oro vale 320 negmit" (i.e. this book cost 8 negmit in Antwerp on July 29, 1531 when the gold ducat was worth 320 negmit). Colón made purchases of "all types of books, without linguistic or ideological restriction" (Wagner 1992; p. 486 – my translation). The purchasing records are a source of evidence which "has no equal in this time" (Dondi 2010; p. 222) in terms of size and the diversity of publications and provide, "an almost unique opportunity to reconstruct the working of the European book market" (Pettegree 2010; p. 87). Second, I gather data from the records of the Venetian book-seller Francesco de Madiis presented by Dondi and Harris (2013).[34] Third, I collect evidence from Neddermeyer (1998), who reports prices for 491 book purchases between 1461 and 1600.[35] Fourth, I collect evidence from the records of the Italian book collector Bellisario Bulgarini for the period 1560 to 1618 (Danesi 2014). These records comprise purchasing notes for individual books, similar to the Colón records, which are also transcribed into a database. Appendix A provides details.

Prices of manuscript books before printing are from copying contracts at the university of Bologna (Devoti 1994) and sales recorded by Neddermeyer (1998). I also present data on

[33]These data were constructed by reviewing physical copies of the editions in question at the Bayerische Staatsbibliotek (Munich), the British Library, Harvard, Shakespeare Folger Library, Yale (Beinecke Library).

[34]These data are for a single year, 1484, but are recognized as the "most extensive and coherent evidence of bookshop prices" that has survived from the Renaissance (Nuovo 2013; p. 338).

[35]These data provide broad time coverage, but do unfortunately do not systematically record the location where purchases were made, due to ambiguity in the underlying source documents.

manuscripts that were individually valued repeatedly at Oxford in both c. 1300 and c. 1400, which provides direct evidence on the evolution of manuscript values (Overty 2008).

Publications – Data on printed publications are drawn from the the USTC (2012), which catalogues all known books published 1450 to 1600. For each publication, we observe: year, title, location of publication, language of publications, and subject matter as classified by the USTC. I examine scientific and technical publications, defined to include: scientific and mathematical books, medical texts, navigational texts, and technical books.

Professor Salaries and Teaching – The principal data on professor teaching and salaries are drawn from official records for the universities of Florence, Pisa, Bologna, Perugia, Pavia, Rome, and Padua. Data are constructed at at the professor-year level for 7,775 observations on professor salaries and between 1400 and 1599. The records indicate the faculty a professor taught in, the specific lecture (or lectures) a professor taught, and the salary received.[36]

Salaries. Salaries were denominated in a large number of local currencies which we convert to a common silver standard as detailed in Appendix A. Salaries in silver values can be compared to wages and prices, including wages of high skill workers (Goldthwaite 1980).

Teaching faculties. Universities were organized in three faculties in Italy: Law, Arts and Medicine, and Theology.[37] For some analyses, we separate the Arts and Medicine teachers and consider four sub-faculties that correspond to the organization of Northern universities, which comprised four faculties on the Parisian model: Arts, Law, Medicine, and Theology.

Classification of professors and lectures. Professors are classified as "science professors" when teaching anatomy, astronomy, botany, mathematics, natural philosophy, medical theory, medical practice, surgery, or another course offered through the medical sub-faculty.[38] Professors are classified as "humanist" when teaching courses in rhetoric, grammar, poetry, Greek, Hebrew, and Latin.

Professors' publications. Professors are hand-matched to their printed publications as recorded in the USTC (2012). There is some residual ambiguity here because university records do not always use complete or consistent names for professors, as discussed below.

We observe the following salary observations between 1400 and 1599. Florence: 48 years

[36] In cases where payments were made each semester, we aggregate to obtain annual salaries. Supplementary data on professor salaries at Heidelberg, Leuven, Ingolstadt, and Oxford are presented below.

[37] Italian universities offered minimal teaching in theology, unlike universities outside Italy. In the data, 2 percent of the courses taught are in theology. Note that Canon law was offered through the law faculty.

[38] There is some potential ambiguity in the classification of lectures. The baseline analysis does not classify as "science" the few lectures in alchemy. We also do not class music lectures as scientific although music was considered a branch of mathematics and the math teaching *quadrivium* included music. The results hold when we drop, or reclassify, these few ambiguous lectures.

and 649 salary observations between 1400 to 1463, when the Florentine *Studio* moved to Pisa. Pisa: 101 years; 1796 salary observations. Padua: 7 years; 98 salary observations. Pavia: 86 years; 3,155 salary observations. Perugia: 28 years; 892 salary observations. Rome: 32 years; 953 salary observations. Bologna: 187 years; 232 salaries. See Appendix A.

Two limitations of the data on professors at Italian universities are important to clarify. First, the data provide complete teaching assignments and salaries for each given university-year for all universities except Bologna. For Bologna, we construct complete teaching data for almost every year from Dallari (1888-1924), but have limited and selected evidence on salaries, principally covering "natural philosophers." The empirical analyses of salaries control for fixed differences across universities and the findings hold if Bologna is dropped from the analysis. Second, records on teaching and salaries are not available for every university-year. For Padua, surviving records are especially fragmentary (Grendler 2002). Appendix A details the data and individual sources.

Italian universities provide unique data on professor salaries. In Italy by the 1400s, salary data are available for all professors at a given university in periods before and after the diffusion of printing; salaries were paid in money, not in kind; and professors were in fact forbidden from receiving other sources of income from teaching.[39] Data on professor salaries at universities in German-speaking Europe are more fragmentary and, in effect, limited to the period after printing. Heidelberg records on professor salaries are sparse until the 1520s (Drüll 2011), and while regularly recorded from 1520 through 1600, sometimes include payments in kind, such as ambiguous allocations of wine and grain. Salary records from Basel and Ingolstadt are available 1461 to 1531 and 1472 to 1510, respectively. I use the data from Heidelberg, Basel, and Ingolstadt to test how professor pay responded to publications. Systematic salary data do not survive for French universities, but Verger (1995; p. 183) argues that salary patterns are likely to be similar to those at Pavia.[40] Salaries at Oxford featured payments in complex combinations of privileges and rights, as well as in cash (see Evans 1992). Further information on non-Italian universities is provided in Appendix A.

Careers of Graduates – Data on graduates at 17 German universities are from *Repertorium Academicum Germanicum* (Schwinges and Hesse 2015), which provides individual data on 21,586 degree recipients from 1386 through 1550 and, for approximately

[39] Dallari (1888-1924; Vol. 1, p. vi) records that by the early 1400s professors at Bologna were not allowed to receive university salaries if they received a salary for another office and, similarly, were prohibited from undertaking additional teaching at either public or private schools. Kibre (1961; p. 61) notes that at Padua, "the professors or doctors who were paid salaries by the Commune were forbidden to supplement their stipends by fees from the students beyond what was necessary to pay for the rental of the schools."

[40] Verger (1995; p. 183) explicitly cites the study on Pavia by Zanetti (1962), whose underlying data we recode, correct, and expand upon in this study.

1/3, post-graduation career information. The following careers as classified as "scientific": arithmetician, mathematician, astronomer, or doctor. Appendix A provides details.

Scientific Activity and Invention Across Cities – Data on innovations and discoveries are constructed from Darmstaedter's (1908) *Handbuch zur Geschichte der Naturwissenschaften und der Technik* which records 1,323 major scientific and technical innovations and discoveries from the period 1200 through 1650. I construct data on the date, individual inventor or discoverer, and geographic location of each invention and discovery. I classify innovations: medical; mathematical; new products; and new processes.[41] I construct evidence on scientists active between 1300 and 1650 from Poggendorff's (1863) *Handwörterbuch zur Geschichte der exacten Wissenschaften*, which provides information on location, field of activity, and employment. Darmstaedter (1908) and Poggendorff (1863) are canonical sources in the history of science and technology literatures. Kragh (1987; p. 175) observes: "Poggendorff's... *Handwörterbuch* is an unrivalled source of biographical data... similar to Darmstaedter's *Handbuch*." The empirical work below conducts several analyses, including ones where attention is restricted to cities that adopted printing to limit the scope for potential selective recording of scientific activity.

5 The Shock to the Market for Ideas

Price and quantity evidence from book markets provides a first characterization of the shock to the market for ideas, and motivates the analysis of evidence on salaries and invention.

5.1 Prices

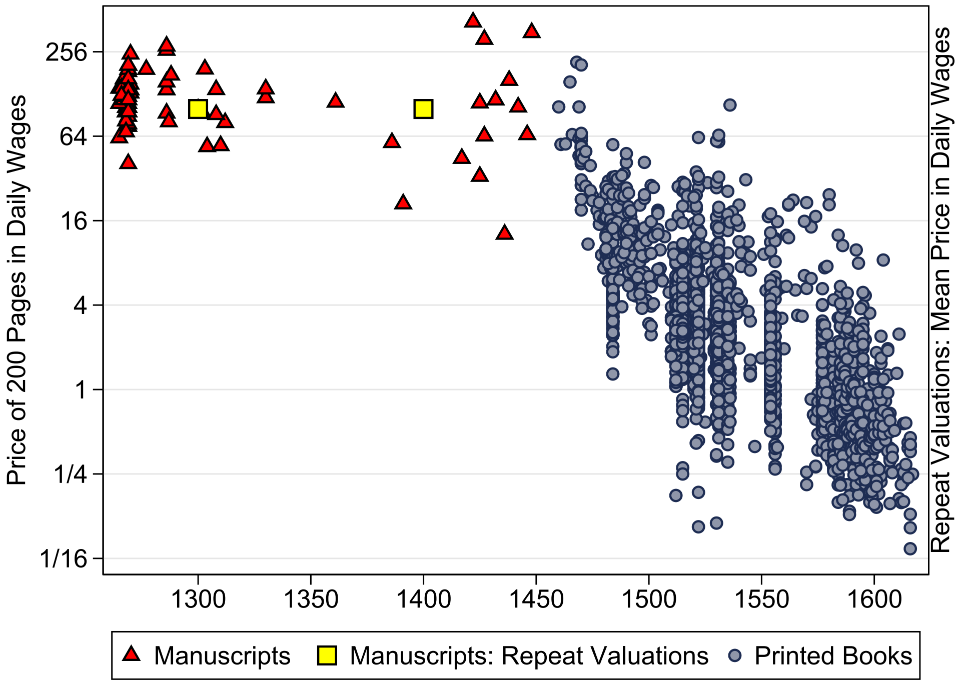
Book prices provide a summary statistic characterizing markets for ideas (Cipolla 1956), but no existing research provides systematic evidence on the price of books following the introduction of printing (Nuovo 2013).[42] To document the shock printing delivered, I collect evidence on the prices hand-written manuscripts and printed books. Figure 2 plots prices a normalized basis: per 200 pages and relative to the daily wage of an unskilled worker.

[41] Inventions and discoveries are matched to locations using information provided by Darmstaedter (1908), the *Dictionary of Scientific Biography*, and Poggendorff (1863).

[42] Dittmar and Seabold (2019) examine data on the prices and characteristics of books between 1510 and 1535. Clark (2004) uses evidence from estate appraisals to construct a proxy index of English book prices, not accounting for book characteristics. Van Zanden (2009) constructs a proxy for Dutch book prices based on input prices and a functional form assumption. Angeles (2017) compares a "European" and a "Chinese" book price, relying on a small number of prices observed decades after printing diffused. See Appendix A.

Following the introduction of printing, we observe book prices falling steadily from close to 100 days of wages in the 1460s to under 1 day of wages by 1600.

Figure 2: The Price of Books in Europe



This figure presents data on the price of books. Prices are measured in days of laborers' wages for 200 pages. Manuscript prices include prices for scribal production from the university of Bologna (Devoti 1994), manuscript purchases from Neddermeyer (1998), Overty (2008), and Oxford archives. Prices for printed books are from Colón archive, Danesi (2014), Dondi and Harris (2013), and Neddermeyer (1998)

To interpret the observed declines in book prices, a key question is to what extent the variation in prices reflects differences in the characteristics of books in the market. To address this question, I investigate the factors influencing the price of printed books, and find changes in the physical and content characteristics of books account for only 1/3 of the price decline. Historical evidence further indicates that printed books were typically both cheaper and *higher* quality than the handwritten manuscripts they supplanted. Notably, printed books were far easier to read.

To characterize the evolution of prices for printed books, I document how book prices evolved controlling for changes in the physical and content characteristics of books. I estimate hedonic regressions of the form:

$$p_{it} = \alpha trend_t + \beta X_i + \epsilon_i$$

The outcome p_{it} is the log book price per page, which I model as a function of an annual time trend and book characteristics (X). I control for whether a book was formatted as a folio, quarto, octavo, or other format, which reflected the size and lay out of the pages.[43] I also control for the presence of illustrations; the use of multi-colored ink; whether a book was sold bound or as was more frequent unbound; and printing on parchment as opposed to paper. I control for book content in 37 different content categories following the classification of the USTC (2012). The content categories, for example, distinguish bibles; religious (non-bible) publications; books on law and jurisprudence; publications on science and mathematics; books on etiquette; books on dialectics.

Table 1 presents the estimates showing the raw price for printed books fell by 2.4 percent per year and 1.8 percent per year controlling for variation in physical and content characteristics. Column 1 shows that prices fell approximately 2.4 percent per year. Column 2 shows that prices fell by 1.8 percent per year controlling for physical characteristics. Column 3 shows that including fixed effects for 37 different types of content has almost no impact on the estimated price trend. Column 4 shows that controlling for the price of paper does not shift the estimates. Column 5 shows that there was no significant difference in the trend in prices in the mid-1500s or in the late 1500s, relative to the underlying trend. The estimates are also not driven by unobserved differences across cities: results are similar when we restrict the analysis to the observations for which we know where a given purchase was made and study the within-city trend in prices.

Manuscript prices reflected the labor involved in writing a book and the sharp trade-off between reductions in labor costs and the quality of hand-writing. Payments for the labor of writing typically represented two-thirds of the cost of books. Attempts to speed up or otherwise reduce the costs of production entailed large sacrifices in the quality of writing which imposed significant costs in time and effort on readers (Ornato and Bozzolo 1997).[44] Prices varied with quality even for a given scribe: formal schedules show the different types of handwriting a scribe could produce and the corresponding prices (see Appendix A).

5.2 Quantities

Figure 3 presents data on scientific publications following the introduction of printing. In the 1450s, virtually no books in the sciences had been printed. The number and the share of scientific publications printed rose sharply. By the late 1500s, 3 percent of books were on

[43] A folio was produced by folding a sheet once, yielding two pages of text on each side of the sheet. A quarto was produced by folding a sheet twice, yielding four pages of text on each side of the sheet. An octavo was produced by folding a sheet to yield eight pages of text on each side of the sheet.

[44] This trade-off was binding even for the quasi-mass production of manuscripts at universities under the *pecia* system. Indeed, Figure 2 above presents prices from *pecia* writing contracts (Devoti 1994).

Table 1: The Trend in Book Prices 1460 to 1618

	(1)	(2)	(3)	(4)	(5)
	Outcome: Ln Price per Page				
Trend: Annual Trend	-0.024***	-0.018***	-0.017***	-0.018***	-0.018***
	(0.002)	(0.001)	(0.002)	(0.003)	(0.004)
Trend × Period 1518-1555					-0.000
					(0.000)
Trend × Period 1556-1618					0.000
					(0.000)
Book Physical Characteristics	No	Yes	Yes	Yes	Yes
Book Content Fixed Effects	No	No	Yes	Yes	Yes
Paper Price	No	No	No	Yes	Yes
Observations	1474	1474	1474	1474	1474
R^2	0.55	0.70	0.72	0.72	0.72

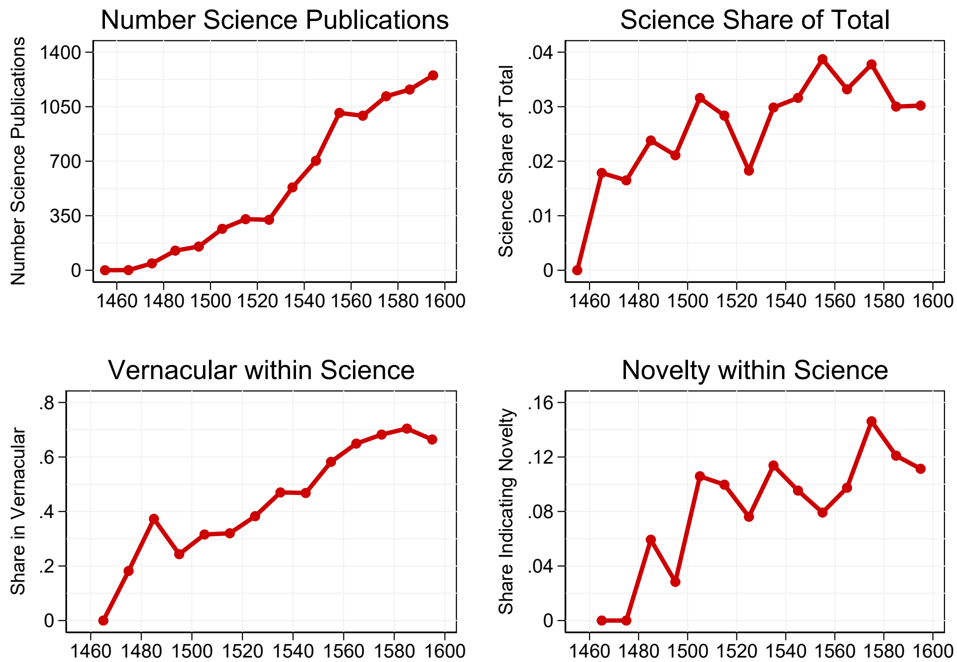
This table presents regression estimates of the trend in book prices in transactions between 1460 and 1618, as described in the text. The outcome is the natural logarithm of the price of books in days of laborers' wages, measured as the mean laborers' wage across European cities from Allen (2013). The trend interactions multiply the time trend with indicators for designated sub-periods. "Book Physical Characteristics" comprise indicators for physical characteristics: indicators for books printed in the format of folios, quartos, and octavos (the omitted reference category consists of books formatted as 12o's, 16o's, and a small number of hybrid format books), as well as indicators for illustrated (illuminated) books and for books printed in multiple ink colors, such as black and red ink. Content fixed effects comprise 37 different subject matter types. "Paper Price" denotes regressions that control for paper prices using the logarithm of the annual paper price series from Van Zanden (2009).

scientific topics. Increasingly, these publications appeared in local vernaculars, not Latin.

The scientific and technical literature spread knowledge and cultural values. For example, Girolamo Ruscelli (1540) used a book preface to frame the motivations of the *Accademia Segreta*: "we devoted ourselves to the benefit of the world in general…by reducing to certainty and true knowledge so many most useful and important secrets…I now send these to the printer for the benefit and the common pleasure of all" (cited in Eamon and Paheau 1984; pp. 339-340). Similarly, Hall (1983) observes that, "the 15th and 16th centuries were the first in which there had been any self-conscious literary interest in crafts and technology…producing a host of books perfused by the belief that innovation and improvement in techniques is both possible and necessary." Printing contributed to a larger and multi-faceted process through which beliefs and attitudes towards science shifted over the early modern period (Mokyr 2016). Changes in cultural values influenced the nature of academic celebrity, the priorities of employers, and students' educational choices. They are thus are likely to be embodied in evidence from the labor market on professor salaries and teaching assignments that is examined below.

Historians specifically suggest that printing led to the diffusion of new knowledge and

Figure 3: Scientific Printing



This figure presents evidence on (A) the number of scientific publications printed, (B) the share of publications on science, (C) the share of scientific publications printed in local vernaculars, and (D) the share of scientific publications using language claiming novelty in their titles by decade. Data for all European cities with printing are from USTC (2012). The calculation of the share of science publications claiming novelty is restricted to publications in Latin, German, Italian, French, and English.

new cultural discourses concerning progress (Wootton 2015). This is borne out in the titles of historic books on science and technology, which increasingly use language that advertises the novelty of their content, as shown in the last panel of Figure 3. While cultural factors certainly influenced these trends, the shifts in publishing towards science and novelty also reflected the economics of printing. The high fixed costs and low marginal costs in printing led to a competitive environment with incentives for product differentiation and the introduction of new content (Ornato 1985).

Evidence on the quantities of books printed should be viewed as suggestive. Manuscript production did not disappear with the introduction of printing, and our evidence on the ideas in manuscript production before Gutenberg is limited by the fact that the transition to printing itself imposed a "pitiless selection on the cultural heritage transmitted from Antiquity and the Middle Ages" (Ornato 1985; p. 81 – my translation).[45] The fact that printing may have shaped the selective transmission of knowledge previously in manuscripts,

[45]In the original: "la transition de l'époque du manuscrit à celle de l'imprimé constitue une sélection impitoyable du patrimoine culturel transmis par l'Antiquité et le Moyen Âge." Only a small share of medieval manuscripts survive and loss rates are likely to vary across periods and literatures (Ornato and Bozzolo 1997; p. 182 – see also Buringh 2011).

including by influencing the survival of manuscripts themselves, provides one reason to examine evidence on salaries that are not subject to this sort of selection.

6 Labor Market Evidence: Universities and Science

This section examines the evolution of university professors' salaries, the allocation of teaching, and the career choices of graduates.

6.1 Professor Salaries

Stylized facts – The key stylized facts concern: the overall evolution of professor salaries before and after printing; how the changes compare for professors of scientific and non-scientific subjects; and how salaries evolved across and within faculties.

1. The overall salary distribution.

Table 2 presents summary statistics on the overall distribution of professor salaries. The mean salary rose from 1.7 years of skilled wages in the early 1400s to 1.9 years of skilled wages between 1450 and 1474. Before printing, the median salary was effectively unchanged. At the 90th percentile, salaries grew in the early 1400s, but were stable between 1425 and 1474. After the introduction of printing, salaries rose sharply. The salary of the mean professor rose to 3 times skilled wages; the median salary rose to approximately two times the wage for a skilled worker; at the 90th percentile of the professor salary distribution, we also see an even larger increase in salaries. Between 1400 and 1600, we observe virtually no change in the premium skilled workers earned relative unskilled workers. The salaries of bank clerks, who were numerate and literate, were also stable. School teachers salaries' were also relatively stable in the 1400s, and appear to rise in the early 1500s.

Comparisons between professor salaries and wages do not account for differences in the cost of living across consumer groups. Hoffman et al. (2002) observe that the prices of goods and services purchased by the affluent fell relative to those of wage goods after 1500. Hoffman et al. (2002) consider a range of goods and services but not books. Given the importance of books for affluent consumers, and especially professors, the welfare and real inequality effects associated with printing are likely to be larger than the relative income effects. Significantly, however, inequality *within* the professoriate *fell* after printing was introduced, as shown by the changes in the ratio of the 90th percentile to the 50th percentile salary in Table 2.

Table 2: Professor Salaries Relative to Skilled Wages

	Quarter Century Starting							
Income Comparison	1400	1425	1450	1475	1500	1525	1550	1575
Professor: Mean	1.70	1.87	1.93	2.87	3.46	3.66	3.21	3.42
Professor: 25th Pct.	0.55	0.53	0.47	0.60	1.00	0.92	0.93	1.29
Professor: 50th Pct.	1.00	0.98	0.94	1.36	1.74	2.07	1.76	2.29
Professor: 90th Pct.	3.52	4.88	4.95	7.38	7.99	8.08	7.63	7.79
Skilled Wages	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Unskilled Wages	0.58	0.55	0.56	0.64	0.56	0.56	0.54	0.47
Bank Clerks: Mean	0.99	1.02	0.70	0.90	–	–	–	0.96
School Teachers: Mean	1.31	0.81	1.01	1.20	1.94	–	–	–
90-50 Ratio for Professors	3.52	4.98	5.27	5.43	4.59	3.90	4.34	3.40

This table presents evidence on professor salaries relative to the level of skilled wages. Data on professor salaries are compared to the skilled wage in that year and comprise 7,015 individual salary observations. Data on skilled wages are from Goldthwaite (1980) and record wages of skilled craftsmen in the construction industry in Florence. These data on daily wages in a given year are multiplied by 250 to obtain a "yearly wage." Mean salaries and salaries at the 25th, 50th (median), and 90th percentiles are calculated across observations in a given quarter century. Data on unskilled wages Goldthwaite (1980). Data on 137 annual bank clerk salaries are from Goldthwaite (1998), Tognetti (1999), and de Roover (1963). Data on 222 annual school teacher salaries are from Siena archives (Denley 2007). All data are indexed to the skilled wage.

2. Salaries for science and non-science professors.

Table 3 compares the salaries for science and non-science professors. The gap between science professors and non-science professors increased after the introduction of printing. The mean science professor earned just over two years of skilled wages before printing, while non-science professors earned 1.75 times skilled wages. After printing, the mean non-science salary rose to 2.9 times skilled wages, whereas the mean scientist earned 3.9 times skilled wages. At the 90th percentile, non-science and science professors earned similar salaries before printing. After printing, at the 90th percentile non-science professors earned 6.95 times skilled wages, whereas science professors earned 9.19 times as much.

To interpret the magnitudes in Table 3, a comparison to recent history is helpful. Goldin and Katz (2008; p. 68) use the ratio of professor salaries to wages as evidence on the "great compression" in inequality in the 1900s. Full and associate professors in the USA earned 4.2 and 3.0 times the income of manufacturing workers, respectively, in 1908. These pay ratios declined to 2.1 and 1.6 times manufacturing wages in 1960. The levels and the magnitude of the shift in the ratio of professor salaries to wages in Renaissance Italy are similar. However, after the introduction of printing, we observe a "great expansion" in inequality.

3. Salaries across and within faculties.

Table 3: Salaries for Science and Non-Science Professors

	Observations		Professor Salaries in Years of Skilled Wages					
			Median		Mean		90th Percentile	
Subject Taught	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Science	819	1,471	1.23	2.46	2.07	3.90	4.87	9.19
Non-Science	1,919	2,806	0.89	1.46	1.76	2.91	4.52	6.95

This table presents summary statistics on the distribution of professor salaries for science and non-science professors. "Science" professors are defined as those teaching courses in astronomy, botany, mathematics, medicine, "natural philosophy." "Non-science" professors comprise all other professors and cover teaching in canon and civil law, theology, Greek, Latin, Hebrew, and other non-science subjects. The median, mean, and 90th percentile professor salaries are calculated across observations before and after printing, defined as 1400 through 1474 and 1475 through 1599 respectively. The underlying salary data are observed at the individual professor-year level for a given professor and academic year. Salaries are compared to wages for skilled crafts workers from Goldthwaite (1980); Malanima (2013a;b). Daily wages for craft workers are multiplied by 250 to obtain a "yearly wage."

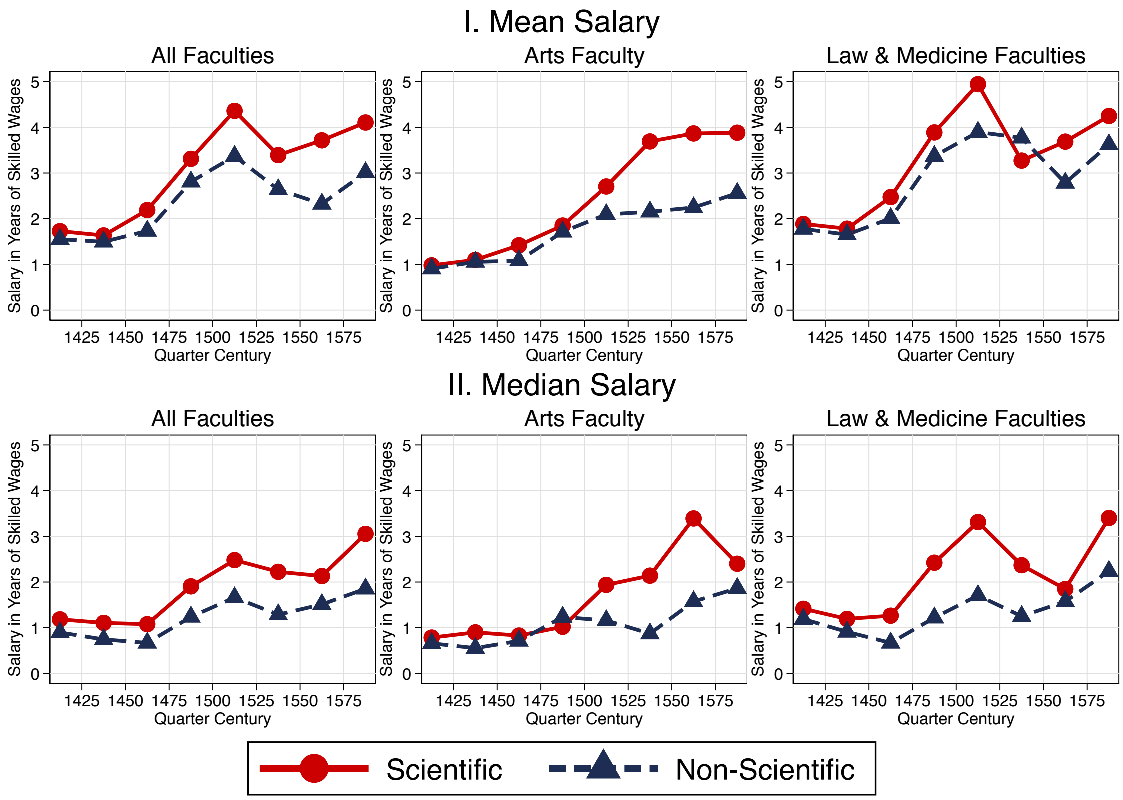
Figure 4 summarizes the raw data on the salaries for scientific and non-scientific professors. Panel I presents data on mean salaries by faculty, while panel II presents median salaries. The left panels show that salaries for all professors increased after 1475, and that salaries for scientific professors increased differentially more. The center panel shows that salaries for scientific and non-scientific professors in the arts were similar and exhibited modest growth until the early 1500s, when the salaries for scientific professors increased sharply. From 1500 forwards, salaries for scientific courses in the arts rose dramatically. By the 1540s, the average science professor in the arts was earning a salary almost equal to four years of skilled wages while the average non-science professor in the arts earned almost two times the skilled wage. Thus pay went up the most for teaching in astronomy, mathematics, and natural philosophy; pay increases were more modest for teaching in rhetoric, poetry, moral philosophy, and classical languages. The right panel shows salaries in law and medicine, which were the higher pre-professional faculties before the advent of printing. Salaries in medicine and law increased after the introduction of printing. The post-1475 increases in the mean and median salaries were larger in the medical faculty; median salaries increase post-1475, while there is some evidence of an increase in mean medical salaries 1450-1474.

Regression analysis – To investigate the variation in professor salaries, I test whether the pay of scientific professors went up following the introduction of printing; whether there were underlying or subsequent trends in pay; and how outcomes responded to publications. I first estimate a flexible difference-in-differences model:

$$y_{ijkt} = \beta_0 + \sum_{s=1400}^{1575} \beta_s (sci_i \cdot period_s) + \theta_{jt} + \gamma_k + \lambda_{kt} + \epsilon_{ijkt}$$

The outcome is the logarithm of ratio of professor salaries to the wage of skilled workers.

Figure 4: Salaries for Scientific and Non-Scientific Professors



This graph presents data on professor salaries at Italian universities. Panel I presents the mean salary for scientific and non-scientific professors and Panel II presents median salaries. In each panel: the first graph compares all scientific and non-scientific professors; the second graph compares scientific and non-scientific professors within the Arts faculty; and the third graph compares professors of Medicine, classified as scientific, and professors of Law, classified as non-scientific. The underlying data comprise 7,015 salaries at the professor-year level at the universities of Bologna, Florence, Padua, Pavia, Perugia, Pisa, and Rome. Salaries in a given year are indexed to skilled wages observed in that year from Goldthwaite (1980), with daily wages multiplied by 250 to obtain a "year of skilled wages." The mean and median salaries in a given faculty and time period are calculated across observations in a quarter century.

Professors are indexed i, universities j, faculties k, and time periods t or s. The parameters of interest are the β_s, which estimate how scientific teaching is associated with variation in salaries in different time periods. These parameters capture how interactions between an indicator for scientific teaching ("sci_i") and period fixed effects ($period_s$) explain salaries. University-time-period fixed effects (θ_{jt}) absorb any differences in pay across universities in different periods and restrict the analysis to comparisons between the salaries of "science" and "non-science" professors *within* a university-period such as Florence 1500-1524. Faculty fixed effects (γ_k), and faculty-specific trends (λ_{kt}), are introduced to control for potential underlying differences across faculties in the underlying level of or the trend in salaries.

1. Changes in the returns to science

Table 4 presents estimates examining how professors' salaries evolved. Column 1 shows that salaries for science professor rose by 25 percent post-1475 relative to the omitted 1450-1474 period, that there were no significant increases in salaries before the spread of printing, and that salaries for scientists remained elevated across the 1500s. The comparison here is between "scientists," like professors of mathematics, astronomy, and natural philosophy, and "non-scientists," like professors of canon and civil law, theology, moral philosophy, poetry, rhetoric, Hebrew, Greek, and Latin. The estimates control for time invariant differences across universities and for time period and faculty fixed effects, accounting for the fact that the law and medicine faculties in general offered higher salaries.

We obtain very similar estimates when we compare salaries for scientific and non-scientific professors teaching at the same university and at the same time, as shown in column 2. This comparison is implemented by introducing university-×-time fixed effects, for university-time-periods such as "Florence in the 1500-1524 period." These fixed effects absorb differences in pay across universities that may vary over time but are shared by science and non-science professors employed at the same university in the same period. We also obtain similar estimates when we control for underlying faculty-specific trends in column 3. When we control for potentially different trends in salaries for professors of arts, medicine, and law, we observe a small and statistically insignificant increase in pay for scientists in the early 1400s, effectively no change in scientists' relative pay between 1425 and 1450, and then a sharp increase in both the level and trend in pay for scientists' after 1475.

2. Pretrends in the returns to non-scientific human capital

The salary data also permit us to test whether printing led to shifts in the returns to human capital in a world already under-going cultural change, as narrative evidence suggests (Grafton 1980). The estimates above indicate very limited if any increases in the relative salaries of scientists before the spread of printing. However, the development of humanism was the leading change in elite culture and education in Italy in the decades before printing. Humanistic studies were increasing in the universities in the early 1400s as cultural values and labor market demand changed: the chancelleries and diplomatic services of states in Italy increasingly demanded professionals with humanistic training (Burke 1972). It is thus natural to examine the evolution of pay for professors teaching core courses in humanistic training: rhetoric, grammar, poetry, and classical languages, which I classify as proxying for humanism. In the data, I find that there was a positive underlying differential trend in pay towards humanism before the introduction of printing. After the diffusion of printing, there was a significant and quantitatively large decline in the trend in salaries for humanists. I discuss these analyses in Appendix B.

The evidence on the returns to humanism helps us interpret the shifting returns to

Table 4: Salary Premia for Science Professors

	(1)	(2)	(3)
	Outcome: Ln Salary Premium		
Science × 1400	-0.03	-0.00	-0.16
	(0.07)	(0.11)	(0.13)
Science × 1425	0.07	0.09	-0.03
	(0.06)	(0.11)	(0.13)
Science × 1475	0.25***	0.27**	0.25**
	(0.06)	(0.12)	(0.11)
Science × 1500	0.30***	0.28***	0.31***
	(0.09)	(0.10)	(0.10)
Science × 1525	0.17	0.23	0.36*
	(0.13)	(0.22)	(0.21)
Science × 1550	0.25***	0.20**	0.37***
	(0.09)	(0.09)	(0.11)
Science × 1575	0.28***	0.26**	0.41***
	(0.10)	(0.10)	(0.12)
University Fixed Effects	Yes	No	No
Time Period Fixed Effects	Yes	No	No
University × Time Fixed Effects	No	Yes	Yes
Faculty Fixed Effects	Yes	Yes	Yes
Faculty-Specific Trends	No	No	Yes
Observations	7015	7015	7015
Mean Outcome	0.415	0.415	0.415

This table presents regression estimates examining variation in professor salaries observed at the individual professor-year level. The outcome is the logarithm of the ratio of professor salary to the skilled wage. Data on skilled wages in Northern Italy are from Goldthwaite (1980) and Malanima (2013a;b). "Science × 1400" is the interaction between an indicator for teaching a scientific course ("Science") and an indicator for the 1400 period, defined as running 1400 to 1424. Other interactions defined similarly. The omitted category is "Science × 1450." Column 1 includes separate university and time period fixed effects, with time measured in 25-year periods. Columns 2 and 3 include university-time-period fixed effects. "Faculty" fixed effects are separate fixed effects for (1) Arts, (2) Law, and (3) Medicine. Faculty-specific trends are separate time trends for each of these faculties. Robust standard errors in parentheses, clustered by university-time-period. Statistical significance at the 90 95, and 99 percent level denoted *, **, and ***, respectively.

science. Narrative evidence indicates that printing arrived in a world characterized by ongoing cultural change, and that printing shifted intellectual activity away from previously dynamic areas and towards science. The data on professor salaries confirm these dynamics. The returns to human capital were trending towards humanistic knowledge before printing. After printing, we observe a sharp shift in compensation towards science.

3. The impact of publishing on professor pay

The salary data can be used to investigate the relationship between publishing and pay. I construct evidence on each professor's cumulative publications in each year using data from the USTC (2012). I then estimate how a given professor's salary responded to changes in their own publication record in a model with professor fixed effects.

Table 5 shows that professor pay responded sharply to scientific and mathematical publications. In the data for Italian professors, salaries rose by over 60 percent when professors published an additional scientific or mathematical publication (column 1). The correlations between publications and salaries are smaller and less precisely estimated for legal and medical publications (columns 2 and 3). For professors at German-speaking universities, an additional scientific or mathematical publication was associated with a 22 percent increase in salary (column 4); the effects for publications in law and medicine are far smaller, though more precisely estimated than for Italian professors (columns 5 and 6).

To interpret these findings several observations are important. First, it is important to clarify the nature of the data. University records sometimes designate professors with ambiguous names, limiting our ability match evidence on a professor's salary to evidence on publications and to form panel data on salaries, especially in the Italian data. Second, the within-professor variation in the data on salaries and publications is limited. Publications were not a *sine qua non* for an academic career (Burke 1972), and the majority of professors were not published authors. For many professors who were published, we do not observe variation in publications over the periods for which salary data are available. Some had already published when they enter the salary data; others published after the years in which salary data are observed. Third, the differences in the estimates across Italian and German universities may reflect differences in returns to publishing and aspects of the underlying data. Qualitative evidence suggests that there were especially high returns to science and mathematics in Italy. That said, the Italian records are more ambiguous in naming professors and it is possible that this introduces forms of measurement error in constructing individual publication records that could bias parameter estimates. While the evidence strongly indicates that scientific publications led to salary increases, these considerations suggest some caution in interpreting the parameter estimates as causal effects.

6.2 The Allocation of Teaching and Supply of Training

The increases in salaries for science professors following the introduction of printing invites questions about the provision of scientific training and the supply-side of labor markets for upper tail human capital. Two observations are central here.

Table 5: Publications and Professor Salaries

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome: Ln Salary Premium					
	Italian Universities			German Universities		
Science & Math Publications	0.67***			0.22**		
	(0.23)			(0.10)		
Law Publications		0.42			0.03*	
		(0.66)			(0.02)	
Medicine Publications			0.07			0.08**
			(0.35)			(0.03)
Annual Time Trend	Yes	Yes	Yes	Yes	Yes	Yes
Professor Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7015	7015	7015	1642	1642	1642
Mean Outcome	0.41	0.41	0.41	0.36	0.36	0.36

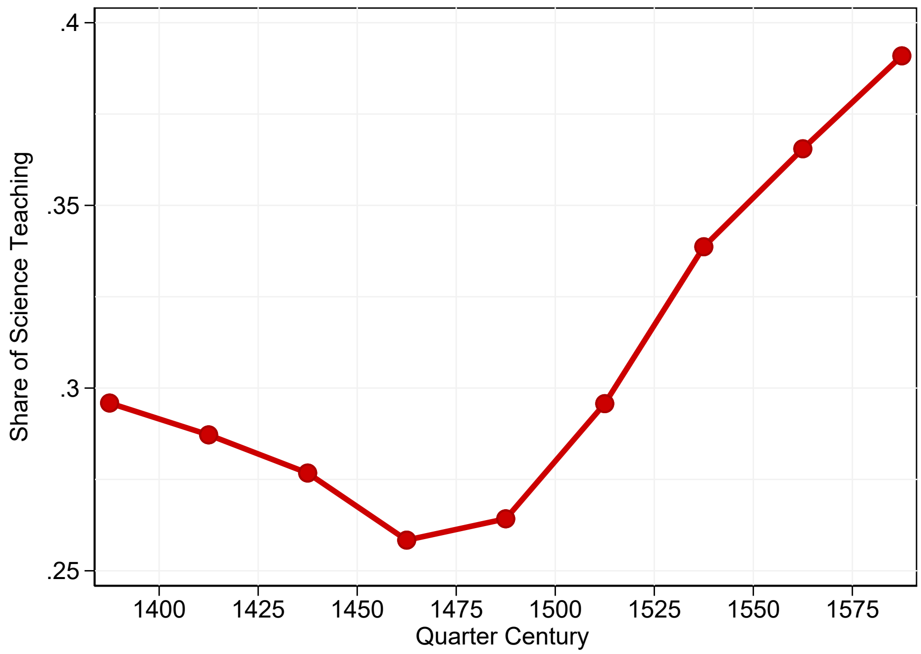
This table presents estimates examining the relationship between professors' printed publications and salaries. Columns examining Italian universities examine the baseline data on professor salaries at Italian universities, as described in the text. Columns examining German universities examine salaries at Heidelberg (1520-1600), Basel (1461-1531), and Ingolstadt (1472-1510). The outcome is a given professor's salary premium relative to the prevailing skilled wage in that year. Italian professor salaries are examined relative to skilled wages in Northern Italy from Goldthwaite (1980) and Malanima (2013a;b). German professor salaries are examined relative to skilled wages in Strasbourg/Straßburg from Allen (2013). Printed publications are measured by total cumulative publications of a given type as of the given academic year. Publications data are constructed by matching individual professors to their publications as recorded in the *Universal Short Title Catalogue*. Publications are are classified as "Scientific & Math", "Law", and "Medicine" following the subject classification in the *Universal Short Title Catalogue*. Standard errors are clustered at the professor level. Statistical significance at the 90, 95, and 99 percent level denoted *, **, and ***, respectively. Note that professor identity is measured at the university level due to uncertainties in tracking professors who may have moved across universities. The fixed effects and standard error clustering thus capture a given professor at a given university.

First, the supply of scientific training within universities shifted following the introduction of printing. The university records enable us to track the composition of teaching, and in particular the share of courses offered on scientific subjects. Figure 5 shows that the share of professors teaching scientific subjects was declining somewhat before the introduction of printing and afterwards rose sharply starting in the later 1400s. This implies that the returns to science, as measured by professor salaries, rose in an environment in which the relative supply of scientific instruction was also increasing.[46]

Second, over the period in question university enrolments rose in absolute numbers but university students remained a relatively stable share of the population. While historical evidence indicates that university education was expanding, the exact number of students studying at universities, and enrolled in different courses of study at Italian universities, is

[46]While the share of courses on scientific subjects summarizes the supply of education, it abstracts from variation in the number of students in specific courses and from changes in the quality of instruction.

Figure 5: Share of Courses on Scientific Subjects



This graph plots the share of courses on scientific subjects, by quarter century, in Italian universities. The underlying data comprise records on 29,016 individual lecture courses. Scientific subject courses are defined to include all courses in Medicine (theory, practice, surgery, botany) and scientific courses in Arts (mathematics, astronomy, natural philosophy). The data comprise all observations on professor teaching with the exception of observations from select university-years in which teaching records are only available for a particular faculty. For Bologna, the years 1405, 1425, 1437, 1450, and 1457 are excluded because surviving records only record either the law faculty or the arts and medicine faculty. Similarly, Padua records are excluded for 1424, 1430, 1500, 1506, and 1507.

not known as complete enrolment and graduation records do not survive (Grendler 2002). The existing estimates are thus subject to considerable uncertainty, but suggest that student populations grew roughly in line with total urban population in Italy, as shown in Table 6.[47] While there is uncertainty due to the nature of the surviving evidence, it appears that the shifts in the relative salaries of professors occurred while the share of people with university training grew approximately in line with the overall population. This suggests that demand-side factors drove the changes in returns, but also points to factors that may have limited supply side expansions of university education.[48]

[47] There is considerable uncertainty about the size of the university student population. Table 6 presents growth rates calculated from data in (Grendler 2002) that, for some university-years provide a range of possible student populations. The table calculates growth rates under the assumption that the number of students is equal to the mid-point in any such range.

[48] As noted above, universities were reliant on the support of political authorities, which served to limit the number of universities. University growth also required budgetary commitments and the historical evidence suggests that political authorities frequently tried to limit budgets. In addition, no state was able or willing to support more than one university. Thus Florence moved its university to its subject city of Pisa, which it controlled, but did not support two universities.

Table 6: Growth in Student and Total Population

	Annualized Growth			
	Total Population	Total Urban Population	Urban North-Central	University Students
Italy across 1400s	0.12%	0.57%	0.30%	0.53%
1400-1450	-0.13%		-0.19%	0.74%
1450-1500	0.37%		0.79%	0.33%
Italy across 1500s	0.39%	0.46%	0.25%	
1500-1550	0.49%		0.39%	0.38%
1550-1600	0.29%		0.12%	

This table summarizes evidence on student enrolments and total population in Italy. Growth in university students is calculated using enrolment estimates from Grendler (2002; see also Appendix A below). Data on urban and total population are from Malanima (1998) and Malanima (2002)*. Urban population is defined as the population of cities and towns with at least 5,000 inhabitants.

6.3 The Careers of University Graduates

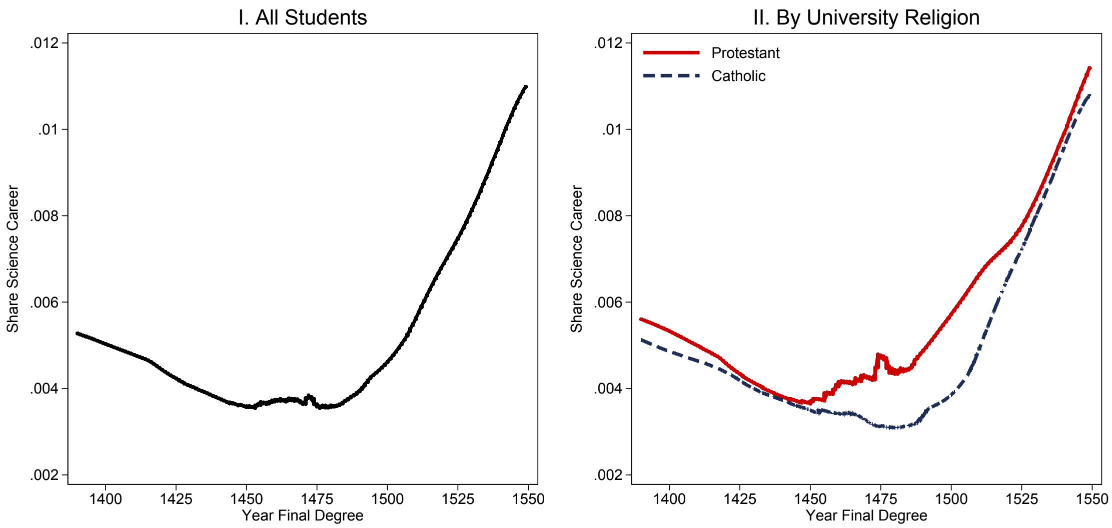
Data on the careers of university graduates provide corroborating evidence on the shifts in economic activity associated with the introduction of printing. We expect that higher returns to scientific activity would induce graduates to enter scientific careers. Evidence on graduates from Italian universities is limited: neither matriculation nor graduation records survive in any systematic way (Grendler 2002). However, systematic records on individual graduates, and rich evidence on their careers, exist for German universities from the *Repertorium Academicum Germanicum* (Schwinges and Hesse 2015). These data can be used to examine whether the probability that a graduate is observed in a scientific career shifted with the introduction of printing. These data also help us assess how economic changes in Italy compare to those in other regions and to assess hypotheses on the role of religious change.

Figure 6 plots estimates showing that the probability of an individual graduate having a scientific career.[49] Panel I examines all graduates and documents a shift towards scientific careers following the introduction of printing in the mid-1400s. The timing of this change corresponds closely to the shift in pay and teaching in Italy universities, suggesting a similar underlying process. The German data also enable us to assess the hypothesis that scientific activity may have responded to the introduction of Protestantism, either directly or through the influence of religious competition. Panel I shows that the Reformation, which began in late 1517, did not lead to an overall acceleration in scientific activity. Panel II distinguishes graduates from universities that eventually adopted Protestantism and that

[49] Schwinges and Hesse (2015) provide occupational titles that I classify as "scientific" or not. For example, the analysis considers mathematician (*Mathematiker*), surgeon (*Chirurgicus*), medical doctor (*Stadtarzt*, *Leibarzt*, *Hofarzt*), and astronomer and astrologer (e.g. *Hofastrologe*) as scientific careers. Monk (*Mönch*), deacon (*Dekan*), and humanist (*Humanist*) are examples of "non-scientific" careers.

remained Catholic. We observe similar patterns in scientific careers across university types before printing and during the Protestant Reformation. Strikingly, however, universities that would adopt Protestantism produced differentially more graduates with scientific careers in the intermediate period after the introduction of printing and before the Reformation. This is consistent with historical evidence indicating that universities that adopted Protestantism were *ex ante* different and more open to intellectual innovation (Grendler 2004; Spitz 1981).

Figure 6: Scientific Careers Among University Graduates



This figure presents estimates of the probability that a university graduate had a scientific career. The data comprise records on 21,586 individual students who completed their final degree at a German university before 1550. The outcome is an indicator for university graduates with a scientific occupation recorded in Schwinges and Hesse (2015). The figure shows estimates from locally weighted regressions studying how career outcomes varied with year of final degree. Panel I examines careers for all students by year of final degree. Panel II distinguishes students who received their final degree at a university that adopted Protestantism during the Reformation and those who received final degrees at universities that remained Catholic, labeled "Protestant" and "Catholic." Protestant universities are: Basel, Erfurt, Frankfurt an der Oder, Freiburg, Greifswald, Heidelberg, Leipzig, Marburg, Rostock, Tübingen, and Wittenberg. These universities only formally adopted Protestantism starting in the 1520s.

To interpret this evidence several observations are important. First, the analysis classifies careers as scientific if and only if a directly scientific occupation is recorded in Schwinges and Hesse (2015). This implies we measure science careers outside universities. This is because consistent evidence on teaching assignments do not survive for German universities, so we are unable to systematically classify those students who went on to be professors as "scientific." Second, the data record careers for approximately one-third of graduates. This invites questions about potential selection in the available evidence. Significantly, there is no increase in the share of students with career information following the introduction of printing and we find a similar shift to scientific careers when we analyse only students with career information, as shown in Appendix B. Third, it is possible that printing shifted the nature of the surviving evidence. To the extent that printing shifted cultural values towards science, or simply differentially favored the reputations of scientists broadly defined, this may have influenced which graduates enter the historical record. If printing indeed shifted which activities contributed to reputation and fame, such "selection" effects may represent a key outcome of printing. Finally, while the data on German graduates indicate that shifts towards scientific activity were not limited to Italy, there were significant differences in higher education, labor markets, and institutional and cultural factors across regions. To consider regional variation more closely, evidence on science and invention across Europe is useful.

7 Scientific Activity and Invention Across Cities

The historical evidence and our analysis of scientific activity at universities invite questions about the overall distribution of inventive and scientific activity, including outside the university, and whether political competition and universities explain the variation in invention and scientific activity when we examine evidence from across Europe. This section presents *preliminary* evidence on scientific activity and invention across European cities. This should be viewed as an initial illustration of on-going research.

7.1 Time Series Evidence

The data on innovations and discoveries, and on the research activities of scientists, reveal sharp increases dating from the mid-1400s. Figure 7 summarizes the distribution of inventive activity from 1200 to 1650. Inventions and discoveries arrived at a low rate and exhibited no growth before 1450. After 1450, we observe steady growth. Figure 7 similarly shows that the number of active scientists was extremely low and exhibited no growth before the 1450s and steady growth after 1450.

7.2 Universities, Politics, and Printing

Several institutional features of pre-modern Europe have been identified as factors that influenced drove the development of science in Europe. Arguably the most significant were: (1) universities, which trained and employed scholars and provided resources for research; (2) royal courts, which were centers of wealth and patronage, including in the sciences, and which reflected competitive dynamics among rulers; and (3) political fragmentation, which contributed to political competition that historians argue influenced the level of support for science.

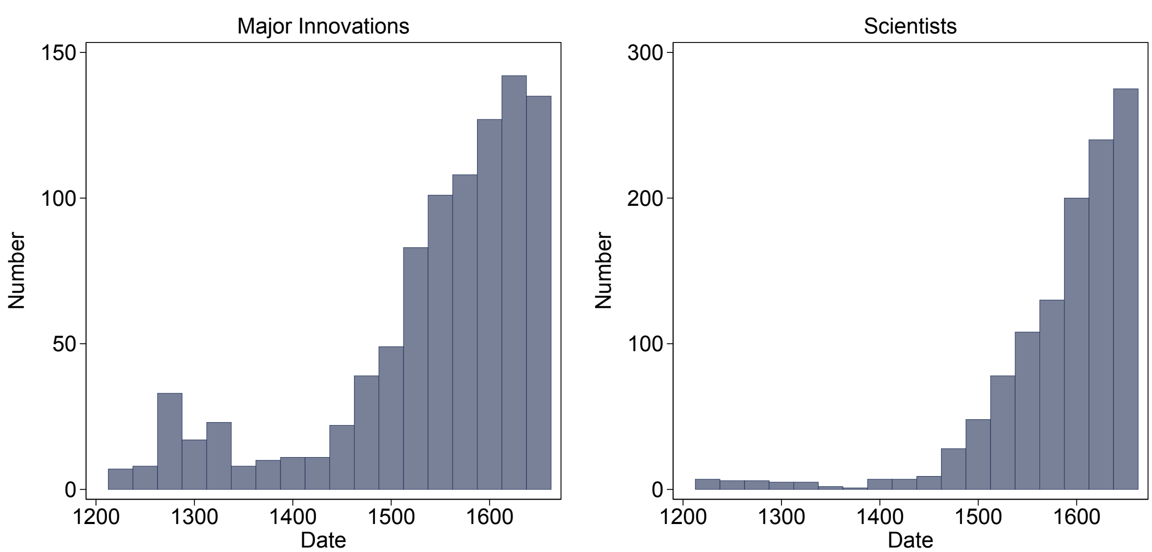
To assess the role of these factors, I examine how their relationship to scientific activity across all European cities. I test whether these features of the European economic and intellectual landscape, which varied across cities, indeed have a relationship to science. I examine the location of scientific activity across cities and time periods. As a baseline, I examine 2,202 European city locations from Bairoch et al. (1988) and time in 50-year periods from 1300-1349 (period 1) through 1600-1649 (period 7), estimating a regression model:

$$y_{it} = \alpha_i + \delta_t + \beta_U(univ_i \times post_t) + \beta_C(court_i \times post_t) + \beta_P(polifragment_i \times post_t) + \epsilon_{it}$$

The outcome is an indicator for the presence of a scientist in a city-time-period. The key independent variables examine whether cities with universities or with royal courts or in more politically fragmented regions were more likely to be locations with scientific activity following the introduction of printing.

Table 7 presents estimates that indicate that universitieis, royal courts, and political fragmentation were associated with greater scientific activity following the diffusion of printing. Significantly, this holds for non-academic science activity, measured by the presence of a "scientist" *not* working at a university. Similarly, this holds for scientists in non-mathematical fields, such as medicine and the biological sciences (column 4), and for

Figure 7: Major Technical Innovations and Scientists Active



This figure presents the major innovations (technical inventions and discoveries) and scientists active. Data are from Darmstaedter (1908) and Poggendorff (1863).

scientists in more mathematical fields, such as mathematics and astronomy (column 5).

Table 7: Scientific Activity Across European Cities

	Binary Outcome: Scientists in City-Period				
	All Types	Not Academic	Only Academic	Not Math	Broad Math
Uni × Post-1450	0.18***	0.13***	0.11***	0.20***	0.08***
	(0.05)	(0.04)	(0.04)	(0.05)	(0.03)
Uni	0.05	-0.03	0.09**	0.05	-0.04
	(0.06)	(0.05)	(0.05)	(0.06)	(0.03)
Court × Post-1450	0.15***	0.14***	0.07*	0.17***	0.08***
	(0.05)	(0.05)	(0.04)	(0.05)	(0.03)
Court	-0.06	-0.06	-0.04	-0.05	-0.04*
	(0.06)	(0.05)	(0.04)	(0.06)	(0.02)
Fragmentation × Post-1450	0.02***	0.01***	0.01***	0.02***	0.01***
	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)
City and Time Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	15414	15414	15414	15414	15414
Mean Outcome	0.04	0.03	0.02	0.03	0.01

This table reports regression estimates examining scientific activity at the city-time-period level. Scientific activity is measured with a binary variable for a scientist active. Time periods are half centuries 1300 through 1649. Variables are defined as follows. "Post" period is an indicator for periods post-1450. "University" is an indicator for cities with universities. "Court" is an indicator for cities the seat of royal courts. "Fractionalization" is an indicator for cities in locations with a high degree of political fractionalization in 1300.

To examine the variation more flexibly, we also estimate regressions in which we study the variation period-by-period using a model:

$$y_{it} = \alpha_i + \delta_t + \sum_s \beta_s^U univ_{it} + \sum_s \beta_s^C court_{it} + \sum_s \beta_s^P polifragment_{it} + \epsilon_{it}$$

Figure 8 plots the regression estimates (β's) and shows that, before printing, scientific activity was no more likely at university towns or where there were courts or political fragmentation was higher. After printing we observe that each of these features of cities becomes a positive and significant correlate of science.

Finally, we examine innovation across European cities. We measure innovation by the presence of an innovation (1/0) in a city-time-period. Table 8 reports our estimates. We find that universities, courts, and political fractionalization were all differentially associated with innovation after the introduction of printing. We find that the estimate for political

Figure 8: Difference-in-Differences Estimates

fractionalization is somewhat less precise, but that our findings hold when we control for changes in which locations had universities (column 2) and when we restrict the analysis to cities that adopted printing (column 3). In column 4, we consider whether *local* printing was interacted with these features of cities to predict innovation. We find, somewhat unsurprisingly, that local printing mattered in more fractionalized places but not, for example, in university cities. To be clear, this is unsurprising because there is minimal variation in printing for university cities in the post period.

These suggestive correlations provide several preliminary indications on the pattern of scientific activity and innovation. These results suggest that printing had its most notable effects where it interacted with universities, the political and patronage structures of royal courts, and political fragmentation. We interpret our findings with caution, not least because the data could reflect forms of selective survival promoted by printing. Our analysis attempts to control for this by restricting some estimates to cities that adopted printing. It should be noted that the selective survival of information about scientific activity and innovation could be an important effect of printing – a form of non-depreciation via data preservation.

Table 8: Innovation Across European Cities

	Outcome: An Innovation in a City-Period			
	All	All	Printing	All
University Ever × Post	0.16***	0.10**	0.10**	0.07**
	(0.03)	(0.04)	(0.04)	(0.03)
Court Ever × Post	0.19***	0.22***	0.20**	0.21***
	(0.05)	(0.08)	(0.08)	(0.05)
Fractionalization × Post	0.01**	0.01**	0.03	0.00
	(0.01)	(0.01)	(0.02)	(0.00)
University Ever × Post × Printer Active				0.00
				(0.13)
University Ever × Post × Printer Competition				0.24
				(0.16)
Court Ever × Post × Printer Active				-0.09
				(0.22)
Court Ever × Post × Printer Competition				0.03
				(0.27)
Fractionalization × Post × Printer Active				-0.00
				(0.06)
Fractionalization × Post × Printer Competition				0.22**
				(0.10)
Time Period & City Fixed Effects	Yes	Yes	Yes	Yes
Control Extensive Margins (e.g. Uni Founded)	No	Yes	Yes	Yes
Observations	15414	15414	3654	15414
Mean Outcome	0.015	0.015	0.058	0.015
Mean Outcome Post-1450	0.023	0.023	0.089	0.023

This table reports regression estimates examining innovation at the city-time-period level. Innovation is measured with a binary variable and time periods are half centuries 1300 through 1649. Variables are defined as follows. "Post" period is an indicator for periods post-1450. "University Ever" is an indicator for cities ever with universities. "Court Ever" is an indicator for cities ever the seat of royal courts. "Fractionalization" is an indicator for cities in locations with a high degree of political fractionalization in 1300. "Printer Active" is the share of years with an active printer in a given time period of 50 years. "Printer Competition" is the share of years with at least two active printers in a given time period. We control for the direct effects of printing in column 4.

8 Conclusion

The diffusion of printing provides a canonical example of how a revolutionary information technology may transform society. This paper traces hows the introduction of printing in 1400s Europe delivered a shock to markets for ideas and to labor markets. It documents that the interaction between these two markets was critical: it generated a sharp increase in the returns to and the quantity of scientific training and activity, leading to profound changes in knowledge production.

The nature of the historic interaction between the market for ideas and the market for labor carries general and more conceptual lessons for economics. Printing was an archetype of capitalist industry. Printing transformed the market for ideas by introducing a new technology and new forms of competition, which reflected the high fixed and low marginal costs in the industry and generated incentives for product differentiation and the introduction of new content. The emergence of printing shifted the market for ideas towards a dispensation in which ideas and knowledge were partially commodified, most clearly in publications that were bought and sold.

The transformation of the market for ideas delivered a shock to existing labor markets for upper tail human capital. States and parastatal organizations like universities were key purchasers and demand-side competitors in the market for upper tail human capital and remained so in the era of printing. However, universities and political competition were transformed. Institutions which previously provided minimal support for empirical research and science were activated to support the production of new, scientific knowledge. The introduction of printing thus provides us a canonical case in which private sector behavior impacted the public sector and the system of higher education. It indicates how the interplay between private and public sector was fundamental in the emergence of science and, more broadly, in the transformation of knowledge production that ultimately supported modern growth. It also highlights how technological change can generate significant feedback effects on the knowledge production process itself.

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