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 posit that towns with clocks became upper-tail human capital hubs—clocks required extensive technical know-how and fine mechanical skill. This meant that clock towns were in position to adopt the printing press soon after its invention in 1450, as presses required a similar set of mechanical and technical skills to operate and repair. A two-stage analysis confirms this conjecture: we find that clock towns were 30–40 percentage points more likely to also have a press by 1500. The press, in turn, helped facilitate the spread of the Protestant Reformation. 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. Our analysis therefore suggests that the mechanical clock was responsible—directly and indirectly—for two of the most important movements in the making of the modern world: the spread of printing and the Reformation.

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; 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 consequences—both direct and indirect—of the spread of one of the most important technologies of the late medieval period: the public mechanical clock. This is not an arbitrarily chosen technology. 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." Along with the printing press, the mechanical clock was the most important innovation of late-medieval Europe. Yet, its effect on long-run economic and political outcomes is far from clear. Were clocks simply mechanical wonders with little economic utility? Or were there consequences to there spread that were not immediately obvious, even to observers at the time?

Why might clocks have contributed to economic growth in early modern Europe? We argue that there were two pathways, one direct and one indirect. The direct pathway was through *technological agglomeration*. Clocks required an immense amount of mechanical knowledge to build and operate, and their production required precision, technical skills, and dexterity in using different metals. These were precisely the type of skills that were useful for operating and repairing printing presses. In fact, 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). In short, clockmakers and early printers were the knowledge elites of their day.

Our paper provides evidence of such technological agglomeration. We find that those places with clocks were 30–40 percentage points more likely to later adopt the printing press, depending on the specification. To our knowledge, this is the first paper to provide systematic empirical evidence of technological spillovers in the late medieval period. The importance of this link goes beyond simply documenting that technology agglomerations existed before the Industrial Age, however. The printing press was arguably the most important Western technology of the last millennium. It led to an information and communication revolution (Eisenstein 1979) and, ultimately, sustained economic growth (Dittmar 2011).

The importance of the printing press extends beyond the narrowly economic. It has long been conjectured that the press helped facilitate the spread of the Protestant Reformation, arguably the most important social, religious, and political movement in early modern 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. Our analysis finds that cities with presses *and* clocks were more likely to adopt the Protestant Reformation. We find 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. Clocks mattered for the Reformation because they facilitated technological agglomeration. Meanwhile, technological agglomeration mattered for the spread of the Reformation not because technology as a whole played a role in the movement, but because it facilitated the spread of printing, which did play a unique role in the Reformation.

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. Moreover, if our hypothesis is correct, then the determinants of the spread of clocks and the printing press must be estimated sequentially, with the spread of clocks being estimated first, its effect on the spread of printing second, and the spread of both on the Reformation third.

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 first test whether the spread of the mechanical clock facilitated the spread of printing, and then whether the spread of both clocks and the press 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, 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 60 (30) 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 17 to 20 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; 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

[1] We find that the clock is positively and significantly related to the adoption of the Reformation by 1600 (but not before 1600). Nearly all of the conversion to Calvinism between 1560 and 1600 occurred in the Dutch Republic, yet our analysis does not pick this up because we include a Dutch fixed effect. The historiography of the Dutch Reformation suggests that clocks may have played a role, via coordination, in its success. Since our empirical framework can only indirectly speak to this possibility, we do not emphasize this result. See the Appendix for a brief narrative of the link between clocks and the Dutch Reformation.

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.

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]

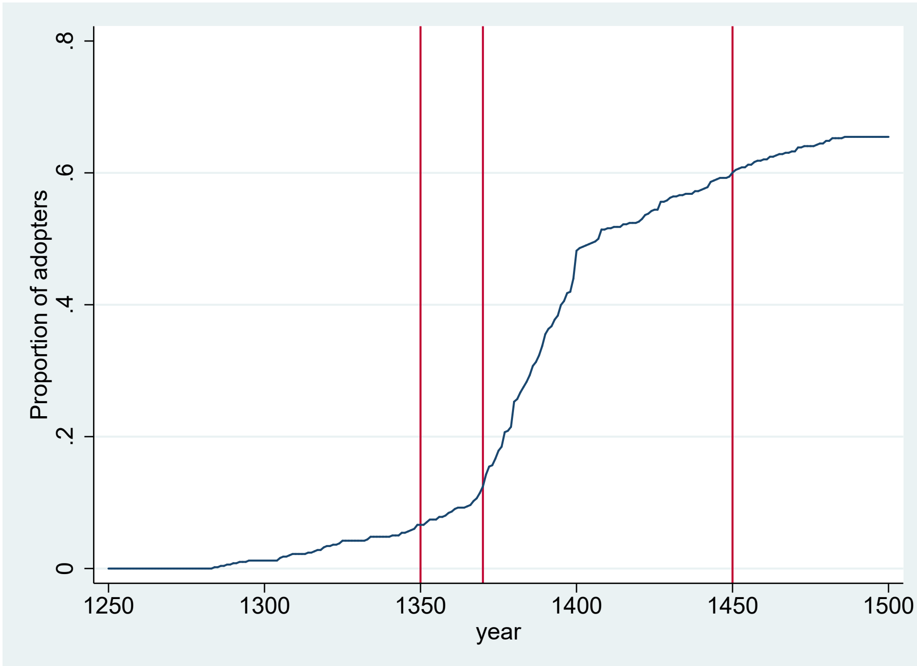
The public measurement of time was something completely new in the late medieval period. Clocks existed before in the form of sand, sun, or water clocks, but they were not previously used for daily activities because they were not very reliable or functional. As a result, one's sense of time was mainly 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. 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 church tower roof in the year 1401 cost 60 Gulden. The new church cross cost 35 Gulden in 1365 (Mihm and Mihm 2007).

[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."

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). 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).

Given the need for theoretical astronomical knowledge and the practical expertise of a smith constructing clocks, it is not obvious how both knowledge streams interacted to become the skill base for mechanical clocks. The life and career of Richard of Wallingford, Abbot of St. Albans and an early clock-maker, may provide some answers (North 2005). Wallingford was the son a of a blacksmith, but he received a university education at Oxford which included (beside theology) mathematical and astronomic education, before he started constructing clocks and other astronomical calculation devices at St. Albans. His expertise was based on both theoretical university knowledge and practical skills picked up from his family environment. Even though the life and career of Wallingford was exceptional, the frequent admission of children from wealthy artisanal families to universities, such as Oxford, Cologne, or Heidelberg is documented as early as the early 14th century (Miethke 2004). Thus, a general exchange of theoretical knowledge and practical skills, which likely generated new human capital, arose as early as the late medieval period.

2.2 The Printing Press

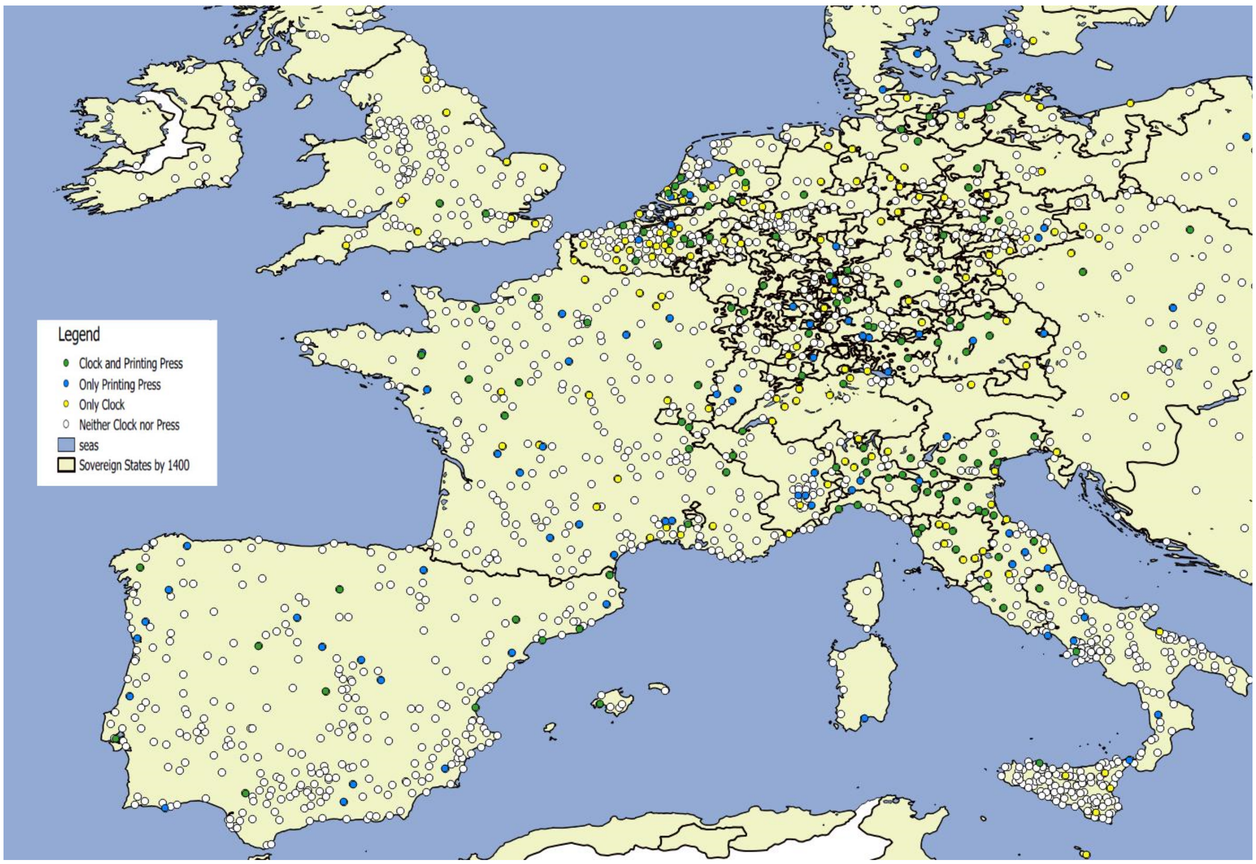
Johann Gutenberg invented the movable type printing press in his workshop in Mainz, Germany circa 1450.[5] By 1455, Gutenberg and his assistants produced the first major work using the new invention, the famous Gutenberg bible. There were significant barriers to entry in the early printing business, 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 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 (Mc-

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

Cusker 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



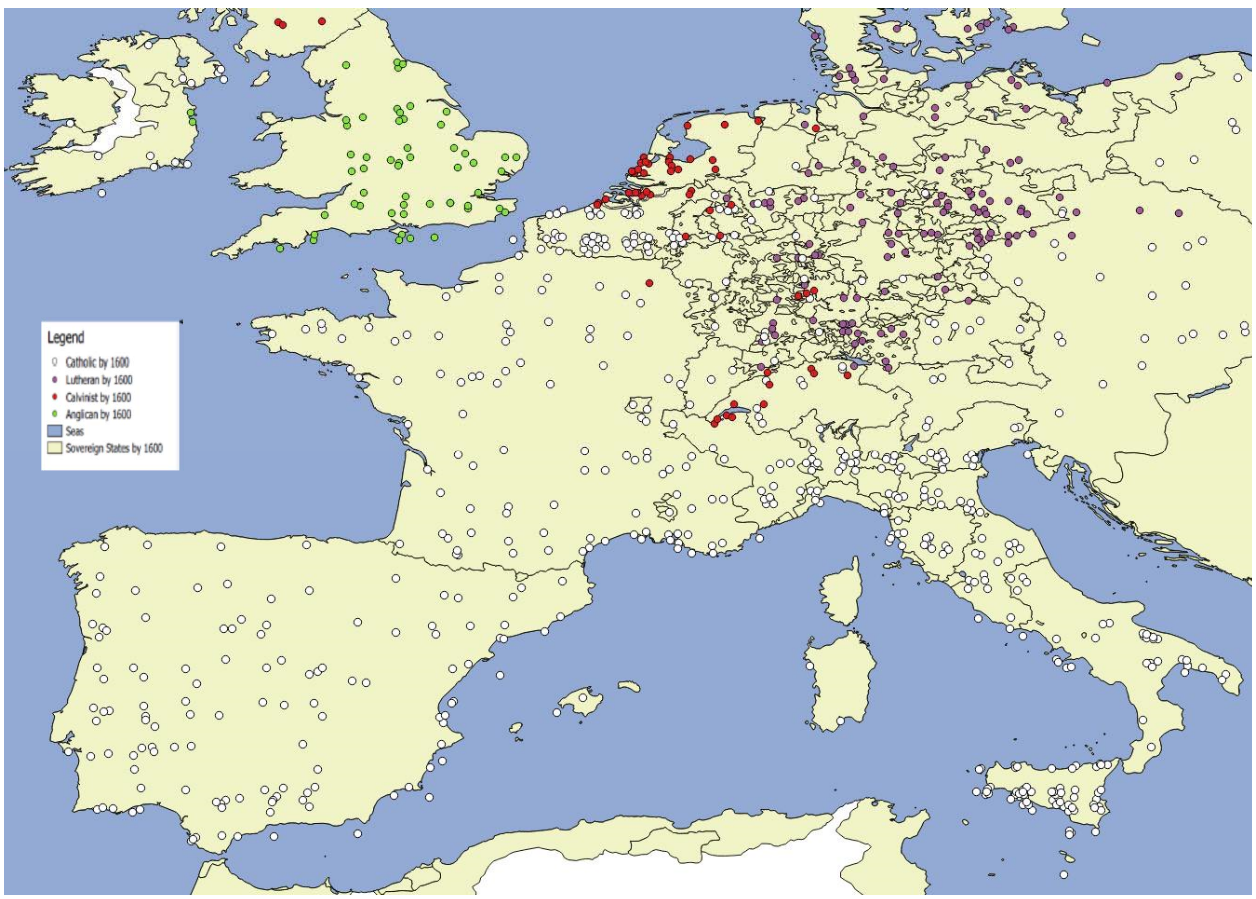
Sources: Rubin (2014) for the printing press, Boerner and Severgnini (2019) for the mechanical clock, and GIS border from Nuessli (2011).

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.

Figure 3: The Diffusion of Lutheranism and Calvinism through 1600



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

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, 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. A third key to the success of the Reformation was pre-existing networks associated with the Protestant epicenters of Wittenberg and Basel. Kim and Pfaff (2012) show that cities with more students attending university in Wittenberg and Basel were much more likely to adopt the Reformation, while those with more students attending university in Cologne and Louvain—two Catholic strongholds—were less likely to become Protestant.[6] A fourth, and related, mechanism encouraging the adoption of the Reformation was proximity to other reformed polities. Cantoni (2012) shows that those parts of the Holy Roman Empire that had more close neighbors adopt the Reformation were themselves more likely to adopt the Reformation, likely because they were more insulated from pushback from the emperor.[7]

After its early spread in the Holy Roman Empire, the Reformation eventually spread throughout much of Europe, although it ultimately splintered into multiple groups (see Figure 3). The largest non-Lutheran group were the Calvinists, who followed the teachings of the French theologian John Calvin (1509–64). In the early 1530s, Calvin fled to Basel, Switzerland and was recruited to reform the church in Geneva. His brand of Protestantism, which departed from Lutheranism largely on theological grounds, such as transubstantiation, spread throughout Switzerland, southern Germany, and parts of eastern and southern France. The French Calvinists, known as Huguenots, were violently suppressed until a series of peace

[6] Becker et al. (2020) propose a related mechanism, showing that towns in which Luther had some connection to—via letter, visit, or student—were more likely to adopt the Reformation by 1530.

[7] Plenty of other causes of the Reformation exist in the literature. These are overviewed in Becker, Pfaff and Rubin (2016). Beyond printing, these causes include aristocratic patronage (Kim and Pfaff 2012), urbanization (Ozment 1975), the presence of monasteries (Pfaff and Corcoran 2012), and ideological influence via proximity to a Protestant hub (Becker and Woessmann 2009). The Reformation did receive some push back from the Church and the Holy Roman Empire in its first two decades, but not enough to contain its spread. One reason is that the Reformation coincided with the height of Ottoman power. The Habsburg Holy Roman Emperor Charles V did not quickly crush the Protestant alliances in part due to Ottoman incursions into central Europe. The Ottoman threat diverted resources that could have fended off the Reformation, and when the Ottoman threat was starkest, conflict between Catholics and Protestants was rare (Iyigun 2008).

edicts were agreed upon in the 1570s–1590s (Cameron 1991). Calvinism also caught on in the Low Countries, which was an early hotbed of Protestant activity until it was violently suppressed by the Spanish Habsburgs (who burned nearly 2,000 Protestants between 1523 and 1555). Beginning in the 1560s, Calvinist thought played an important role in instigating the Dutch Revolt against Spanish rule (van Gelderen 1992). William of Orange co-opted the new religion and, regardless of his personal convictions, employed it as effective propaganda in the early stages of the Revolt. England also adopted its own unique brand of Protestantism during the reign of Henry VIII. The Anglican Church formed in the wake of Henry VIII's confiscations of the monasteries and the removal of all Church institutions from England, and it was formalized under Elizabeth I (r. 1558–1603). Since the Anglican Church, along with the various state churches of Scandinavia, was imposed largely from the top down, we do not focus on it in our analyses.[8]

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.[9]

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

[8] For more on the economic consequences of Henry VIII's removal of the Catholic Church, see Rubin (2017) and Greif and Rubin (2019). They cite the secularization of politics as a key consequence of England's Reformation. Empirical evidence of post-Reformation secularization in the Holy Roman Empire is provided by Cantoni, Dittmar and Yuchtman (2018), who employ an extensive data set and find that the places that adopted the Reformation invested less in religious buildings, had fewer university students earn degrees in theology, and had more university graduates take (secular) bureaucratic roles after graduation.

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

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.[10] 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). Bairoch, Batou and Pierre collected population data for every European city that reached 5,000 inhabitants at some point by 1800, and thus some cities in Bairoch, Batou and Pierre (1988) are not included in our data set. 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

[10] 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
Latitude	46.76	5.83	27.90	63.43
Longitude	6.23	7.50	-15.63	22.28
	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).

(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 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.

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).[11] 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 other city's population divided by their distance to the city in question), the minimum of its distance to Wittenberg and Zürich (the latter being Zwingli's home), and its latitude and longitude.[12]

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

[11]The calories variable has the immense benefit of having fewer missing observations prior to 1500. Many of the main results are robust to replacing the calories variable with a log of population variable, although some of the results are less precisely estimated. These results are found in Appendix Table A.2. The main issue with these results is that the loss of over half of the observations substantially weakens both instruments; this is almost certainly why the results are less precisely estimated. As a result, we prefer (and report) regressions using the calories variable as a population proxy.

[12]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.

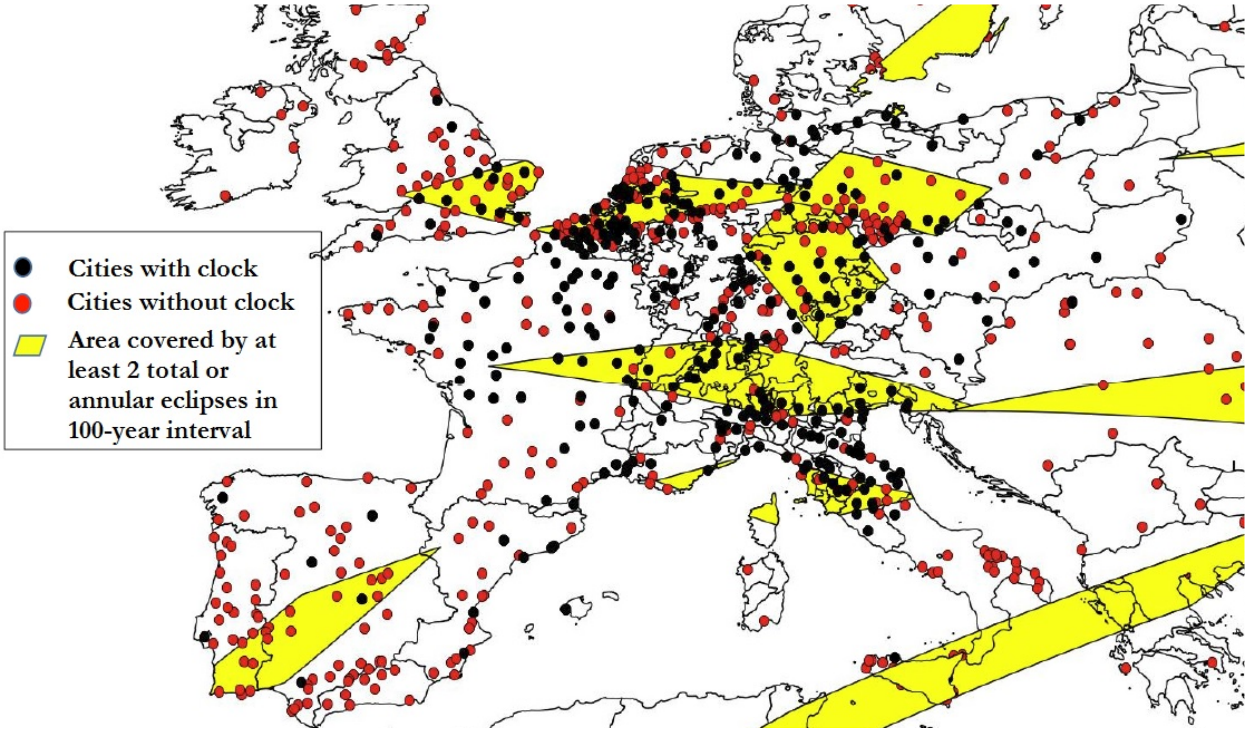
have been more likely to adopt the printing press *and* the Reformation. Demand for printed works was almost certainly higher in more literate towns, while literacy may have also aided the reformers' efforts to spread their anti-papal message. Indeed, literacy may have *also* contributed to the spread 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 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 plausibly 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. 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 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). We do not consider lunar eclipses because they can be easily confused with other type of weather conditions. 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 so-

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



Source: Boerner and Severgnini (2019).

lar 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 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.[13] Indeed, the motivation for using multiple eclipses in a 100-year span is 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

[13] 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.

next generation. In two robustness checks (Appendix Tables A.1 and A.3) we also cover a 200-year period.

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. 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.[14]

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

[14]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.

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.[15]

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	0.12*	0.01**	-0.00	-0.03	-0.08	0.09	-0.09	0.07	-0.00	-0.00
	(0.03)	(0.01)	(0.02)	(0.02)	(0.04)	(0.05)	(0.06)	(0.05)	(0.09)	(0.06)
	[0.05]	[0.03]	[0.88]	[0.15]	[0.14]	[0.11]	[0.37]	[0.47]	[0.96]	[0.95]
Log(Dist. to Mainz)	0.04	-0.09	-0.06*	-0.02	0.04	-0.04	-0.00	0.30	0.10	-0.07
	(0.06)	(0.03)	(0.02)	(0.01)	(0.03)	(0.05)	(0.03)	(0.30)	(0.08)	(0.10)
	[0.85]	[0.28]	[0.05]	[0.34]	[0.40]	[0.33]	[0.90]	[0.45]	[0.39]	[0.81]
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	0.19	0.80	0.11	0.29

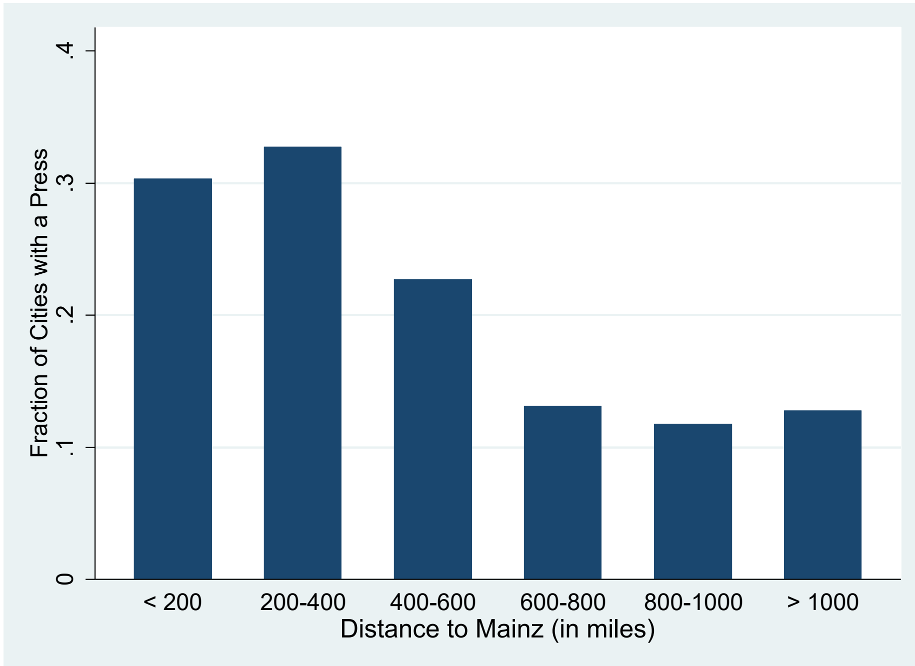
Notes: ***p $<$ 0.01, **p $<$ 0.05, *p $<$ 0.1. Robust standard errors clustered by country code in parentheses. In brackets are $p-$values for testing the potential over-rejection of the null with a small number cluster (Cameron and Miller 2015) obtained from a wild cluster bootstrap based on 10,000 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. These printers were capitalists, and they consequently spread to cities where demand for the technology was greatest (larger cities, university cities, and bishoprics, although none of these would qualify as instruments since they may have been independently related to the acceptance of the Reformation). 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

[15] 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 and Miller (2015) and considering a wild cluster bootstrap technique based on 10,000 replications.

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

5.1 Connecting the Clock to the Printing Press

We begin the empirical analysis by estimating the effect of the spread of the mechanical clock on the spread of the printing press. In Section 2.4.1, we provided numerous reasons why the spread of the mechanical clock may have affected the spread of printing.

We test these conjectures in Table 3. The first stage (clock) is OLS (column (1)) and the second stage (print adoption) is probit (column (2)). We show robustness to linear probability in column (3).[16] 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.

The results in column (1) indicate that the eclipse instrument is strong (F-stat = 15.44, above the threshold of 10 suggested by Staiger and Stock (1997) and Stock and Yogo

[16] In Appendix Table A.1, we show that the results are robust to the eclipse variable being multiple eclipses over 200 years, instead of 100 years as in our main analysis.

Table 3: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press

	(1)	(2)	(3)
	First Stage	Second Stage	Second Stage
Regression Technique:	OLS	Probit	OLS
Dependent Variable:	Clock by 1450	Press by 1500	Press by 1500
Eclipse	0.12***		
	(0.03)		
Clock by 1450		0.30***	0.40***
		(0.11)	(0.15)
Calories in 1450 (by 10,000)	0.02***	0.02*	0.01
	(0.01)	(0.01)	(0.01)
Independent City in 1450	0.10**	-0.03	-0.02
	(0.04)	(0.05)	(0.08)
Lay Magnate in 1500	-0.08	-0.06	-0.10
	(0.05)	(0.05)	(0.06)
University by 1450	0.37***	0.17**	0.34***
	(0.04)	(0.09)	(0.08)
Bishop by 1450	0.17***	0.05	0.09**
	(0.04)	(0.04)	(0.04)
Hanseatic	0.11*	0.02	0.02
	(0.05)	(0.04)	(0.04)
Water	0.09**	0.10**	0.10***
	(0.04)	(0.04)	(0.03)
Market Potential in 1500	0.01***	-0.00	-0.00
	(0.00)	(0.00)	(0.00)
Minimum distance to	-0.05	-0.05*	-0.06**
Wittenberg/Zürich	(0.09)	(0.03)	(0.03)
Mean of Dep. Var.	0.29	0.21	0.21
Latitude/Longitude	YES	YES	YES
Nation Fixed Effects	YES	YES	YES
Observations	741	741	741
No. of Clusters	18	18	18
R-squared	0.29		0.30
Log (pseudo-)likelihood		-596.1	
F-stat on instrument	15.44		

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). Average marginal effects reported in probit regressions. All regressions include a constant term (not reported). Distance to Mainz and Zürich in miles. Nation fixed effects include Belgium, Denmark, England, Finland, France, Ireland, Italy (outside of HRE), Netherlands, Norway, Poland, Portugal, Scotland, Spain, Sweden, and Switzerland, with the HRE as the omitted nation.

(2005)).[17] The second stage results reported in column (2), which are marginal effects of a probit regression, indicate that cities with clocks were 30 percentage points more likely to adopt the printing press than cities without clocks. Column (3) indicates that these results are not simply a reflection of the distributional assumptions of the probit model. A 2SLS (LPM) regression reveals that cities with a clock were 40 percentage points more likely to adopt the printing press, ceteris paribus.

In short, there is strong evidence of a positive association between the spread of the mechanical clock and the spread of the printing press. These results suggest that agglomeration of elite human capital in certain European cities was enhanced by (or perhaps initiated by) the spread of the public mechanical clock. This result sheds additional light on the the findings of Boerner and Severgnini (2019), who find that the spread of the clock had long-run consequences for city growth, but not short-run consequences (i.e., cities with clocks started to grow faster beginning in the 16th century). If the mechanism underlying their findings is (in part) the agglomeration of elite human capital spurred on by the clock—a possibility suggested by our results—then we would expect this effect to arise over a longer time horizon and not necessarily immediately.

5.2 Connecting Clocks and the Press to the Reformation

In this section, 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.[18] The first two stages (clock and press adoption) are OLS and the third stage (Reformation adoption) is probit. We report the results of these estimations in Table 4.

These results confirm most of the primary hypotheses suggested earlier in the paper. First, note that the eclipse instrument is strong (F-stat = 16.31). The distance to Mainz instrument is weaker (F-stat = 9.77), but close to the strong instrument threshold. Second, clocks once again have an economically and statistically significant effect on the adoption of the printing press (column (2)). Clock towns were 36 percentage points more likely to eventually adopt the press than non-clock towns. This is consistent with the results found in Table 3, further confirming our finding in favor of technological agglomeration in late medieval Europe.

[17] For more on tests of weak instruments under various assumptions regarding the variance of the sample, see Andrews, Stock and Sun (2018).

[18] 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 1.53 and 1.16, respectively. Since Kelly (2019) suggests 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 4: 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	0.12***				
	(0.03)				
Log(Distance to Mainz)		-0.10***			
		(0.03)			
Clock by 1450		0.36**	-0.07	0.30	0.37***
		(0.18)	(0.16)	(0.21)	(0.10)
Press by 1500			0.60***	0.43***	0.30**
			(0.10)	(0.19)	(0.13)
Calories in 1450	0.02***	0.01	-0.03*	-0.01	-0.02**
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)
Independent City in 1450	0.10**	-0.04	0.03	0.08**	0.09**
	(0.04)	(0.08)	(0.04)	(0.04)	(0.04)
Lay Magnate in 1500	-0.08	-0.08	0.01	0.14***	0.12***
	(0.05)	(0.06)	(0.02)	(0.02)	(0.03)
University by 1450	0.37***	0.35***	-0.28***	-0.29***	-0.28***
	(0.04)	(0.08)	(0.07)	(0.08)	(0.07)
Bishop by 1450	0.17***	0.10**	-0.08**	-0.17***	-0.14***
	(0.04)	(0.04)	(0.03)	(0.03)	(0.02)
Hanseatic	0.11**	0.03	-0.06***	-0.08**	-0.07**
	(0.05)	(0.03)	(0.02)	(0.04)	(0.03)
Water	0.09**	0.10***	-0.07***	-0.06**	-0.06**
	(0.04)	(0.03)	(0.01)	(0.03)	(0.03)
Market Potential in 1500	0.01***	-0.00	-0.01**	-0.01***	-0.01***
	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Minimum distance to	-0.05	-0.05	-0.03	-0.04	-0.05
Wittenberg/Zürich	(0.08)	(0.03)	(0.03)	(0.06)	(0.06)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Latitude/Longitude	YES	YES	YES	YES	YES
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	16.31	9.77			
Log (pseudo-)likelihood			-664.68	-680.01	-656.56

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. Nation fixed effects as in Table 3.

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 significant in the Protestant in 1600 regression. This result arises due to the conversion of just a few cities to Protestantism. 35 of the 41 cities that adopted Protestantism between 1560 and 1600 were Dutch, but the regressions include a Dutch fixed effect. In the absence of a proper experiment or within-country variation, we are hesitant to make a causal claim. Yet, there is suggestive historical evidence, provided in the Appendix, that the presence of clocks may have facilitated the rise of Dutch Calvinism.

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 5, 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 4. 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 agglomeration played on the spread of the Reformation. The ACMEs of the 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 contribution of the mediated ratio is between 17 to 20 percentage points of the effect of the printing press variable on the spread of the Reformation. The ACME is statistically significant in two of the three regressions, indicating there was a large and significant indirect effect of the mechanical clock on the early spread of the Reformation.[19]

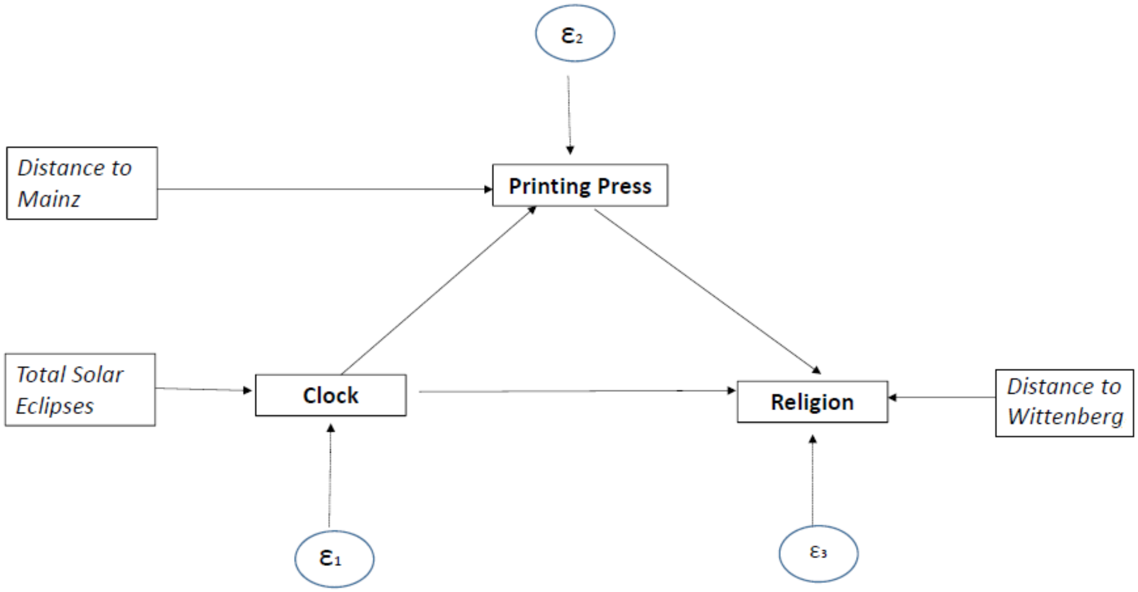
[19]The reported tests indicate that there is no correlation among the errors of the estimated regressions, implying that the basic assumption of the ACME is not violated (the so called "sequential ignorability" assumption; see Conley, Hansen and Rossi (2012)).

Table 5: 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	0.36**	-0.07	0.30	0.37***
	(0.18)	(0.16)	(0.21)	(0.10)
Press by 1500		0.60***	0.43***	0.30**
		(0.10)	(0.19)	(0.13)
		Indirect Effect		
ACME of Clock		0.06**	0.07	0.07*
		(0.03)	(0.04)	(0.04)
Contribution of Mediated				
Ratio Indirect/(Indirect+Direct) (%)		17%	17%	20%
ρ at ACME=0		0.00	0.00	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 4. 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.

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 4.

6 Conclusion

This paper documents the contribution of one of the two great general purpose technologies of the late medieval period—the public mechanical clock—to the spread of the other great general purpose technology of the period: the movable type printing press. We proceed to document the role that these technologies 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.

More generally, this study indicates just how much technological spillovers can affect social and religious movements in unforeseeable ways. In the context of our study, the spread of the mechanical clock had the consequence of facilitating the spread of the printing press. Both required elite human capital with similar sets of skills, and it was therefore natural that places that already housed such individuals would be more likely to adopt the printing press. In turn, the spread of printing had the unforeseeable consequence of facilitating the Reformation. The press was the cutting-edge information technology of its day, permitting anti-papal grievances to spread fast enough that the Church (and its sympathizers) had a difficult time suppressing them. But towns with presses were not randomly located. Beyond the conventional supply and demand explanations for the spread of printing, our study highlights an important supply-side factor, the spread of clocks, with deep historical roots. Clocks spread via an organic process of supply and demand. However, once in place, clocks had unforseeable spillover effects (the press) that themselves played a massively influential role in the economic, political, religious, and social life of early modern Europe.

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.

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A Online Appendix

Table A.1: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press with clock instrument overlapping eclipses within 200 years

	(1)	(2)
	First Stage	Second Stage
Regression Technique:	OLS	Probit
Dependent Variable:	Clock by 1450	Press by 1500
Eclipse (200 years)	0.08***	
	(0.01)	
Clock by 1450		0.46***
		(0.08)
Calories in 1450 (by 10,000)	0.02***	0.01
	(0.01)	(0.01)
Independent City in 1450	0.09**	-0.04
	(0.04)	(0.03)
Lay Magnate in 1500	-0.08	-0.02
	(0.05)	(0.04)
University by 1450	0.37***	0.01
	(0.04)	(0.10)
Bishop by 1450	0.16***	-0.01
	(0.04)	(0.03)
Hanseatic	0.10*	-0.02
	(0.05)	(0.03)
Water	0.09**	0.04*
	(0.04)	(0.02)
Market Potential in 1500	0.01***	-0.00
	(0.00)	(0.00)
Minimum distance to	-0.05	-0.02
Wittenberg/Zürich	(0.08)	(0.04)
Mean of Dep. Var.	0.29	0.21
Latitude/Longitude	YES	YES
Nation Fixed Effects	YES	YES
Observations	741	741
No. of Clusters	18	18
R-squared	0.29	
Log (pseudo-)likelihood		-595.8
F-stat on instrument	45.51	

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 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	0.13***				
	(0.05)				
Log(Distance to Mainz)		-0.12*			
		(0.06)			
Clock by 1450		0.29	-0.28	0.38	0.50***
		(0.34)	(0.21)	(0.25)	(0.13)
Press by 1500			0.31**	0.25	0.12
			(0.16)	(0.28)	(0.13)
Log(Population in 1450)	0.16***	0.14	-0.00	-0.10***	-0.12***
	(0.02)	(0.07)	(0.03)	(0.03)	(0.03)
Independent City	-0.03	-0.09	0.03**	0.12**	0.15**
	(0.07)	(0.08)	(0.01)	(0.06)	(0.07)
Lay Magnate	-0.06	-0.05	-0.07***	0.11**	0.08*
	(0.07)	(0.06)	(0.02)	(0.04)	(0.04)
University	0.19***	0.20***	-0.04	-0.12**	-0.12**
	(0.04)	(0.07)	(0.05)	(0.05)	(0.05)
Bishop	0.13***	0.12	-0.02	-0.10**	-0.08**
	(0.05)	(0.09)	(0.04)	(0.05)	(0.04)
Hanseatic	-0.05	-0.04	0.01	0.02	0.06
	(0.08)	(0.08)	(0.02)	(0.06)	(0.07)
Water	0.04	0.05	0.02	-0.04	-0.05
	(0.07)	(0.03)	(0.04)	(0.04)	(0.04)
Market Potential in 1500	0.00	-0.00	0.00	-0.01	-0.00
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)
Minimum distance to	-0.20***	-0.00	-0.11***	-0.03	0.03
Wittenberg/Zürich	(0.07)	(0.08)	(0.02)	(0.06)	(0.06)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Latitude/Longitude	YES	YES	YES	YES	YES
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	7.70	3.44			
Log (pseudo-)likelihood			-295.06	-309.07	-294.52

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 4.

Table A.3: 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 (200 years)	0.08***				
	(0.01)				
Log(Distance to Mainz)		-0.09***			
		(0.03)			
Clock by 1450		0.88*	-0.26	0.16	0.30
		(0.45)	(0.45)	(0.45)	(0.23)
Press by 1500			0.61***	0.47*	0.33
			(0.11)	(0.26)	(0.24)
Calories in 1450	0.02***	0.00	-0.03	-0.01	-0.02**
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)
Independent City in 1450	0.09**	-0.09	0.05*	0.10***	0.10*
	(0.04)	(0.06)	(0.03)	(0.03)	(0.05)
Lay Magnate in 1500	-0.08	-0.04	-0.01	0.13***	0.12***
	(0.05)	(0.07)	(0.03)	(0.03)	(0.02)
University by 1450	0.37***	0.16	-0.21	-0.26***	-0.27***
	(0.04)	(0.19)	(0.16)	(0.09)	(0.07)
Bishop by 1450	0.16***	0.01	-0.05	-0.15***	-0.14**
	(0.04)	(0.09)	(0.08)	(0.05)	(0.02)
Hanseatic	0.10*	-0.04	-0.04	-0.07	-0.07**
	(0.05)	(0.05)	(0.05)	(0.05)	(0.03)
Water	0.09**	0.06*	-0.06**	-0.05*	-0.05*
	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)
Market Potential in 1500	0.01***	-0.01	-0.01	-0.01**	-0.01***
	(0.00)	(0.01)	(0.01)	(0.01)	(0.00)
Minimum distance to	-0.05	-0.02	-0.04**	-0.05	-0.06**
Wittenberg/Zürich	(0.08)	(0.07)	(0.02)	(0.03)	(0.03)
Mean of Dep. Var.	0.29	0.21	0.10	0.27	0.32
Latitude/Longitude	YES	YES	YES	YES	YES
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	45.52	7.26			
Log (pseudo-)likelihood			-663.83	-679.23	-656.00

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 4.

B The Clock and the (Dutch) Reformation

The historical narratives of the lives of the most important reformers, Luther and Calvin, suggest that the impact of the innovation of the mechanical clock and the concept of time on the Protestant Reformation was very different for the two. Whereas we can identify a clear link between Calvin's ideas and the concept of time, very little evidence can be derived from Luther and the Wittenberg school of thinking related to clocks or an elaborated use of time.

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.

On the other hand, there is little evidence that clocks or the concept of time had a major impact on Luther's thoughts or his movement. When Luther started developing his knowledge base for his later reformists ideas and beliefs, he also must have been exposed to mechanical clocks and some ideas of the concept of time. In Erfurt, where he begun to study law in 1505 and later entered the Augustine order in 1506, the first clock had already been built in 1306. During his Augustine education he must have been in contact with the study of astronomy and astronomical time. Based on his recorded dinner speeches, it can be derived that he was knowledgeable in astronomy: he was open-minded to the study of astronomy, understanding the movements of the heavenly bodies as a precise and rational system which was God-given, but he rejected astrology, i.e. predicting the future based on star constellations. This was in the tradition of Augustine, but also his teacher at the faculty of art in Erfurt, Jodokus Truttvetter. In addition, his reformist collaborator Melanchthon was knowledgeable in astronomy and astrology (Ludolphy 1986; Wright 2010). It is also documented that Luther received twice a clock as a gift in 1527 and 1529 from the abbot of Nuremberg (Köstlin 1875, p. 167). Luther wrote back in a thank you letter in 1527 that he was delighted to receive the clock but must first become a student of "our mathematics" until he understands "all rules and formulas of this unique clock" (Neumann 2010, p. 137). In short, contrary to Calvin, time did not play any important role in Luther's reformist thinking.

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