A Time to Print, a Time to Reform*

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Abstract

The public mechanical clock and movable type printing press were arguably the most important and complex technologies of the late medieval period. We document two of their most important, yet unforeseeable, consequences. First, towns that were early adopters of clocks were more likely to also be early adopters of presses. We posit that towns with clocks became upper-tail human capital hubs—both technologies required extensive technical know-how that had many points of overlap. Second, a three-stage instrumental variables analysis indicates that the press influenced the adoption of Protestantism, while the clock's effect on the Reformation was mostly indirect.

Keywords: mechanical clock, printing press, technology, Reformation, human capital, instrumental variables

JEL codes: N33, N73, O33, O34, P48, Z12

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1 Introduction

This paper addresses two related issues that are key for understanding the rise of the modern state and the modern economy. First, to what extent did innovations spill over into the spread of other technologies *prior to* industrialization? Second, what were the unforeseeable consequences of technological agglomeration on the social and political equilibria of the pre-modern period? These issues are far from trivial historical footnotes: technology agglomeration and political and social upheaval have long been viewed as key elements of Europe's economic rise (Weber 1905; Mokyr 1990*a*; Nexon 2009; Mokyr 2016; Tilly 1990; Greif 2006; Acemoglu and Robinson 2012; Stasavage 2014, 2017; Rubin 2017).

We contribute an answer to these questions by analyzing the causes and consequences of the spread of the two most important technologies of the late medieval period: the public mechanical clock and the movable type printing press. These are not arbitrarily chosen technologies. Mumford (1934) argued that "[t]he clock, not the steam engine, is the key-machine of the modern industrial age." Landes (1983) compared the appearance of the clock to the introduction of the modern computer. Historian Donald S.L. Cardwell (1972, p. 12) noted that "there can be little doubt, however, that of all the great medieval inventions none surpassed the weight-driven clock and the printing press, measured by the scales of inventive insight on the one hand and social, philosophical, even spiritual, importance on the other . . . the clock and the printing press are, in fact, the twin pillars of our civilizations and modern organized society is unthinkable without them." These were the most important innovations of late-medieval Europe, and in studying them we are able to address two related issues. First, we provide evidence of technological agglomeration in the late medieval period: those places with clocks were more likely to later adopt the printing press. Second, we find an interaction between technology and *religious* change: cities with presses and clocks were more likely to adopt the Protestant Reformation, arguably the most important social, political, and religious movement of the early modern period. Our analysis suggests that the role of printing on the Reformation was direct while the role of clocks on the Reformation was mostly indirect (via the press). Combined, these results suggest a role for path dependence. Technological agglomeration mattered for the spread of the Reformation not because technology as a whole played a role in the movement, but because it specifically facilitated the spread of printing, which did play a unique role in the Reformation.

Both clocks and printing presses required an immense amount of mechanical knowledge to build and operate, and the production of both required precision, technical skills, and dexterity in using different metals. For these reasons, clockmakers and printers often belonged to guilds of the smiths: approximately 60% of medieval and Renaissance clockmakers came from the ranks of blacksmiths, goldsmiths, and locksmiths (Dohrn-Van Rossum 1996; Zanetti 2017, p. 113–122). Johann Gutenberg (the inventor of the press) himself was a blacksmith and goldsmith, as were many of the early printers (Febvre and Martin 1958, p. 49–51, 168, 201). Clockmakers and early printers were the knowledge elites of their day, and the historical record notes numerous spillovers between the two professions. Were such spillovers of actual economic significance, as was the case in England and France on the eve of industrialization (Mokyr 2009; Squicciarini and Voigtländer 2015)?

The most obvious candidates for locating positive spillovers were European cities prior to the Industrial Revolution. Cities were the best places for stimulating and developing innovation. On the demand side, better transportation technologies and organized markets facilitated the availability of cheaper inputs for producing new products. On the supply side, cities facilitated the exchange of ideas and the availability of skilled artisans who were able to create final products derived from inventors' blueprints (Mokyr 1990*b*). Furthermore, in cities there is an endogenous element of technology adoption (as found in modern American cities by Moretti (2012)). The clustering of skilled workers and smart inventors enabled new learning processes for the next generation of new ideas.

If the connection between clocks and the press is an open empirical question, such questions have largely been answered about the connection between the printing press and the Reformation. Martin Luther himself viewed the press as one of the key reasons why his reform movement succeeded. The major problem for the initial reformers was information dissemination. Previous attempts at reform (e.g., the Hussite movement of the early 15th century) were unable to get off the ground, in part because there was no printing press to spread propaganda rapidly enough before the Church could react. The Lutherans were able to overcome this problem by spreading propaganda via printed pamphlets. The early Lutheran leaders, led by Luther himself, wrote thousands of anti-papal pamphlets in the Reformation's first decades. These works spread rapidly through reprinting in various print shops throughout central Europe. The connection between printing and the Reformation was confirmed by Rubin (2014) and Dittmar and Seabold (2019), both of whom provide empirical evidence linking the spread of the printing press and print workshops to the spread of the Reformation.

The role the clock played in the spread of the Reformation has been the subject of much less study. There is reason to believe the clock may have played a role in the spread of the Reformation, as it served as a coordinating device which created a sense for time, punctuality, and discipline that was key to the ideas of the Calvinist movements. In fact, Calvin himself was inspired by the opportunities clocks offered, and he embedded rules of order and discipline in his religious beliefs following the newly available precise time measurement (Engammare 2010). In this vein, Gorski (2003) claims that the Calvinist spirit towards a new culture of punctuality, order, and social-disciplining facilitated the success of the Dutch Revolt (1568–1648) by a well-organized minority and let Calvinism succeed to become the dominant religion, and it later enabled successful state formation.

While it is possible that the spread of the clock directly affected the spread of the Reformation, the causal channel is unclear. In any case, we only find weak evidence of a direct effect. Yet, it is possible that clocks *indirectly* affected the Reformation by affecting the spread of printing.

Testing these conjectures is an empirical challenge. Neither mechanical clocks nor printing presses were randomly assigned to towns, indicating that any econometric specification must consider the endogeneity of the primary independent variables of concern. We address these issues using data from Rubin (2014) on printing presses and the Reformation (and various other town characteristics) and data from Boerner and Severgnini (2019) on the early spread of mechanical clocks. These data allow us to test whether the spread of the press and the spread of clocks affected the adoption of Protestantism. We address potential endogeneity and omitted variable biases by instrumenting for the presence of a clock with the town's past experience with solar eclipses. The idea behind this instrument, which is also used by Boerner and Severgnini (2019), is based on the fact that eclipse activities stimulated the construction of astronomical tools such as astrolabes, which were the prototype of mechanical clocks. In other words, we posit that eclipses were events which lasted in the psyche of the population (as did earthquakes; see Belloc, Drago and Galbiati (2016); Bentzen (2019)), and this encouraged experimentation to understand the world better. We instrument for the spread of the printing press with the town's distance to Mainz, the birthplace of Gutenberg's press. This instrument is used in Dittmar (2011) and Rubin (2014), and it works intuitively as an instrument because printing spread over time in relatively concentric circles emanating from Mainz, and Mainz was not an important enough of a city where distance from Mainz should have had an independent impact on other outcomes of interest.

A three-stage regression analysis yields numerous results. First, the adoption of the printing press is positively and highly significantly related to the spread of the mechanical clock: towns with mechanical clocks were around 17 percentage points more likely to adopt the printing press, all else equal. Further, we find that the spread of the printing press is a strong, positive predictor of a town being early an adopter of Protestantism: press towns were 79 (62) percentage points more likely to adopt the Reformation by 1530 (1600). On the other hand, the presence of a mechanical clock was not related to the spread of the Reformation in any statistically meaningful way, although its *indirect* effects, via the press, were substantial: between 9 to 11 percentage points of the effect of the printing press variable on the spread of the Reformation can be explained by the prior existence of a clock.[1]

This paper therefore provides an additional technology link to the thesis that the Protestant movement led to capitalism and economic development in the long-run, an idea most prominently argued by Weber (1905). Weber's argument that a new work ethic propagated by the Reformation is closely linked to Calvinist ideas, which were embedded in the new use of time. Furthermore, Gorski (2003) outlined that the new Calvinist culture of social-discipline led to successful state formation, for instance in the Netherlands, and paved the way for colonialism and western development. Moreover, the sequential nature of the events we analyze—clocks spread prior to the press, which spread prior to the Reformation—allows us to avoid reverse causality. A large literature suggests that religion and religious authorities can both inhibit the spread of technology (Mokyr 1990*a*; Coşgel, Miceli and Rubin 2012; Bénabou, Ticchi and Vindigni 2016; Chaney 2016) or facilitate its spread (White 1978; Davids 2013, ch. 2–3). The argument presented in this paper focuses on the other side of this self-enforcing pattern, revealing how certain types of technological change can affect religious change.

The rest of this paper is structured as follows. The next section provides the historical background of clocks, printing presses, and their role in the Reformation. The subsequent sections describe the data collected for this study, describe the instruments, and report the empirical results. The final section offers some concluding thoughts.

[1] We find suggestive evidence that clocks may have played a more direct role in the spread of Dutch Calvinism. See the Appendix for a brief narrative of the link between clocks and the Dutch Reformation.

2 Historical Background

2.1 The Mechanical Clock

Public mechanical clocks first arrived in Europe at the end of the 13th century.[2] Clocks appeared simultaneously around the turn of the century in northern Italy, southern England, and southern Germany. During the 14th century, clocks spread in towns all over western Europe, penetrating further into Germany, Italy, and England, and for the first time into Belgium, the Netherlands, France, Spain, Switzerland, Austria, and neighboring Central European territories. During the 15th century, clocks first appeared in Eastern Europe and Scandinavia (Dohrn-Van Rossum 1996). The spread of clocks followed an S-shape diffusion curve, which is typical for the spread of a general purpose technology (see Figure 1).[3]

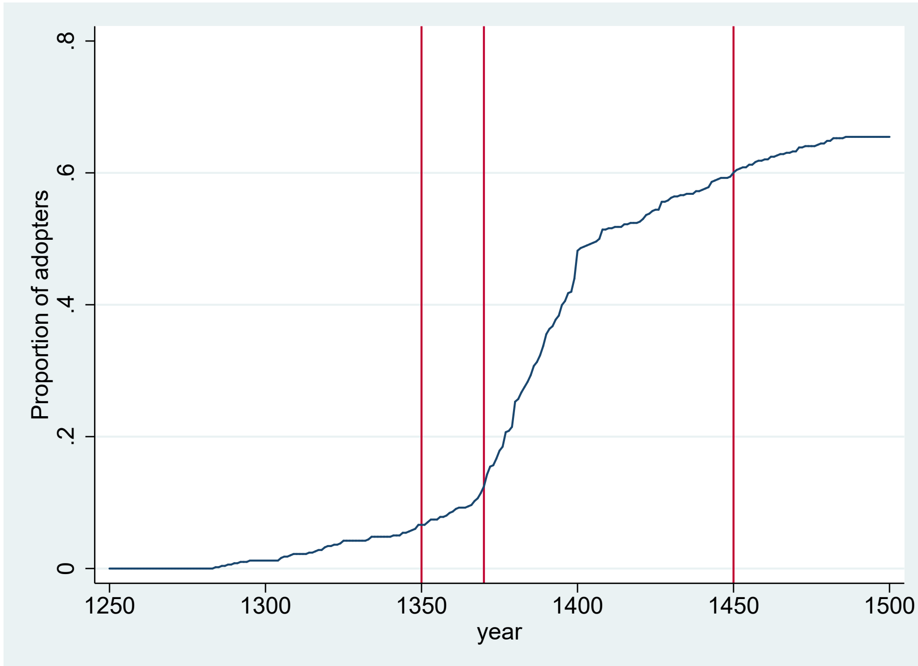
The public measurement of time was something completely new in the late medieval period. Clocks existed before in the form of sand, sun, or water clocks, but they were not previously used for daily activities because they were not very reliable or functional. As a result, one's sense of time was mainly defined by the position of the sun. However, soon after the initial spread of public mechanical clocks, clocks were used to coordinate activities such as fixing market time or agreeing on public town hall meetings (Dohrn-Van Rossum 1996). Public mechanical clocks were publicly accessible focal points that created common knowledge for anyone within listening distance. In addition, publicly available time began to affect the measurement of working time, and it created a new attitude of punctuality, discipline, and order (Thompson 1967).

The original motivation behind the commissioning of clock construction was generally not economic. The building of a clock was a sign of prestige, openness, and progressiveness of a city (Boerner and Severgnini 2019). Clocks were typically built on church towers or the

[2] Much of this subsection is a condensed history of the mechanical clock presented in Boerner and Severgnini (2019).

[3] In Figure 1, the inflection point of the S-shaped curve was around 1450 and the cumulative distribution converges to about 0.7. This is likely due to the fact that we take into consideration only the early adoption of mechanical clocks. It is estimated that the public clocks arrived in almost all the cities by the end of the 18th century.

Figure 1: Cumulative Distribution of the Mechanical Clock, 1250–1500



Cumulative distribution of mechanical clock based on the cities available in Bairoch, Batou and Pierre (1988). Source: Boerner and Severgnini (2019). The vertical red lines represent the end of the three phases of early adoption (i.e., 1350, 1370, and 1450).

communal tower of the town hall.[4] They were mechanical devices that produced a weight-driven acoustic signal every hour. The construction and maintenance of a clock was not that costly compared to other public expenses—although it was not negligible either—and it was typically mentioned in the town account books. The following example from the city of Duisburg (in western Germany) in 1401 supports this claim. Duisburg was a rather small town. Its town account books note that construction and installation of the first clock cost 10 Gulden. The daily maintenance cost 2 Gulden per year (paid as yearly wage to the local sexton) and a general overhaul, which took place every couple of years (normally carried out by a foreign expert), cost about 10 Gulden. In comparison, the complete renovation of the

[4]It is worth noticing that, despite the contrast between the "Church's time" and the "merchant's time" observed by le Goff (1980), Dohrn-Van Rossum (1996, p. 231–32) rejects any hypothesis of Church resistance to the public mechanical clock. Supported by several historical sources, he argues that churches and monasteries "did not hesitate in introducing and making practical use of the new technology as soon as it was available."

church tower roof in the year 1401 cost 60 Gulden. The new church cross cost 35 Gulden in 1365 (Mihm and Mihm 2007).

The construction of mechanical clocks, while not incredibly expensive relative to other major expenses incurred by medieval towns, was a difficult task which could not easily be learned. Moreover, a profession or guild of clockmakers did not exist. The first clockmakers came from various backgrounds which brought knowledge and expertise from various theoretical and practical disciplines. For instance, some clockmakers had an education in astronomy. Such knowledge was learned in monastic education, university studies, or elite circles of the Jewish scientific culture, where Islamic scientific knowledge was preserved. These clockmakers typically had a theoretical knowledge of astronomy, and they would also learn to build astronomic instruments, and thus had some mechanical skills (Dohrn-Van Rossum 1996). Indeed, clocks were often astronomic instruments and the dials indicated (beside the time) the movements of the celestial bodies. The acquisition of such knowledge was quite advanced and placed these individuals among the upper-tail of human capital elites during the late medieval period. Clockmakers did not have any theoretical training, but developed a technical-artisanal versatility which enabled them to draw, design, and construct all kind of machines, including clocks (Dohrn-Van Rossum 1996; Zanetti 2017). Finally, a large share of clockmakers were specialized smiths, in the form of locksmiths or goldsmiths. These crafts were among the most advanced in terms of artisanal skill of the time. Early locksmiths and goldsmiths were specialized fine mechanics who were able to build clocks based on experimentation, imitation, and learned professional skills (Dohrn-Van Rossum 1996). In the case of engineers and smiths, their skills were based on tacit knowledge. In other words, much of their skill was the result of "learning by doing" based on transmission from their colleagues and masters rather than any abstract theoretical knowledge formation (Mokyr 2002; de la Croix, Doepke and Mokyr 2018).

2.2 The Printing Press

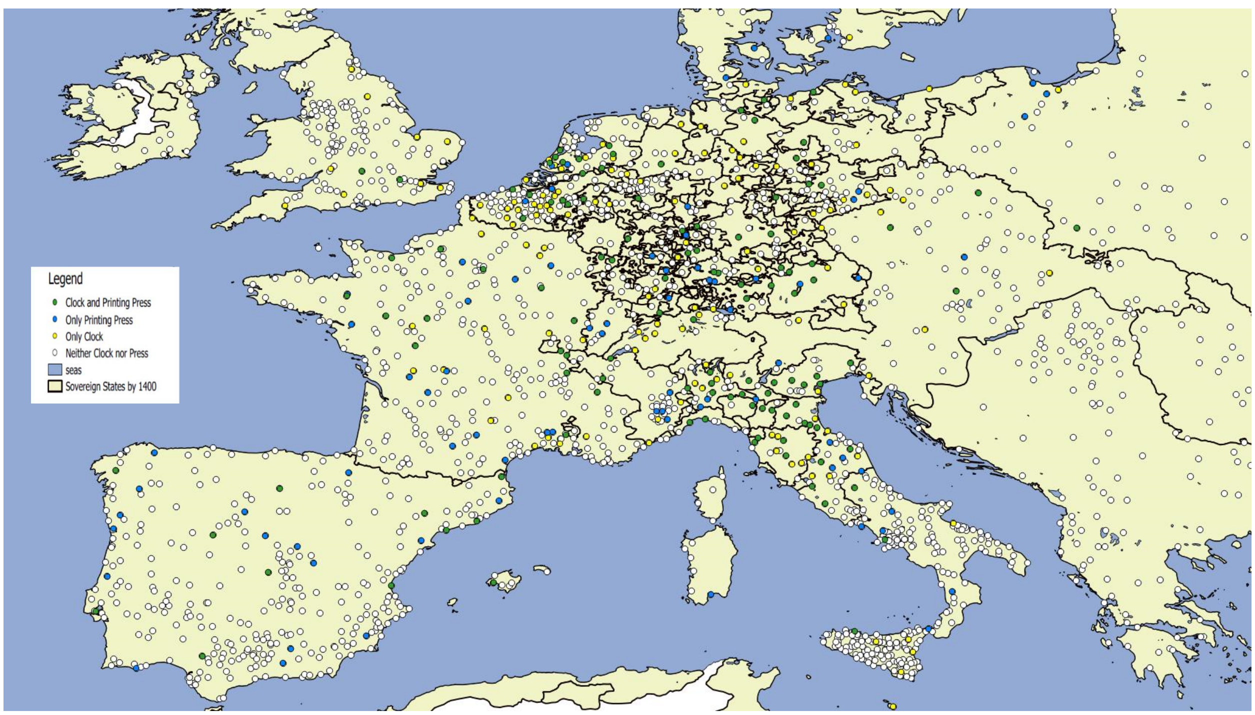
Johann Gutenberg invented the movable type printing press in his workshop in Mainz, Germany circa 1450.[5] By 1455, Gutenberg and his assistants produced the first major work using the new invention, the famous Gutenberg bible. There were significant barriers to entry in the early printing business, most of which were due to the intricacies of the new technology. Gutenberg's primary breakthrough was casting the metal type with a specific combination of alloys that permitted the blocks to be used repeatedly without breaking. The secrets of the new technology were closely guarded by Gutenberg and his assistants, many of whom eventually set up their own shops (Dittmar 2011). This small group had a near monopoly on printing. Indeed, the art of printing took such a large amount of skill-specific human capital that its initial spread was enabled only by those who had previous experience in a print workshop.

These early printers went first to where demand was highest: commercial centers, university towns, and monasteries, where literacy rates were much higher than elsewhere in Europe (Eisenstein 1979). Religious works were the most popular, comprising 45 percent of all books published by the end of the century (Febvre and Martin 1958, p. 249). The large print centers in Europe were among the most important commercial towns; the top 10 print cities, in terms of volume of printed works prior to 1500, were Venice, Paris, Rome, Cologne, Leipzig, Lyons, Augsburg, Strasbourg, Milan, and Nuremberg. By the end of the 15th century, printing spread well beyond Mainz—nearly eight million books were printed across the continent (Eisenstein 1979). Sixty of the 100 largest cities in Western and Central Europe had presses, as did 30 percent of cities with population of at least 1,000 (Dittmar 2011; Rubin 2014, 2017). Printing spread throughout the continent by 1500, with printers establishing shops in (modern day) Austria, Belgium, Czech Republic, Denmark, France, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Switzerland, and the United Kingdom (see Figure 2). The outward supply shift in the market for books resulted in an 85 percent decrease in

[5] Much of this section is a condensed version of printing history found in Rubin (2014, 2017).

their price by the end of the century (Buringh and Van Zanden 2009). This made books affordable to people well outside the merchant elite and monastic cloisters, and it was a key reason that literacy increased dramatically in subsequent centuries, particularly in Great Britain, the Netherlands, Germany, and Sweden (Buringh and Van Zanden 2009). Presses also made financial information much more readily available. News-sheets containing price and exchange rate information were printed in large quantities soon after the spread of the press, facilitating the integration of financial markets and opening up new trade routes (McCusker 2005). Early adopting cities grew much faster in the long-run than non-adopting cities, all else equal (Dittmar 2011).

Figure 2: The Diffusion of Clocks by 1450 and the Movable Type Printing Press by 1500



Sources: Rubin (2014) for the printing press, Boerner and Severgnini (2019) for the mechanical clock, and GIS border from Nuessli (2011).

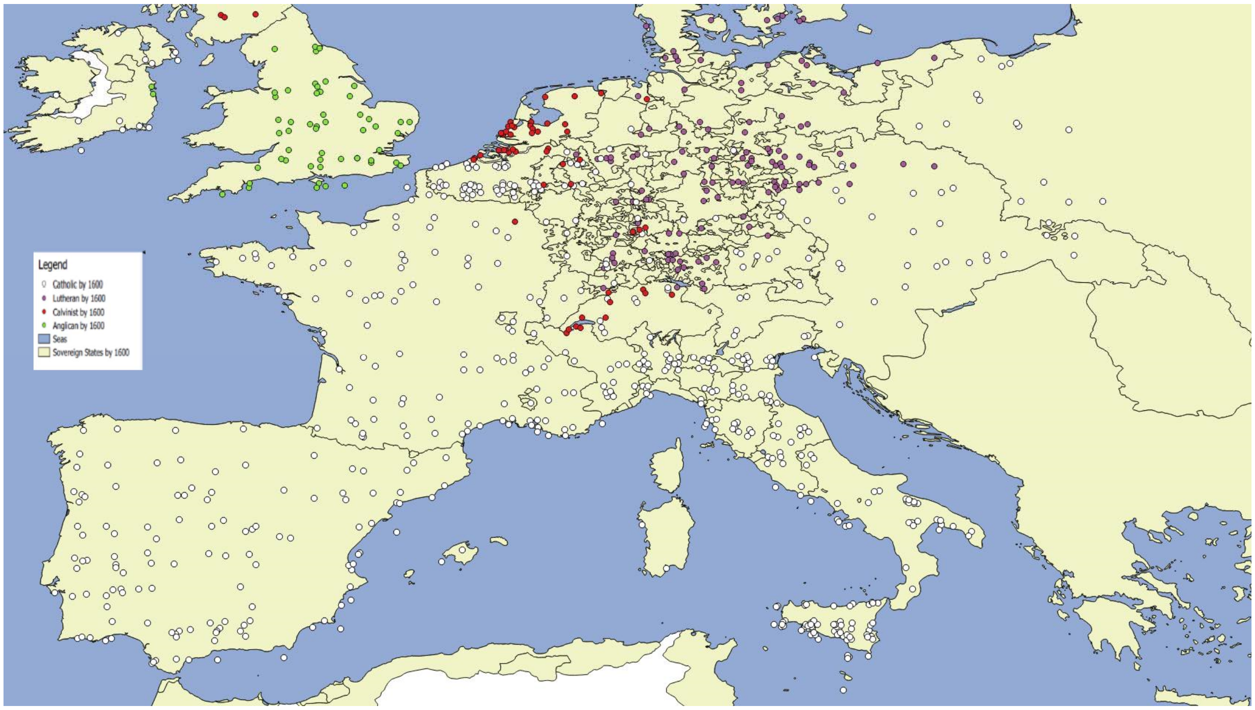
2.3 The Protestant Reformation

The Protestant Reformation was one of the most transformative events of the last millennium. It undermined the power of the Church, altered political power structures across Europe, and triggered over a century of violent religious wars. It began on October 31, 1517, when a little-known professor named Martin Luther nailed his Ninety-Five Theses to the door of the All Saints Church in Wittenberg. His words found a sympathetic audience in northern Europe, and Luther quickly became the leader of the Protestant movement.

Print editions of Luther's theses spread to nearby cities in the Holy Roman Empire, including Leipzig, Magdeburg, Nuremberg, and Basel. In the Holy Roman Empire, local lords maintained purview over small, decentralized regions and numerous independent cities ruled themselves, ostensibly free from outside interference. These were ideal conditions for Luther's ideas to spread (Nexon 2009). Powerful lords, seeking to undermine the power of the Church, offered Luther and his cadre protection, and they appointed preachers sympathetic to reform ideas. Luther's message was particularly attractive in the free cities of central Germany. In Switzerland and southern Germany, a similar movement led by Huldrych Zwingli (1484–1531) undermined Church influence throughout the 1520s. It was especially effective in free cities such as Strasbourg and Constance (Cameron 1991). This movement laid the groundwork for the much more effective and long-lasting Calvinist movement of the 1550s. Figure 3 shows a map of the spread of the Reformation in the 16th century.

The Reformation spread throughout the Holy Roman Empire in a variety of ways. The most important was through literate preachers, who went from town to town spreading the Reformation message. These preachers held positions in the established Church and directly questioned congregations about the nature of worship and the practices of the Church hierarchy. Luther wrote numerous pamphlets in support of their arguments. Between 1517 and 1520 alone, he wrote 30 treatises which sold over 300,000 copies. These copies quickly spread throughout Europe via re-printing (Spitz 1985; Pettegree 2015). A second, and complementary, manner in which the Reformation spread was through broadsheets and pamphlets,

Figure 3: The Diffusion of Lutheranism and Calvinism through 1600



Sources: Rubin (2014) for the printing press and GIS border from Nuessli (2011).

most of which were written by Luther and other lead reformers. Even though literacy rates were low, it was common for pamphlets to be read in the public square. The accompanying broadsheets were often graphic, and their anti-papal message was unmistakable to the intended audience.[6]

2.4 Causal Channels: Linking the Clock, Printing Press, and the Reformation

In this section, we provide suggestive historical support for the two primary causal channels tested in this paper: i) the spread of clocks and the spread of printing; and ii) the spread of the printing press and the spread of the Reformation.[7]

[6]Many other causes of the Reformation exist in the literature; see Becker, Pfaff and Rubin (2016).

[7]We also provide a brief overview of the role that the clock may have played in the Dutch Reformation in the Appendix.

2.4.1 Channel #1: the Clock and the Press

The evolution of high-tech skills was embedded in the larger development of technological and cultural change beginning in the late Middle Ages and further evolving during the Renaissance. Several scholars (Zilsel 2000; Mokyr 2009; Long 2011; Zanetti 2017) have claimed that during this period artisans not only became increasingly specialized, but also started combining practical skills and expertise with theoretical knowledge. This enabled the spread of upper tail human capital, which triggered and potentially even anticipated the Scientific Revolution of the early modern period.

In addition, this period can be characterized by a new conscious perception of technological innovation and recognition of innovators by contemporary writers. Towns started to actively support the immigration of artisans and helped to protect their skills and innovations. Contemporary witnesses also started to identify and characterize some towns, such as Nuremberg, as centers for high skilled artisans and innovation (Schremmer 1997). Indeed, our data reveal that Nuremberg was both a very early adopter of the clock and the printing press.

These cultural and technological developments affected the spread of both clocks *and* the printing press. As outlined earlier, clockmakers came from various backgrounds and expertise. They had skills in astronomy, engineering, or fine mechanics and metal processing. The early clockmakers passed on their knowledge directly to other skilled artisans, engineers, and astronomers. While no formal process (e.g., guild membership) is documented from this period, by the 15th century some clockmakers were occasionally mentioned as members of a sub-group belonging to various guilds of smiths. Nevertheless, many clockmakers were independent experts and part of "non-corporative elites" of towns (Sasson 1961; Dohrn-Van Rossum 1996). Thus the profession of the clock-maker became at least partly institutionalized over time. In accordance with this development, the invention of the movable type printing press by Gutenberg, a goldsmith, can be directly linked to both the highly specialized technical skills of fine mechanics and the institutional frame of the guilds of the smiths. Consequently, it is possible that towns with a tradition and expertise in fine mechanics, engineering, and related skills had the capacity to absorb the new technology of the printing press relative to other towns missing such a cluster of upper tail human capital. In what follows we test whether such agglomerations of upper-tail human capital manifested themselves in a connection between the spread of the mechanical clock and the spread of the movable type printing press.

2.4.2 Channel #2: the Press and the Reformation

The connection between the printing press and the Reformation is among the oldest and well-known linkages in Reformation historiography. Even Luther himself noted that "[The printing press is] God's highest and ultimate gift of grace by which He would have His Gospel carried forward" (quoted in Spitz (1985)). Rubin (2014) econometrically tested the connection between the spread of printing and the Reformation and found that cities that adopted the printing press were 29.0 percentage points more likely to adopt the Reformation by 1600 than those that were not. Similarly, Dittmar and Seabold (2019) find that Protestant ideas spread to a much greater extent in cities with pre-existing print competition.

The primary connection given in the literature connecting the printing press and the Reformation is the reformers' use of the press in anti-papal propaganda. Febvre and Martin (1958, p. 288) describe the Reformation as the "first propaganda campaign conducted through the medium of the press," while Edwards (1994, p. 1) begins his book on Luther and the printing press by noting that "the Reformation saw the first major, self-conscious attempt to use the recently invented printing press to shape and channel a mass movement." Rubin (2014) shows that the top print centers in the Holy Roman Empire were much more likely to adopt the Reformation, and those cities producing religious pamphlets in the 16th century were likewise much more likely to have adopted the Reformation. The proposed connection is thus a supply-side one: cities that had access to inexpensive pamphlets were much more likely to be exposed to the new Protestant ideas before the Catholic Church had time to respond.[8] Such access to cheap, printed material was crucial for the traveling preachers disseminating the newest pamphlets written by Luther and other top reformers. There was no copyright at this time; given high transport costs, important printed works (like Luther's) most commonly spread via reprinting in a nearby print shop (Edwards 1994). In short, the historical record provides plenty of reason to believe that there is a causal linkage connecting proximity to printing with adoption of the Reformation.

3 Data

The universe of observations is all cities in Central and Western Europe which had some population by 1500 according to Bairoch, Batou and Pierre (1988). The three dependent variables in our study are dichotomous variables which take a value of one if a city had a clock by 1450, a city had a printing press by 1500, and a city was Protestant by time $t \in \{1530, 1560, 1600\}$. As seen in Table 1, which presents summary statistics of all data used in the analysis, 29 percent of cities had a mechanical clock by 1450, 21 percent had a printing press by 1500, and 32 percent were Protestant by 1600.

The clock data come from Boerner and Severgnini (2019). Clocks spread through many of the larger cities in Europe, although they were by no means uniformly dispersed. Clocks were widespread in the wealthier areas of Europe, such as the Low Countries, northern Italy, and the independent cities of the Holy Roman Empire. Yet their reach was limited. Few cities in the Iberian Peninsula or southern Italy had clocks, and even well-off France contained relatively few cities with clocks. Printing and Reformation data come from Rubin (2014). Printing spread outward from Mainz soon after its invention in 1450. Printers generally moved to places where demand for printed works was greatest: large population centers, university towns, and bishoprics contained a disproportionate share of presses. As with clocks, there was a spatial component to the spread of the printing press. As Figure

[8] The press may have also increased demand for the Reformation by elevating the desires of the bourgeoisie or enhancing vicarious participation in far away events (Eisenstein 1979, p. 132). Our analysis does not permit us to disentangle the supply and demand-side channels.

Table 1: Summary Statistics

Variable	Mean	Std Error	Min	Max
	Endogenous Variables			
Clock by 1450	0.29	0.46	0	1
Printing Press in 1500	0.21	0.41	0	1
	Religion Variables			
Protestant in 1530	0.10	0.31	0	1
Protestant in 1560	0.27	0.45	0	1
Protestant in 1600	0.32	0.47	0	1
	Control Variables			
Calories in 1450	0.09	0.02	0.01	0.14
Independent City in 1450	0.05	0.22	0	1
Lay Magnate in 1500	0.89	0.32	0	1
University by 1450	0.06	0.24	0	1
Bishop by 1450	0.28	0.45	0	1
Hanseatic	0.10	0.30	0	1
Water	0.65	0.48	0	1
Market Potential in 1500	19.20	6.49	5.92	85.90
Min log distance to Wittenberg/Zurich	5.84	0.77	2.52	6.97
	Instruments			
Eclipse	0.34	0.48	0	2
Log (distance to Mainz)	6.02	0.71	2.48	7.09

Notes: Total number of observations: 741. Although the data are a panel, most variables do not vary over time. Hence, we report only the cross-section. Some control variables vary over time: we report values in 1500 or, where available, 1450. All distance variables are in miles. We only include observations for which we have data for all covariates, which is similar to the universe of observations in Rubin (2014).

2 makes apparent, areas such as northern Italy, Germany, and the Low Countries were printing centers, whereas there were few press cities in England and the Iberian Peninsula. Moreover, many of the early print cities were *also* clock cities. This suggests that any analysis connecting the diffusion of clocks or printing to the Reformation must account for the possibility that one cause is mediated by the other. In other words, it is possible that clocks are correlated with the spread of the Reformation via the spread of printing, while it is also possible that the press is correlated with the Reformation due to the fact that clock towns were more likely to adopt the press. Of course, both clocks and the printing press may have had independent direct causal effects on the spread of the Reformation, as well.

As can be seen in Figure 3, there was a strong spatial component to the spread of the Reformation. The Netherlands turned Calvinist between 1560–1600, northern Germany adopted Lutheranism early, and Protestantism barely penetrated southern Europe. Indeed, much of the geographical variation is found in modern-day Germany, Switzerland, western Poland, and eastern France. In earlier versions of this paper, we split the Protestant variable into whether towns adopted Lutheranism or Calvinism. However, digging deeper into the data, we found that, due to nation fixed effects, almost all identification in the Calvinism regressions came from Switzerland and five German towns which switched from Lutheranism to Calvinism between 1560 and 1600. In the latter case, it is not even clear what the regressions are picking up, since the much more important change came from the switch from Catholicism to Protestantism. Hence, specifications with Protestant as the dependent variable are more meaningful, and these are what we report in this paper.

We also include a host of city-level variables that control for the supply and demand for the Reformation, the printing press, and mechanical clocks. In place of a population variable from Bairoch, Batou and Pierre (1988), we employ the number of calories consumed by the town from Galor and Özak (2016).[9] Calories are a good proxy for population size because it provides the maximum amount of potential calories attainable from the cultivation before and after 1500, allowing us to control for potential changes due to the Columbian exchange. Other demand controls include indicators for whether the city was independent (indicating it was economically important), belonged to a lay magnate (it was neither free nor subject to an ecclesiastical lord), housed a university, housed a bishop or archbishop, and was a member of the Hanseatic League (and thus had better access to information flows and greater wealth). Supply controls include indicators for whether the city was on water (ocean, sea, large lake, or river connected to another city), its market potential (the sum of

[9]The calories variable has the benefit of having fewer missing observations prior to 1500. The main results are robust to replacing the calories variable with a log of population variable. These results are found in Appendix Table A.1. The only result that differs is that clocks enter negatively and significantly for the Protestant in 1530 regressions. We have no explanation for this result, except to note that it goes away in the other Protestant regressions.

other city's population divided by their distance to the city in question), and the minimum of its distance to Wittenberg and Zürich (the latter being Zwingli's home).[10]

4 Instrumenting for the Spread of Clocks and Printing

The primary empirical challenge in linking general purpose technologies to widespread social-political movements is the many unobservable variables that may affect both. Clocks and printing presses were not randomly assigned to towns. For instance, a town with high pre-press literacy—a variable for which practically no data exist from the Middle Ages—may have been more likely to adopt the printing press *and* the Reformation. Demand for printed works was almost certainly higher in more literate towns, while literacy may have also aided the reformers' efforts to spread their anti-papal message. Indeed, literacy may have *also* contributed to the spread of the mechanical clock, since clocks were particularly useful for coordinating merchant and commercial activities, and those engaged in such activities were more likely to be literate. Another possible omitted variable is the "entrepreneurial" spirit that may have encouraged the spread of both the clock and the press to a town. Mokyr (2009, 2016) and McCloskey (2010) suggest that precisely such a "spirit" was essential to the Enlightenment ideals that fostered economic growth in early modern England and the Dutch Republic. Yet another potential unobserved variable is a town's attitudes towards public good provision. Dittmar and Meisenzahl (2019) provide evidence that public good provision had a greater association with towns that eventually adopted the Reformation.

Due to these (and potentially other) omitted variables, a straight-forward econometric test linking mechanical clocks and movable type printing presses to the Reformation may contain biased coefficients. Reasonable stories can be told that the bias is positive or negative, but there is no reason to believe these opposing forces necessarily cancel each other out. To account for these biases, we estimate the determinants of the spread of clocks and

[10] All of the "distance to" variables are calculated "as the crow flies." Becker and Woessmann (2009) show that distance to Wittenberg is strongly correlated with the spread of Protestantism in Prussia.

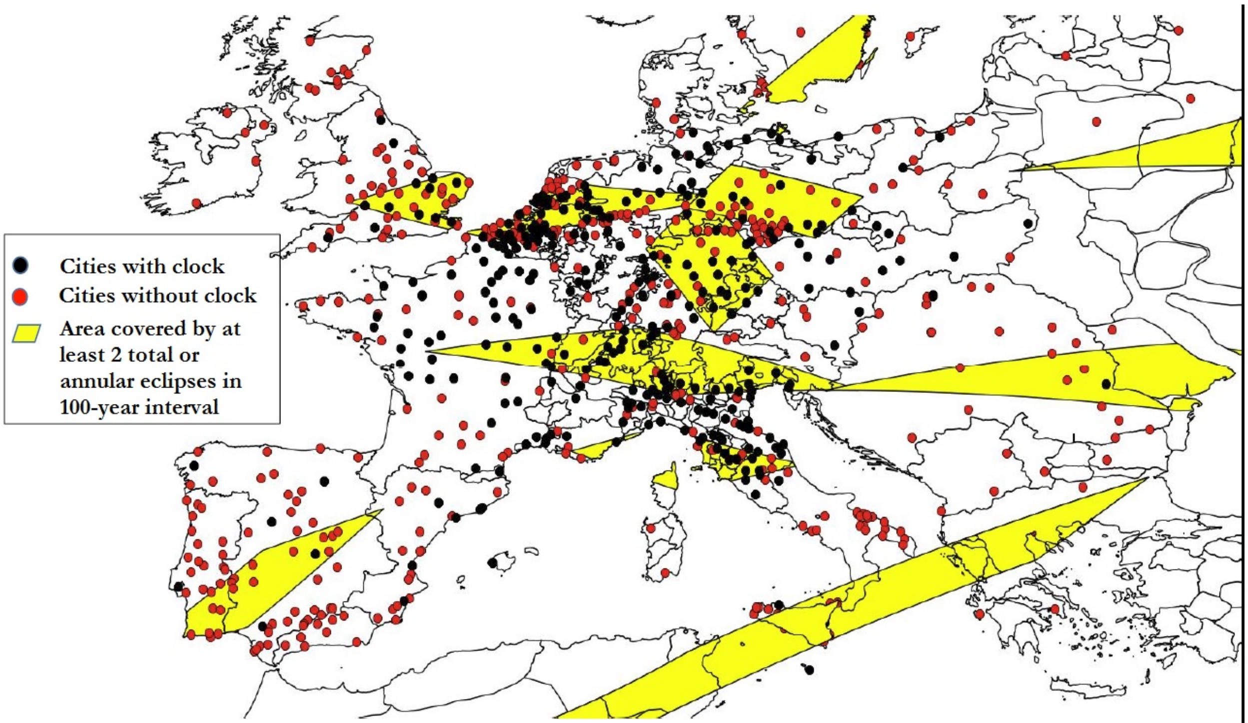
the press separately using instrumental variables. Fortunately, instruments for both clocks (Boerner and Severgnini 2019) and the printing press (Dittmar 2011; Rubin 2014) exist in the literature. We briefly review these instruments below and explain why they are correlated with the variable of interest while also satisfying the exclusion restriction.

We instrument for clocks with the number of times a town experience multiple solar eclipses over a one hundred year span between 800 to 1241.[11] The use of solar eclipses as an instrument follows the approach introduced by Boerner and Severgnini (2019), who study the impact of mechanical clocks on the long-run growth dynamics of European cities. We consider astronomical episodes in which the sun is completely obscured by the moon (total solar eclipses) or the moon seems smaller and at the same time covers the sun (annular solar eclipses). The regions of Europe that experienced at least two eclipses in 100 year interval are shown in Figure 4.

The rationale for using eclipses as an instrument for mechanical clocks follows from two relationships: i) the relationship between solar eclipses and astronomic instruments (astrolabes), and ii) the relationship between astrolabes and clocks. Regarding the first connection, the observation and documentation of the course of the celestial bodies and in particular solar eclipses elicited a special fascination. They could be observed by everyone, and due to their rare appearance, they were perceived as sudden, irregular, and often supernatural events (Stephenson 1997). Thus, the appearance of solar eclipses created curiosity to understand and predict these movements. This encouraged not only the further development of astronomy but also astrology, where personal astrologers advised political leaders on the optimal timing of decision-making (Borst 1989; Mentgen 2005). This broad interest created a demand for the development and use of astronomic instruments to measure and predict

[11] This period covers all eclipses after 800 and before the implementation of the first clock in 1283. Before 800 no solar eclipses appeared in Europe for an extensive time. The instrument is motivated by the idea that repeated observations of eclipses created a stronger interest in understanding this astronomic event, and within one hundred years a society had a stronger likelihood of remembering it, i.e. passing it on to the next generation. However, in a robustness check (Appendix Table A.2) we also cover a two hundred year period. We do not consider lunar eclipses because they can be easily confused with other type of weather conditions.

Figure 4: European Cities that Experienced at least Two Eclipses, 800–1241



Source: Boerner and Severgnini (2019).

the movement of heavenly bodies. In particular, astrolabes and in some cases astronomic water clocks were built (Price 1956; King 2011). The places where astrolabes were found in Europe seem to overlap with areas where solar eclipses frequently appeared.[12]

The second link is that the construction of clocks was often motivated by astronomic instruments (Cipolla 1967; Dohrn-Van Rossum 1996), and that the timekeeping function was stressed in European astrolabes (McCluskey 1998). For instance, Cipolla (1967) states that medieval scholars were only interested in the development of machines that were related to astronomy. Cipolla takes the clock as a prime example of such a machine. This provides a direct evolutionary path between astronomic instruments and the first mechanical clocks.

[12] An astrolabe was able to measure and simulate astronomic constellations and to measure time in equinoctial hours. King (2011) documents places where astrolabes were found in Europe. However, due to the fragmented nature of the source material, further quantification is not possible.

The fact that most early mechanical clocks were also astronomic clocks (and instruments) supports this argument further.

The link between the frequent appearance of eclipses, astronomic (and astrological) curiosity and development of astronomic instruments, and finally the implementation of clocks with astronomic functions is neatly documented in the city of Mechelen. Mechelen, a Flemish city, was covered several times by total solar eclipses prior to the 13th century. The astronomer and philosopher Henry Bate of Mechelen both elaborated tables for predicting eclipses (the so-called *Tabulae Mechlinenses*) and claimed to have built an astrolabe containing a time component at the end of the 13th century (White 1978; Zanetti 2017). This same city was one of the first adopters of the public mechanical clock, which also had an astronomical component. More town case studies and a more detailed analysis can be found in Boerner and Severgnini (2019).

In short, there is little doubt that a correlation exists between the historical presence of eclipses and the spread of the mechanical clock. For reasons given above, there is reason to believe that this relationship is causal, even if the causal pathway is indirect. As long as pre-1450 eclipses did not directly affect the spread of printing or the Reformation—and we have little reason to believe this was the case—we can use the appearance of solar eclipses as an instrument for the positive likelihood of implementing public mechanical clocks.[13]

In Table 2, we test for the exogeneity of the instruments relative to the various control variables included in our analysis. In general, this table reveals that our instruments are not statistically related to any observable characteristics that influenced Reformation adoption. There is a positive relationship between the eclipse instrument and the presence of a printing press, but this is expected in a reduced-form regression if eclipses are positively related to clocks and clocks are positively related to the spread of printing.[14]

[13] It is also important to note that a likely pre-condition for building clocks was the degree of prestige and pride that medieval towns took for being at the forefront of technology. Medieval towns were in competition with each other for the creation of new ideas, technology, and knowledge.

[14] Given that we have only 18 countries, the small number of clusters might negatively bias the standard errors of the estimates. For this reason, we estimate standard errors following Cameron et al. (2008) and Cameron and Miller (2015) and considering a wild cluster bootstrap technique based on 10,000 replications.

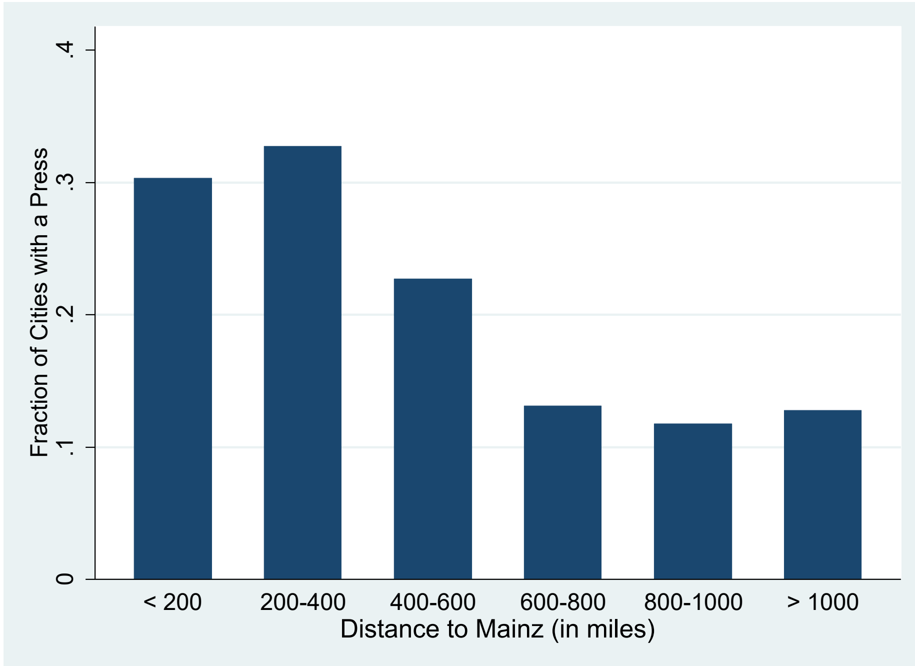
Table 2: Exogeneity test

Dependent variable:	(1) Clock	(2) Press	(3) Indep. City	(4) University	(5) Bishop	(6) Hansa	(7) Water	(8) Min Dist. Witt/Zur	(9) Log 16c Growth	(10) Log 15c Growth
Eclipse	0.10*	0.04**	-0.00	-0.03	-0.08	0.09*	-0.06	0.07	0.01	0.06
	[0.06]	[0.03]	[0.81]	[0.15]	[0.13]	[0.05]	[0.56]	[0.44]	[0.89]	[0.49]
Log(Dist. to Mainz)	-0.01	-0.10*	-0.06*	-0.02	0.04	-0.04	-0.03	0.30	0.09	0.04
	[0.87]	[0.09]	[0.05]	[0.35]	[0.39]	[0.33]	[0.39]	[0.45]	[0.44]	[0.56]
Obs.	741	741	741	741	741	741	741	741	436	251
R-squared	0.29	0.27	0.41	0.10	0.32	0.18	0.16	0.80	0.09	0.25

Notes: ***p $<$ 0.01, **p $<$ 0.05, *p $<$ 0.1. Robust standard errors clustered by country code. In brackets are $p-$values for testing the potential over-rejection of the null with a small number cluster (Cameron and Miller 2015) obtained from a wild cluster bootstrap based on 10,000 replication using the Stata command *boottest* from Roodman et al. (2019). OLS regression with controls used in all regressions in this paper except for the dependent variable in question.

We instrument for the spread of printing by using a town's distance from Mainz, the birthplace of printing. For reasons argued in Dittmar (2011) and Rubin (2014), a town's distance to Mainz should be related to the spread of printing but *not* to a town's eventual adoption of the Reformation (except through the printing channel). Distance to Mainz is highly correlated with the early spread of printing because the first printers were either apprentices or business associates of Gutenberg in Mainz. The secrets of the new technology—most importantly, the process used to cast movable metal type, which required a specific combination of alloys—was closely guarded among this small group for the first few decades of print. Printers also weighed cost when considering where to spread, and they therefore broadly spread out in concentric circles emanating from Mainz (Dittmar 2011; Rubin 2014). This stylized fact is apparent in Figure 5, which shows the share of cities that adopted printing, broken down by distance from Mainz. The trend is clear: cities that were further away from Mainz were less likely to have a press than cities closer to Mainz.

Figure 5: Share of Cities with a Printing Press by 1500, by Distance to Mainz



Source: Rubin (2014).

5 Empirical Analysis

We estimate a three-stage regression which accounts for both the spread of mechanical clocks *and* the spread of the printing press on the adoption of the Reformation.[15] The first two stages (clock and press adoption) are OLS and the third stage (Reformation adoption) is probit. In all regression equations we cluster standard errors by country code, as in Nunn and Qian (2011), and we report average marginal effects in probit regressions. We report the results of these estimations in Table 3.

These results confirm most of the primary hypotheses suggested earlier in the paper. First, note that the eclipse instrument is strong (F-stat = 13.68, above the threshold of 10 suggested by Staiger and Stock (1997) and Stock and Yogo (2005)). The distance to Mainz instrument is weaker (F-stat = 5.91). Second, clocks have an economically and statistically

[15]The nature of the instruments may raise concerns related to spatial autocorrelation of the residuals. The $z - score$ of the Moran tests associated to the OLS estimated of the first and the second stage of our estimation are 1.73 and 1.07, respectively. Since Kelly (2019) suggested that a value of $z - score$ higher than two as an indicator of potential autocorrelation, we rule out that our estimates are inflated by this problem.

Table 3: Connecting the Spread of the Clock and the Printing Press to the Reformation

	(1)	(2)	(3)	(4)	(5)
	First Stage	Second Stage		Third Stage	
	Clock	Press		Protestant by	
Dependent Variable:	by 1450	by 1500	1530	1560	1600
Eclipse	0.04***				
	(0.01)				
Log(Distance to Mainz)		-0.04**			
		(0.01)			
Clock by 1450		0.17**	-0.21	0.08	0.35*
		(0.08)	(0.23)	(0.31)	(0.21)
Press by 1500			0.79***	0.76***	0.62***
			(0.09)	(0.18)	(0.21)
Calories in 1450	0.01***	0.00	-0.03*	-0.02	-0.04***
	(0.00)	(0.00)	(0.02)	(0.02)	(0.01)
Independent City in 1450	0.02*	-0.02	0.02	0.07	0.08
	(0.01)	(0.03)	(0.05)	(0.06)	(0.06)
Lay Magnate in 1500	-0.04*	-0.03	0.01	0.15**	0.17***
	(0.02)	(0.02)	(0.03)	(0.06)	(0.05)
University by 1450	0.14***	0.12***	-0.32***	-0.37***	-0.43***
	(0.01)	(0.03)	(0.06)	(0.08)	(0.08)
Bishop by 1450	0.06***	0.03*	-0.09**	-0.18***	-0.18***
	(0.01)	(0.02)	(0.04)	(0.05)	(0.02)
Hanseatic	0.06***	0.01	-0.01	-0.03	-0.06
	(0.02)	(0.02)	(0.04)	(0.04)	(0.04)
Water	0.03**	0.04***	-0.09***	-0.10***	-0.09***
	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
Market Potential in 1500	0.00***	-0.00	-0.01**	-0.02**	-0.01***
	(0.00)	(0.00)	(0.01)	(0.01)	(0.00)
Minimum distance to	-0.03	-0.01	-0.04	-0.03	-0.00
Wittenberg/Zürich	(0.03)	(0.01)	(0.03)	(0.05)	(0.08)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	741	741	741	741	741
No. of Clusters	18	18	18	18	18
F-stat on instrument	13.68	5.91			
Log (pseudo-)likelihood			-672.66	-696.98	-707.37

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Robust standard errors clustered by country code in parentheses. Regressions calculated using the Stata cmp command from Roodman (2018), with first and second stages as OLS and third stage as probit. Average marginal effects reported in columns (3) through (5). All regressions include a constant term (not reported). Distance to Mainz, Wittenberg, and Zürich are in miles. In all regressions, nation fixed effects include Low Countries, Denmark, England, Finland, France, Ireland, Italy (outside of the Holy Roman Empire), Norway, Poland, Portugal, Scotland, Spain, Sweden, and Switzerland, with the Holy Roman Empire as the omitted nation.

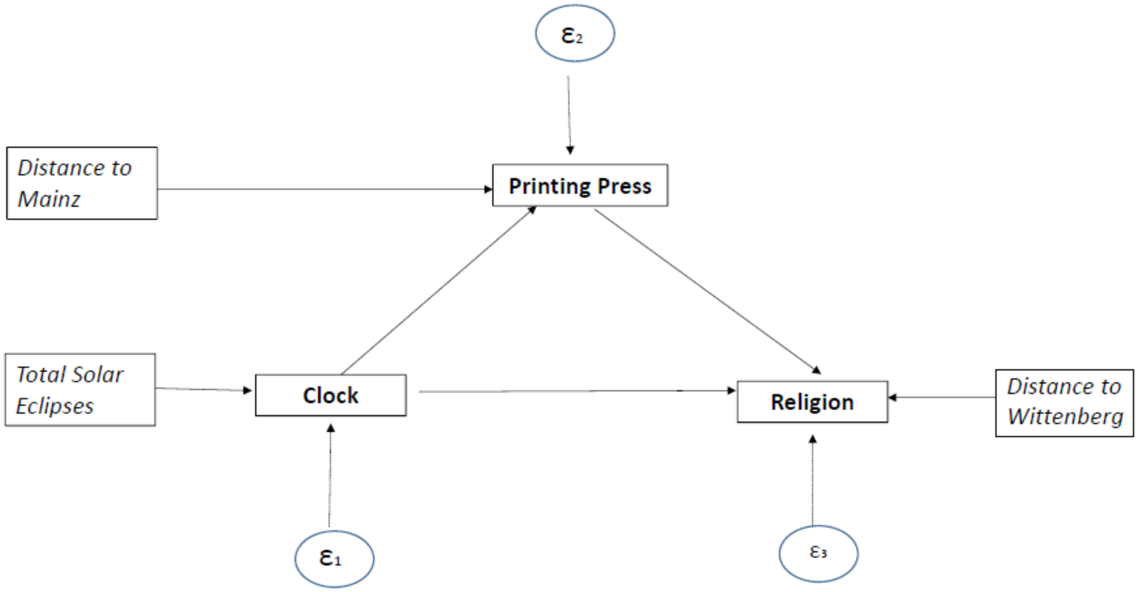
significant effect on the adoption of the printing press (column (2)). Clock towns were 17 percentage points more likely to eventually adopt the press than non-clock towns. This is evidence in favor of technological agglomeration in late medieval Europe.[16]

With respect to the Reformation (columns (3)–(5)), the coefficients on the printing press variable are positive and statistically significant. This suggests that even after controlling for the presence of the clock, the press played an important role in the spread of the Reformation, especially in its early stages. Meanwhile, the clock coefficient is positive and weakly significant in the Protestant in 1600 regression. We provide suggestive evidence in the Appendix that this may be due to the rise of Dutch Calvinism—35 of the 41 cities that adopted Protestantism between 1560 and 1600 were Dutch—but without a proper experiment or within-country variation, we are hesitant to make a causal claim. The Dutch effect is not eliminated by country fixed effects because we include a fixed effect for the Low Countries, which includes Belgium. When we include fixed effects separating the Netherlands and Belgium, the coefficient on the clock is statistically insignificant.

The fact that the effect of the clock on the spread of printing was positive, along with the positive and strongly significant coefficient on the press in the Protestant regressions, indicates that the effect of the clock on Protestantism may have been *indirect*, especially prior to 1600. By enabling agglomeration of elite human capital in certain places, clocks enhanced the spread of the printing press, which itself *was* important for the spread of the Reformation. We test the degree of this indirect effect with a mediation analysis, reported in Table 4, which is divided into two parts (see Figure 6 for a path diagram of the mediation analysis). The upper panel reports the marginal effects of the clock and press obtained from Table 3. These values can be interpreted as the direct effect of the technologies on religion. The lower panel shows the indirect effect of the clock on religion via press (i.e., the average causal mediation effect, or ACME). This can be thought of as the role that technological

[16] In Appendix Table A.2, we check the robustness of the regressions reported in Table 3 using a looser metric for the eclipse instrument (i.e., the presence of two eclipses over two centuries rather than one century). Results are largely similar.

Figure 6: Path Diagram of the Mediation Analysis



The figure displays the relationships, the dependent variables, the instruments, and the errors of the model estimated in Table 3.

agglomeration played on the spread of the Reformation. The ACMEs of clock are computed using the delta-method as a non-linear product of the margins of the impact of the clock on the press with the impact of the press on religion. The ACME is between 9 and 11 percentage points in the three regressions and is statistically significant, indicating there was a large and significant indirect effect of the mechanical clock on the early spread of the Reformation.[17]

[17] The reported tests indicate that there is no correlation among the errors of the estimated regressions, implying that the basic assumption of the ACME is not violated (the so called "sequential ignorability" assumption; see Conley, Hansen and Rossi (2012)).

Table 4: Mediation Analysis: Direct and Indirect Effect of the Mechanical Clock on the Reformation

	(1)	(2)	(3)	(4)
	Press	Protestant by		
Dependent Variable:	by 1500	1530	1560	1600
		Direct Effect		
Clock by 1450	0.17***	-0.21	0.08	0.35*
	(0.08)	(0.23)	(0.31)	(0.21)
Press by 1500		0.79***	0.76***	0.62***
		(0.09)	(0.18)	(0.21)
		Indirect Effect		
ACME of Clock		0.11**	0.10**	0.09*
		(0.05)	(0.05)	(0.04)
Contribution of Mediated				
Ratio Indirect/(Direct) (%)		-149%	57%	21%
ρ at ACME=0		-0.05	-0.01	0.00

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The top part of the table replicates the average marginal effects reported in Table 3. The ACME is calculated as the product of the effect of the clock on the printing press and the effect of the printing press on the adoption of religion. ρ is measured as correlation between the errors of the models estimated by the mediator and the final outcome of the regressions.

6 Conclusion

This paper analyzes the role that the two great general purpose technologies of the late medieval period—the public mechanical clock and the movable type printing press—played in the spread of one of the most important social and religious movements of the last millennium: the Protestant Reformation. Employing a city-level data set which includes various city characteristics in Western and Central Europe from the late medieval period, we find three primary results. First, towns that were early adopters of clocks also tended to be early adopters of printing, even after controlling for unobservable covariates via instrumental variables. This finding suggests that those with the elite human capital necessary to operate and repair clocks tended to agglomerate in the same cities, thus permitting spillovers when new technologies such as the printing press were introduced. Second, the printing press was positively and significantly associated with the spread of the Reformation. This finding confirms the econometric tests conducted in Rubin (2014) and Dittmar and Seabold (2019) and is consistent with a large historical literature. Third, while the clock was, for the most part, statistically unrelated to the spread of the Reformation, a mediation analysis reveals a positive and significant *indirect* effect of the mechanical clock on the Reformation, indicating an important role for technological agglomeration in the spread of the Reformation.

This study presents evidence that information and communication technology can incite religious change, at least under the economic and political conditions of late medieval Europe. It thus presents evidence complementary to the reverse argument, namely that religion can affect technological innovation and adoption. For instance, Bénabou, Ticchi and Vindigni (2016) provide a theoretical argument suggesting that highly religious societies may block technological innovation, which has the effect of increasing religiosity and entrenching a "theocratic" equilibrium. Chaney (2016) and Coşgel, Miceli and Rubin (2012) provide historical evidence from the Middle East in support of this insight. Our results suggest that this equilibrium can be self-reinforcing; where technology is permitted to spread, not only might agglomerations of labor complementary to the technology increase the rate of technological progress and adoption, but the technologies themselves may affect the spread of religious dissent in unforeseeable ways. This is turn suggests that technological adoption and massive religious, social, and political change are highly endogenous processes which are best understood in the context of the broader technological history of the societies in question.

References

Acemoglu, Daron and James A. Robinson. 2012. *Why Nations Fail: The Origins of Power, Prosperity, and Poverty.* New York: Crown.

Bairoch, Paul, Jean Batou and Chèvre Pierre. 1988. *La Population des Villes Européennes de 800 à 1850.* Geneva: Droz.

Becker, Sascha O. and Ludger Woessmann. 2009. "Was Weber Wrong? A Human Capital Theory of Protestant Economic History." *Quarterly Journal of Economics* 124(2):531–596.

Becker, Sascha O., Steven Pfaff and Jared Rubin. 2016. "Causes and Consequences of the Protestant Reformation." *Explorations in Economic History* 62:1–25.

Belloc, Marianna, Francesco Drago and Roberto Galbiati. 2016. "Earthquakes, Religion, and Transition to Self-government in Italian Cities." *Quarterly Journal of Economics* 131(4):1875–1926.

Bénabou, Roland, Davide Ticchi and Andrea Vindigni. 2016. "Forbidden Fruits: The Political Economy of Science, Religion and Growth." NBER Working Paper 21105.

Bentzen, Jeanet. 2019. "Acts of God? Religiosity and Natural Disasters across Subnational World Districts." *Economic Journal* 129(622):2295–2321.

Boerner, Lars and Battista Severgnini. 2019. "Time for Growth." DAFM Working Paper Series.

Borst, Arno. 1989. *Astrolab und Klosterreform an der Jahrtausendwende*. Heidelberg: Universitaet Verlag.

Buringh, Eltjo and Jan Luiten Van Zanden. 2009. "Charting the "Rise of the West": Manuscripts and Printed Books in Europe, a Long-term Perspective from the Sixth through Eighteenth Centuries." *Journal of Economic History* 69(2):409–445.

Cameron, A. Colin and Douglas L. Miller. 2015. "A Practitioner's Guide to Cluster-robust Inference." *Journal of Human Resources* 50(2):317–372.

Cameron, Euan. 1991. *The European Reformation.* Oxford: Oxford University Press.

Cardwell, Donald S.L. 1972. *Technology, Science and History: A Short History of the Major Developments in the History of Western Mechanical Technology and their Relationships with Science and other Forms of Knowledge.* London: Heinemann.

Chaney, Eric. 2016. "Religion and the Rise and Fall of Islamic Science." Working Paper.

Cipolla, Carlo M. 1967. *Clocks and Culture, 1300–1700.* New York: WW Norton & Company.

Conley, Timothy G., Christian B. Hansen and Peter E. Rossi. 2012. "Plausibly Exogenous." *Review of Economics and Statistics* 94(1):260–272.

Coşgel, Metin M., Thomas J. Miceli and Jared Rubin. 2012. "The Political Economy of Mass Printing: Legitimacy and Technological Change in the Ottoman Empire." *Journal of Comparative Economics* 40(3):357–371.

Davids, Karel. 2013. *Religion, Technology, and the Great and Little Divergences: China and Europe Compared, c. 700–1800.* Vol. 32 Leiden: Brill.

de la Croix, David, Matthias Doepke and Joel Mokyr. 2018. "Clans, Guilds, and Markets: Apprenticeship Institutions and Growth in the Preindustrial Economy." *Quarterly Journal of Economics* 133(1):1–70.

Dittmar, Jeremiah E. 2011. "Information Technology and Economic Change: The Impact of the Printing Press." *Quarterly Journal of Economics* 126(3):1133–1172.

Dittmar, Jeremiah E. and Ralf Meisenzahl. 2019. "Public Goods Institutions, Human Capital, and Growth: Evidence from German History." *Review of Economic Studies* forthcoming.

Dittmar, Jeremiah E. and Skipper Seabold. 2019. "New Media and Competition: Printing and Europe's Transformation After Gutenberg." *Journal of Political Economy* forthcoming.

Dohrn-Van Rossum, Gerhard. 1996. *History of the Hour: Clocks and Modern Temporal Orders*. Chicago: University of Chicago Press.

Edwards, Mark U. 1994. *Printing, Propaganda, and Martin Luther*. Berkeley: University of California Press.

Eisenstein, Elizabeth L. 1979. *The Printing Press as an Agent of Change: Communications and Cultural Transformations in Early Modern Europe*. Cambridge: Cambridge University Press.

Engammare, Max. 2010. *On Time, Punctuality, and Discipline in Early Modern Calvinism*. Cambridge: Cambridge University Press.

Febvre, Lucien and Henri-Jean Martin. 1958. *The Coming of the Book: The Impact of Printing 1450–1800*. Vol. 10 London: Verso.

Galor, Oded and Ömer Özak. 2016. "The Agricultural Origins of Time Preference." *American Economic Review* 106(10):3064–3103.

Gorski, Philip S. 2003. *The Disciplinary Revolution: Calvinism and the Rise of the State in Early Modern Europe*. Chicago: University of Chicago Press.

Greif, Avner. 2006. *Institutions and the Path to the Modern Economy: Lessons from Medieval Trade*. New York: Cambridge University Press.

Kelly, Morgan. 2019. "The Standard Errors of Persistence." CEPR Working Paper.

King, David A. 2011. *Astrolabes from Medieval Europe*. Burlington, VT: Ashgate Variorum.

Landes, David. 1983. *Revolution in Time*. Cambridge, MA: Harvard University Press.

le Goff, Jacques. 1980. *Time, Work, and Culture in the Middle Ages.* Chicago: University of Chicago Press.

Long, Pamela O. 2011. *Artisan/practitioners and the Rise of the New Sciences, 1400–1600.* Corvallis, OR: Oregon State University Press.

McCloskey, Deirdre N. 2010. *Bourgeois Dignity: Why Economics Can't Explain the Modern World.* Chicago: University of Chicago Press.

McCluskey, Stephen C. 1998. *Astronomies and Cultures in Early Medieval Europe.* Cambridge: Cambridge University Press.

McCusker, John J. 2005. "The Demise of Distance: The Business Press and the Origins of the Information Revolution in the Early Modern Atlantic World." *American Historical Review* 2(110):295–321.

Mentgen, Gerd. 2005. *Astrologie und öffentlichkeit im Mittelalter.* Stuttgart: Hiersemann.

Mihm, Margret and Arend Mihm. 2007. *Mittelalterliche Stadtrechnungen im historischen Prozess, Die Aelteste Duisburger Ueberlieferung (1348–1449).* Koeln: Boehlau Verlag.

Mokyr, Joel. 1990*a*. *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford: Oxford University Press.

Mokyr, Joel. 1990*b*. Urbanization, Technological Progress and Economic History. In *Urban Agglomeration and Economic Growth*, ed. Herbert Giersch. Berlin: Springer.

Mokyr, Joel. 2002. *The Gifts of Athena: Historical Origins of the Knowledge Economy.* Princeton, NJ: Princeton University Press.

Mokyr, Joel. 2009. *The Enlightened Economy: An Economic History of Britain, 1700–1850.* New Haven, CT: Yale University Press.

Mokyr, Joel. 2016. *A Culture of Growth: The Origins of the Modern Economy*. Princeton, NJ: Princeton University Press.

Moretti, Enrico. 2012. *The New Geography of Jobs*. Boston: Mariner Books.

Mumford, Lewis. 1934. *Technics and Civilization*. Nacourt, Brace & World.

Nexon, Daniel H. 2009. *The Struggle for Power in Early Modern Europe: Religious Conflict, Dynastic Empires, and International Change*. Vol. 116 Princeton, NJ: Princeton University Press.

Nuessli, Cristos. 2011. "Geographical Maps.". http://www.euratlas.com/about.html.

Nunn, Nathan and Nancy Qian. 2011. "The Potato's Contribution to Population and Urbanization: Evidence from a Historical Experiment." *Quarterly Journal of Economics* 126(2):593–650.

Pettegree, Andrew. 2015. *Brand Luther: 1517, Printing, and the Making of the Reformation*. New York: Penguin.

Price, Derek J. 1956. "The Prehistory of the Clock." *Discovery* 17:153–57.

Roodman, David. 2018. "CMP: Stata module to implement conditional (recursive) mixed process estimator.". https://ideas.repec.org/c/boc/bocode/s456882.html.

Roodman, David, Morten Ørregaard Nielsen, James G. MacKinnon and Matthew D. Webb. 2019. "Fast and Wild: Bootstrap Inference in Stata using boottest." *Stata Journal* 19(1):4–60.

Rubin, Jared. 2014. "Printing and Protestants: An Empirical Test of the Role of Printing in the Reformation." *Review of Economics and Statistics* 96(2):270–286.

Rubin, Jared. 2017. *Rulers, Religion, and Riches: Why the West Got Rich and the Middle East Did Not*. New York: Cambridge University Press.

Sasson, P. 1961. “Quelques aspects sociaux de l’artisanat Bruxellois du metal.” *Les Cahiers Bruxellois* 6:98–111.

Schremmer, Eckart. 1997. Die Wirtschaftsmetropole Nürnberg. In *Handbuch der bayerischen Geschichte Bd. III,1: Geschichte Frankens bis zum Ausgang des 18. Jahrhunderts*, ed. Max Spindler and Andreas Kraus. Munich: C.H. Beck’sche Verlagsbuchhandlung pp. 902–929.

Spitz, Lewis William. 1985. *The Protestant Reformation, 1517–1559*. New York: Harper and Row.

Squicciarini, Mara P. and Nico Voigtländer. 2015. “Human Capital and Industrialization: Evidence from the Age of Enlightenment.” *Quarterly Journal of Economics* 130(4):1825–1883.

Staiger, Douglas and James H. Stock. 1997. “Instrumental Variables Regression with Weak Instruments.” *Econometrica* 65(3):557–586.

Stasavage, David. 2014. “Was Weber Right? The Role of Urban Autonomy in Europe’s Rise.” *American Political Science Review* 108(2):337–354.

Stasavage, David. 2017. “When Inclusive Institutions Failed Lessons from the Democratic Revolutions of the Middle Ages.” Mimeo.

Stephenson, F. Richard. 1997. *Historical Eclipses and Earth’s Rotation*. Cambridge: Cambridge University Press.

Stock, James H. and Motohiro Yogo. 2005. Testing for Weak Instruments in Linear IV Regression. In *Identification and Inference for Econometric Models: Essays in Honor of Thomas Rothenberg*, ed. D.W.K. Andrews and J.H. Stock. Cambridge: Cambridge University Press.

Thompson, Edward P. 1967. “Time, Work-discipline, and Industrial Capitalism.” *Past & Present* (38):56–97.

Tilly, Charles. 1990. *Coercion, Capital, and European States, AD 990–1990*. Oxford: Blackwell.

Weber, Max. 1905. *The Protestant Ethic and the Spirit of Capitalism*. New York: Penguin.

White, Lynn. 1978. *Medieval Religion and Technology: Collected Essays*. Vol. 13 Berkeley: University of California Press.

Zanetti, Cristiano. 2017. *Janello Torriani and the Spanish Empire: A Vitruvian Artisan at the Dawn of the Scientific Revolution*. Leiden: Brill.

Zilsel, Edgar. 2000. *The Social Origins of Modern Science*. Dordrecht: Kluwer Academic Publishers.

A Online Appendix

Table A.1: Connecting the Spread of the Clock and Press to the Spread of the Reformation: Population in 1450 as a Control

	(1)	(2)	(3)	(4)	(5)
	First Stage	Second Stage		Third Stage	
	Clock by	Press by		Protestant by	
Dependent Variable:	1450	1500	1530	1560	1600
Eclipse	0.04***				
	(0.01)				
Log(Distance to Mainz)		-0.04*			
		(0.02)			
Clock by 1450		0.20	-0.53**	0.05	0.43
		(0.14)	(0.24)	(0.81)	(0.36)
Press by 1500			0.48***	0.68**	0.56
			(0.14)	(0.31)	(0.39)
Log(Population in 1450)	0.06***	0.03	0.01	-0.11	-0.18***
	(0.01)	(0.03)	(0.05)	(0.09)	(0.01)
Independent City	-0.03	-0.03	-0.00	0.13*	0.18***
	(0.03)	(0.02)	(0.03)	(0.07)	(0.06)
Lay Magnate	-0.03	-0.01	-0.08***	0.11	0.09*
	(0.03)	(0.02)	(0.03)	(0.07)	(0.05)
University	0.07***	0.06*	-0.04	-0.18*	-0.23***
	(0.02)	(0.03)	(0.07)	(0.11)	(0.07)
Bishop	0.05***	0.03	-0.00	-0.15	-0.16***
	(0.02)	(0.03)	(0.07)	(0.10)	(0.04)
Hanseatic	-0.01	-0.01	0.05	0.11	0.10
	(0.03)	(0.03)	(0.05)	(0.08)	(0.07)
Water	0.01	0.02	-0.01	-0.10*	-0.07*
	(0.02)	(0.01)	(0.05)	(0.06)	(0.04)
Market Potential in 1500	0.00	-0.00	-0.01*	-0.01**	-0.01***
	(0.00)	(0.00)	(0.01)	(0.01)	(0.00)
Minimum distance to	-0.08***	0.02	-0.18***	-0.09	0.05
Wittenberg/Zürich	(0.03)	(0.04)	(0.03)	(0.10)	(0.05)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	340	340	340	340	340
No. of Clusters	17	17	17	17	17
F-stat on instrument	9.86	3.01			
Log (pseudo-)likelihood			-303.58	-311.64	-324.39

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 3.

Table A.2: Connecting the Spread of the Clock and the Printing Press to the Spread of the Reformation with clock instrument overlapping eclipses within 200 years

	(1)	(2)	(3)	(4)	(5)
	First Stage	Second Stage		Third Stage	
	Clock by	Press by		Protestant by	
Dependent Variable:	1450	1500	1530	1560	1600
Eclipse	0.03***				
	(0.01)				
Log(Distance to Mainz)		-0.03**			
		(0.02)			
Clock by 1450		0.30**	-0.41	-0.19	0.07
		(0.15)	(0.48)	(0.67)	(0.57)
Press by 1500			0.80***	0.83***	0.79***
			(0.07)	(0.14)	(0.28)
Calories in 1450	0.01***	-0.00	-0.02	-0.02	-0.04*
	(0.00)	(0.01)	(0.03)	(0.03)	(0.02)
Independent City in 1450	0.03*	-0.02	0.03	0.09	0.11*
	(0.01)	(0.02)	(0.03)	(0.06)	(0.07)
Lay Magnate in 1500	-0.03*	-0.01	-0.00	0.13	0.17**
	(0.02)	(0.03)	(0.05)	(0.10)	(0.07)
University by 1450	0.14***	0.07	-0.25	-0.30	-0.41***
	(0.02)	(0.07)	(0.19)	(0.22)	(0.11)
Bishop by 1450	0.06***	0.01	-0.06	-0.15	-0.17**
	(0.01)	(0.03)	(0.09)	(0.12)	(0.07)
Hanseatic	0.05**	-0.02	0.01	0.01	-0.01
	(0.02)	(0.02)	(0.06)	(0.07)	(0.07)
Water	0.03**	0.03**	-0.08***	-0.08***	-0.08**
	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)
Market Potential in 1500	0.00***	-0.00	-0.01	-0.01	-0.01**
	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)
Minimum distance to	-0.03	-0.00	-0.05	-0.05**	-0.03
Wittenberg/Zürich	(0.03)	(0.03)	(0.03)	(0.02)	(0.04)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	741	741	741	741	741
No. of Clusters	18	18	18	18	18
F-stat on instrument	21.50	4.15			
Log (pseudo-)likelihood			-669.4	-693.31	-703.82

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. See notes in Table 3.

B The Clock and the (Dutch) Reformation

The construction of the first public mechanical clock in Geneva dates to 1406. Thus, when Calvin began developing his religious and worldly guidelines in the late 1540s, while residing in Geneva, he must have been exposed to an urban life which had been shaped by a more than hundred years of using and following the beat of the clock (Engammare 2010). Although we are only familiar with a few details of the daily use of clocks in Geneva, we can assume based on sources from other towns that the clock affected the daily life of people—for instance when gathering in markets for business transaction, for administrative town meetings, or by shaping and monitoring labor activities (Dohrn-Van Rossum 1996). This point is important: *if* the clock is directly causally linked to the spread of the Reformation, it was most likely through a *culture of coordinating* around time emerging in the long-run in the presence of a public mechanical clock. Our claim is *not* that the clock itself was used to coordinate revolutionary activities, although we cannot completely dismiss this possibility.

Based on personal notes and private communications, it can be derived that time management played an important role in Calvin's daily life. Calvin used the division of time for his daily routine, and he recognized time scarcity as a major problem which could only be solved by punctuality, discipline, and order. Calvin even used the expression "minutes" in his writings, which was for the middle of the 16th century extremely unusual (Engammare 2010). Calvin introduced his personal daily routine into public recommendations in his sermons, where he approached the scarcity of time, asking his church-members to regularly and punctually attend and to not waste time. His new religious spirit of discipline and order was adopted in many local church regulations and these served as blueprint for the further dissemination of the Calvinist doctrine (Engammare 2010). It was this type of routine centered on time that was central to Weber's famous Protestant Ethic hypothesis.

In the Netherlands, Calvinist preachers spread in towns throughout the mid-16th century. Citizens formed around these preachers in revolutionary groups which followed the discipline and order preached by Calvin. There is much historical evidence on revolutionary movements in Dutch cities which inform us about well-coordinated and punctual revolutionary activities (Mack Crew 1978; Arnade 2008). Typically, Calvinist groups marched in ordered groups from outside into the city center singing psalms. Sometimes they walked into the city from opposite sides in two separate groups at the same time. Parallel to the church mass, they organized their own worship services. Moreover, iconoclasm, which spread extremely quickly throughout the Netherlands, seemed to have been well-organized, even though we do not have detailed evidence how these actions were coordinated. Finally, an interesting (if not anecdotal) piece of evidence suggests that Calvinists seem to have used the clock as a signal for revolutionary action: in 1566 a Catholic spy reported that Calvinists intended to sack the city of Lille and for this purpose they organized a chain of cities in Artois and French Flanders, which communicated by the sequential ringing of bells the start of the revolutionary activity (Mack Crew 1978, p. 15). Although this anecdote suggests the possibility of a *direct* role of the clock in the spread of the Reformation (via coordination), we believe it is more likely that to the extent that the clock played any direct role at all, it was by generating a culture of coordination and timeliness, as is suggested by Calvin's writings and actions at the pulpit.

Once the Calvinist movement settled, either temporarily as in the case of Antwerp (Marnef 1994), or permanently as in the case of the freed Dutch territories after 1572 with the success of the Dutch Revolt (Pettegree 1994), there was an organized and systematic overtaking of all the parishes. In these towns, the new doctrine was generally employed by local municipal governments in order to establish religious change (Pettegree 1994). This anecdotal evidence supports the claim by Gorski (2003) that a highly organized and disciplined group of Calvinists not only succeeded in revolting but also took immediate action after the Revolt to organize the new structures of the state, and in this way implemented a new state culture backed by Calvinist doctrine.

References

Arnade, Peter. 2008. *Beggars, Iconoclasts, and Civic Patriots. The Political Culture of the Dutch Revolt.* Ithaca, NY: Cornell University Press.

Dohrn-Van Rossum, Gerhard. 1996. *History of the Hour: Clocks and Modern Temporal Orders.* Chicago: University of Chicago Press.

Engammare, Max. 2010. *On Time, Punctuality, and Discipline in Early Modern Calvinism.* Cambridge: Cambridge University Press.

Gorski, Philip S. 2003. *The Disciplinary Revolution: Calvinism and the Rise of the State in Early Modern Europe.* Chicago: University of Chicago Press.

Mack Crew, Phyllis. 1978. *Calvinist Preaching and Iconoclasm in the Netherlands, 1544–1569.* Cambridge: Cambridge University Press.

Marnef, Guido. 1994. The Changing Face of Calvinism in Antwerp, 1555–1585. In *Calvinism in Europe, 1540–1620*, ed. Andrew Pettegree, Alastair Duke and Gillian Lewis. Cambridge: Cambridge University Press pp. 143–159.

Pettegree, Andrew. 1994. Coming to Terms with Victory: The Building of a Calvinist Church in Holland, 1572–1590. In *Calvinism in Europe, 1540–1620*, ed. Andrew Pettegree, Alastair Duke and Gillian Lewis. Cambridge: Cambridge University Press pp. 160–180.

Weber, Max. 1905. *The Protestant Ethic and the Spirit of Capitalism.* New York: Penguin.