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A Time to Print, a Time to Reform

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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 34–40 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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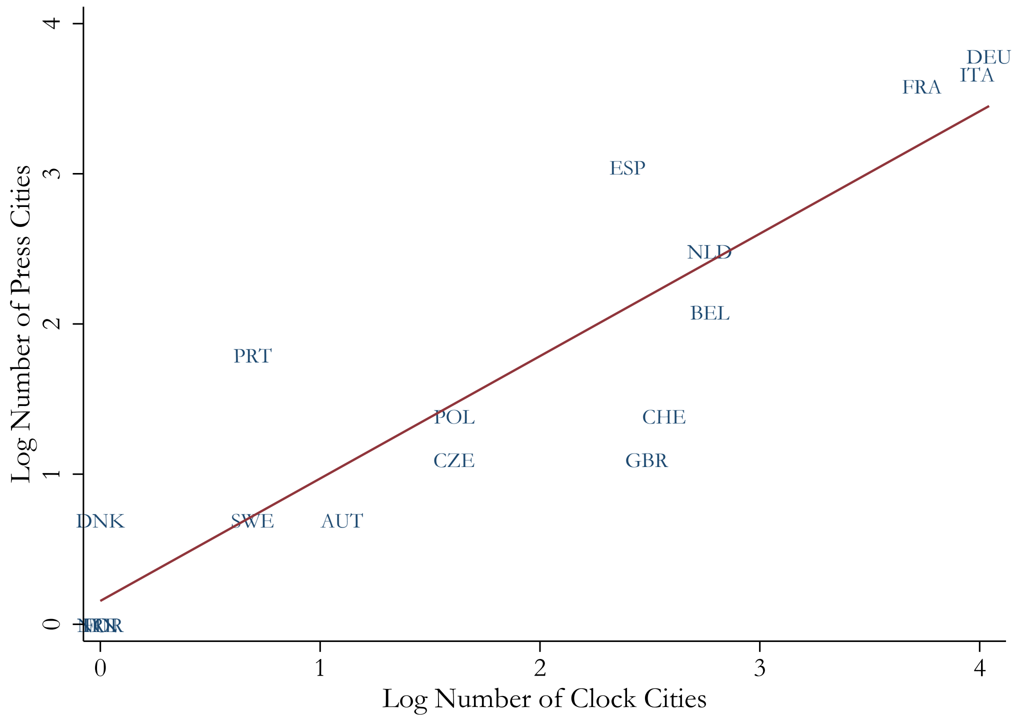
1 Introduction

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; Tilly 1990; Greif 2006; Nexon 2009; Acemoglu and Robinson 2012; Stasavage 2014; Mokyr 2016; Stasavage 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 their spread that were not immediately obvious, even to observers at the time?

We argue that clocks contributed to economic and political change via 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. It is therefore possible that spillovers from the clock's presence encouraged adoption of the press. Our paper provides evidence of such technological agglomeration. The correlation between the two technologies is strong, at least at the country level (see Figure 1). Our city-level analysis finds that those places with clocks were 34–40 percentage points more likely to later adopt the printing press, depending on the specification.

Figure 1: Distribution of Clocks (by 1450) and Presses (by 1500), by current country



Note: values are ln(1+clocks) and ln(1+presses). Data described in Section 3.

This paper provides systematic empirical evidence of technological spillovers in the late medieval period. Unlike papers focusing on the direct economic impact of clocks (Boerner and Severgnini 2019) or printing (Dittmar 2011), or the effects of the press on social and religious change (Rubin 2014; Dittmar and Seabold 2020), our paper provides evidence which places the antecedents of Europe's eventual economic and technological rise even further back in time. While technological agglomeration has long been viewed as important for Europe's rise (Mokyr 1990, 2009, 2016), nearly the entire focus of the literature is on the *industrial* period. We provide empirical evidence that *medieval* technological agglomeration was also important for Europe's rise, albeit indirectly via its effect on the social-political equilibrium that was upended by the Reformation.

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 (2020), 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

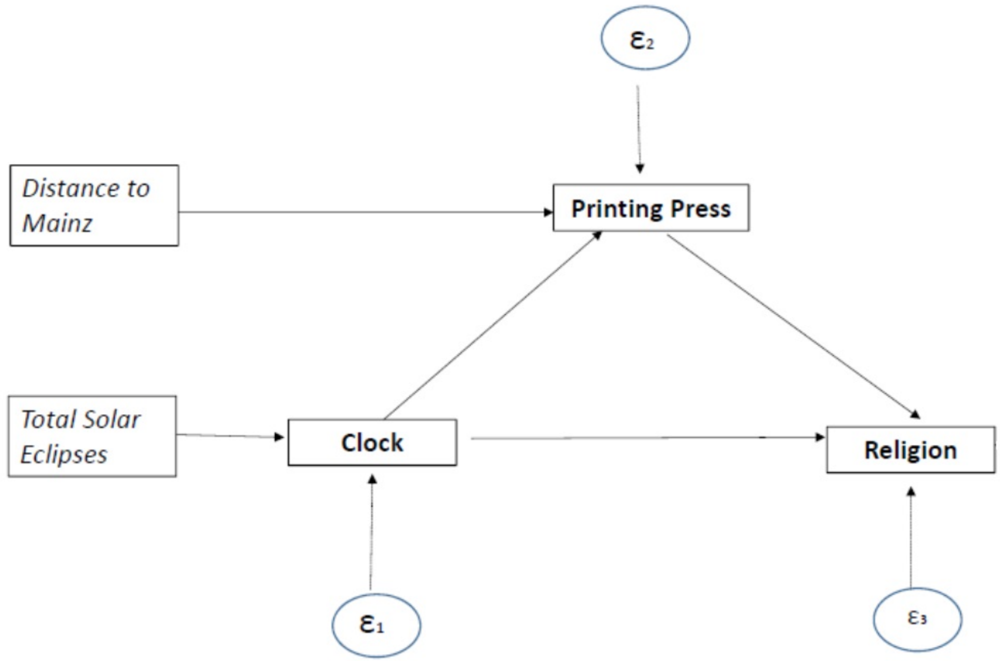
Reformation. We find that the role of printing on the Reformation was direct while the role of clocks on the Reformation was mostly indirect (via the press). Combined, these results suggest a role for path dependence. Clocks mattered for the Reformation because they facilitated technological agglomeration. 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. We address this issue 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. 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. Figure 2 presents a path diagram summarizing our empirical strategy.

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 an early adopter of Protestantism: press towns were 33 (36) 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 (this relationship is not robust), although its *indirect* effects, via the press, were substantial: 34 percent of the effect of the printing press variable on the spread of the Reformation can be explained by the prior existence of a clock.

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

Figure 2: Path Diagram of the Empirical Strategy



use of time. Furthermore, Gorski (2003) outlined that the new Calvinist culture of social-discipline led to successful state formation and paved the way for colonialism and western development. A large literature suggests that religion and religious authorities can both inhibit the spread of technology (Mokyr 1990; Coşgel, Miceli and Rubin 2012; Chaney 2016; Bénabou, Ticchi and Vindigni 2020) 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.

2 Historical Background

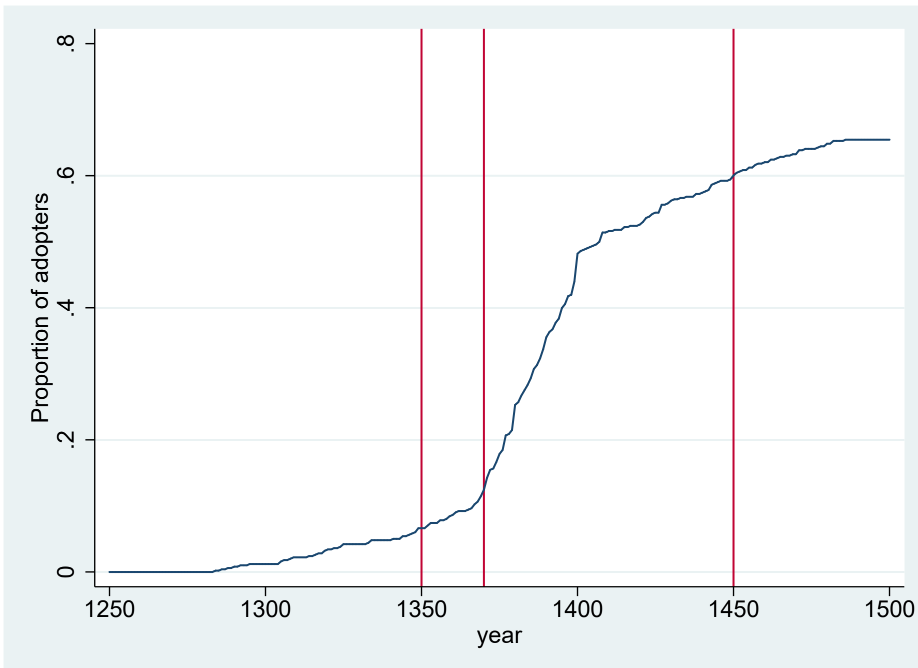
2.1 The Mechanical Clock

Public mechanical clocks first arrived in Europe at the end of the 13th century.[1] Clocks appeared simultaneously around the turn of the century in northern Italy, southern England,

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

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).[2] The spread of clocks followed an S-shape diffusion curve, which is typical for the spread of a general purpose technology (see Figure 3).[3]

Figure 3: 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).

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

[2]Smaller clocks for private homes (i.e., table clocks and portable pocket clocks) appeared mainly during the first half of the 16th century and were available only to the wealthy. Portable spring driven clocks (watches) only became popular during the 17th century (Cipolla 1967; Landes 1983).

[3]In Figure 3, 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.

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).

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 communal tower of the town hall. 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.[4]

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. The first clockmakers came from a variety of 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—i.e., locksmiths or goldsmiths. These crafts were among the most advanced of the time in terms of artisanal skill. 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

[4] The following example from the city of Duisburg (in the western part of 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).

from their colleagues and masters rather than any abstract theoretical knowledge (Mokyr 2002; de la Croix, Doepke and Mokyr 2018).

2.2 The Printing Press

Johannes 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.

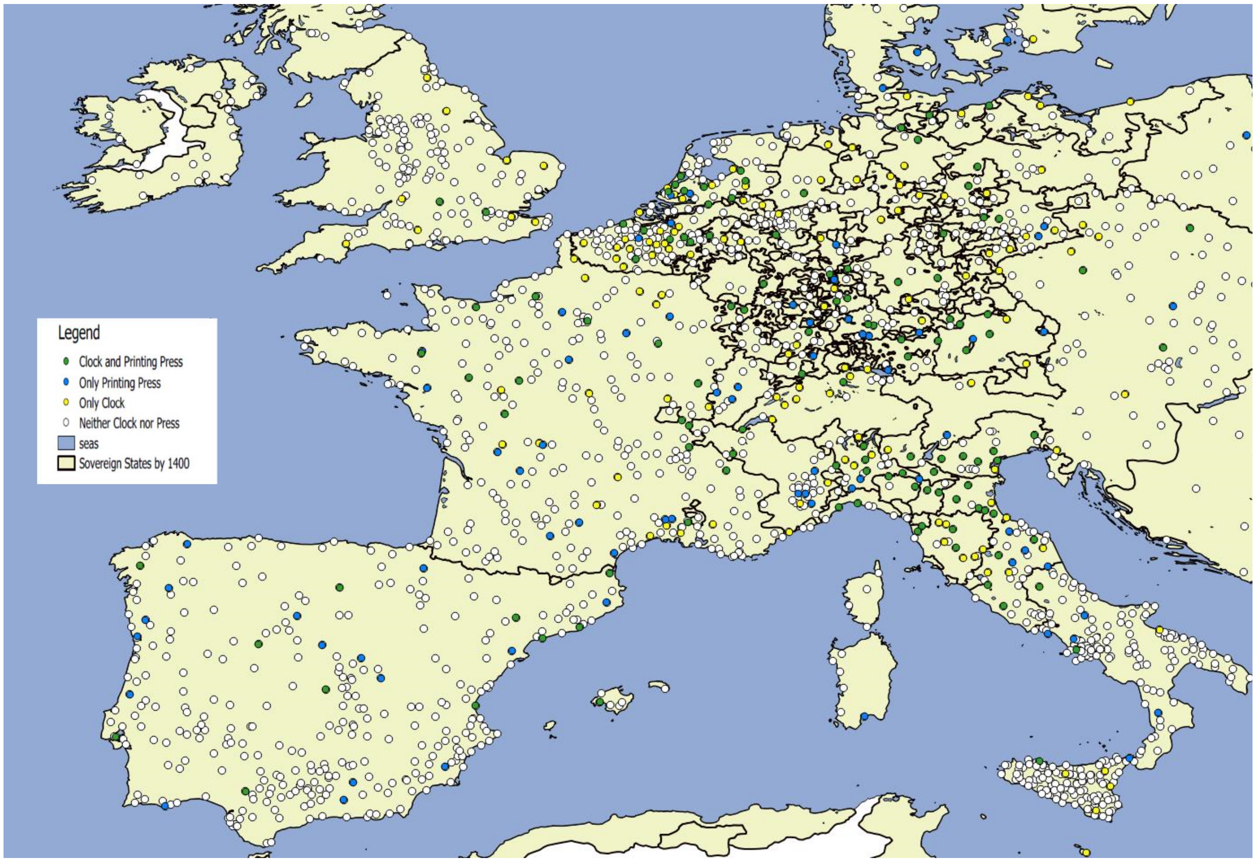
These early printers went first to where demand was highest: commercial centers, university towns, and monasteries, where literacy rates were much higher than elsewhere in Europe (Eisenstein 1979). The large print centers in Europe were among the most important commercial towns; the top 10 print cities, 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); see Figure 4. 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).

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,

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

Figure 4: The Diffusion of Clocks by 1450 and the Movable Type Printing Press by 1500

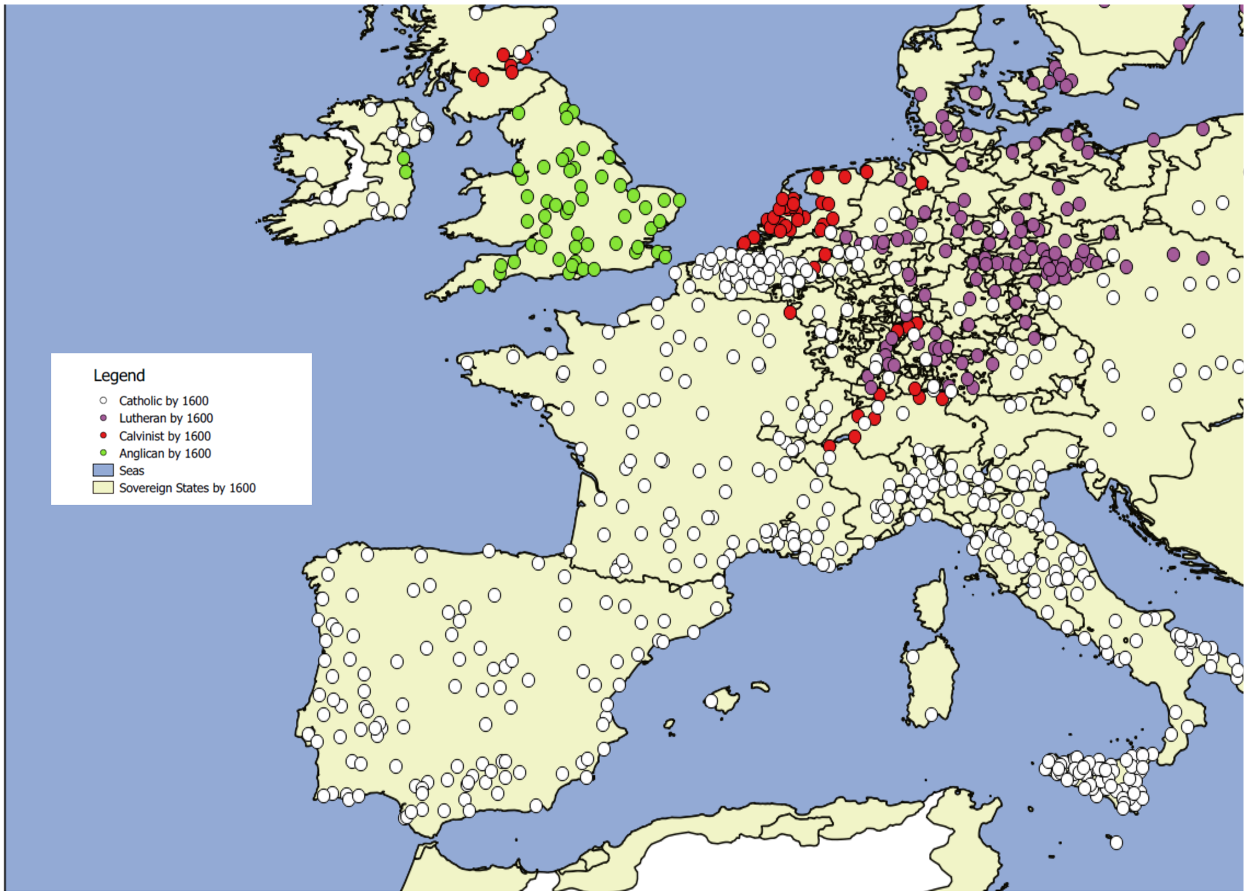


Sources: Rubin (2014) for the printing press, Boerner and Severgnini (2019) for the mechanical clock, and GIS border from Nuessli (2011).

1517 and was led by a little-known professor at the University of Wittenberg named Martin Luther. 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. This movement laid the groundwork for the much more effective and long-lasting Calvinist movement of the 1550s. Figure 5 shows a map of the spread of the Reformation in the 16th century.

Figure 5: 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.[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.

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.

These 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 late 14th century some clockmakers were occasionally mentioned as members of a sub-group belonging to various guilds of smiths, although they were not explicitly labelled as "clockmakers." By the 15th century they were named as clockmakers in these sub-groups, and only by the 16th century were the first clockmaker guilds documented in Paris (1544) and Nuremberg (1565) (Epstein 1991). 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). Johannes 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).

[6] Plenty of other causes of the Reformation exist in the literature. These are overviewed in Becker, Pfaff and Rubin (2016); for a more general overview of religion in economic history, see Becker, Rubin and Woessmann (2021). Beyond printing, causes of the Reformation include aristocratic patronage (Kim and Pfaff 2012), Luther's personal network (Becker et al. 2020), urbanization (Ozment 1975), spatial diffusion (Cantoni 2012), the presence of monasteries (Pfaff and Corcoran 2012), ideological influence via proximity to a Protestant hub (Becker and Woessmann 2009), and the Ottoman threat in Central Europe (Iyigun 2008).

The profession of the clock-maker was thereby at least partly institutionalized over time. In accordance with this development, the invention of the movable type printing press by Gutenberg 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.[7]

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 (2020) 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.

[7] In Figure 3, it can be seen that there are a small number of cities (20) that adopted the clock between 1450 and 1500. None of these cities adopted the press prior to adopting the clock.

[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.

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) and for which data for all controls exist in Rubin (2014). This includes 764 cities. Although we do not include population data in our regression analyses (see below), we use these data as evidence of population by 1500. This is a crucial requirement for inclusion in our data set if our analyses are to make theoretical sense. 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, 30 percent of cities had a mechanical clock by 1450, 22 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 4 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 5, 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,

Table 1: Summary Statistics

Variable	Mean	Std Error	Min	Max
		Endogenous Variables		
Clock by 1450	0.30	0.46	0	1
Ln(1 + years since clock)	1.21	1.90	0	5.12
Printing Press in 1500	0.22	0.42	0	1
		Religion Variables		
Protestant in 1530	0.11	0.31	0	1
Protestant in 1560	0.28	0.45	0	1
Protestant in 1600	0.32	0.47	0	1
		Control Variables		
Cities with clocks within 50 km	0.06	0.29	0	3
Calories in 1450	0.09	0.04	0.01	1.04
Independent City in 1450	0.05	0.21	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	19.22	6.43	5.92	85.90
Roman Road within 40 km	0.76	0.43	0	1
Cistercian within 40 km	0.63	0.48	0	1
Ln(elevation)	6.21	0.99	3.12	7.89
Ln(ruggedness)	2.66	1.00	0.07	7.82
Min log distance to Wittenberg/Zurich	5.82	0.78	2.52	6.97
Latitude	46.79	5.81	27.90	63.43
Longitude	6.26	7.45	-15.63	22.28
		Instruments		
Eclipse	0.33	0.47	0	2
Log (distance to Mainz)	6.00	0.72	2.48	7.09

Notes: Total number of observations: 764. 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. Distance to city 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).

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 order to account for the possibility that the initial spread of clocks was simply a spatially-driven process, we control for the number of cities with clocks within 50 kilometers of the city in question. Including this variable helps alleviate some concern of spatial autocorrelation—a problem in long-run historical studies noted by Kelly (2019). 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, was close to a Cistercian monastery, 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), proximity to a Roman road, the minimum of its distance to Wittenberg and Zürich (the latter being Zwingli's home), and its elevation, ruggedness, latitude, and longitude.[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-

[9]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.6.

[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 Roman road and Cistercian data are from Talbert (2000) and Jedin, Latourette and Martin (1970), respectively. Another demand control for which we collected data is the presence of guilds, from the dataset collected by Ogilvie (2019). Since these data are missing some large cities, we do not include them in the primary analysis. Nonetheless, we report our main results including a control for guild presence in Appendix Table A.7 and the results are nearly identical to those reported in the body of the paper.

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 (2020) 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. To account for these biases, we estimate the determinants of the spread of clocks and the press separately using instrumental variables. If our instruments are valid, our analysis connecting clocks to the printing press and both of these technologies to the Reformation can be interpreted as causal.

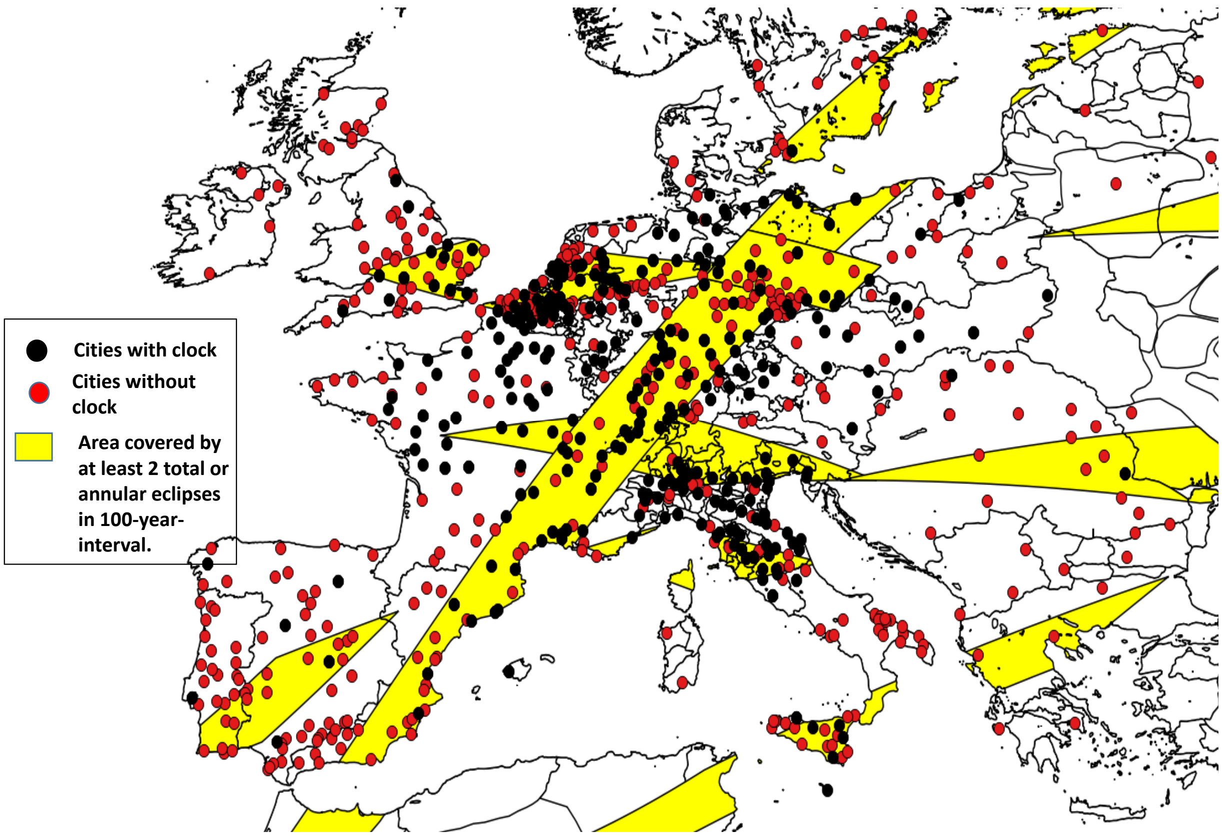
We stress that this does not mean that the previously mentioned omitted variables played no role in medieval technological agglomeration or the Reformation. They clearly did. We simply note that good instruments allow us to parse the causal roles we are interested in from the role of other, unobservable factors. 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 experienced multiple solar eclipses over a one hundred year span between 800 to 1283. This period covers all eclipses after 800 and before the implementation of the first clock in 1283. Before 800 there was a long period without multiple solar eclipses occurring in the same region in the same century.[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

[11]There were indeed eclipses in Europe prior to 800, but there were no places that had *multiple* eclipses in the same century for hundreds of years prior to the ninth century. The presence of multiple eclipses in the same region is key to our identification strategy, as well as the one used in Boerner and Severgnini (2019). Some parts of Europe started seeing repeated eclipses beginning in the ninth century, and others did not. We conjecture that this was one of the reasons behind the rise in astronomical inquiry in these parts of Europe.

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 6.

Figure 6: European Cities that Experienced at least Two Eclipses within a Century, 800–1283



Source: Boerner and Severgnini (2019).

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 the movement of heavenly bodies.[12] 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] 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 next generation. In two robustness checks (Appendix Tables A.1 and A.8) 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, the development of astronomic instruments, and 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-1283 eclipses did not directly affect the spread of printing or the Reformation—and we

[12] To the best of our knowledge, information on production and adoption of astronomical instruments is not available at city level. See, for example, the problems related to the compilation of historical astrolabes by Price (1955).

[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.

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.

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 A.1, 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.

In Table 2, we test for the exogeneity of the instruments relative to the various control variables included in our analysis. Of particular importance is the fact that the eclipse instrument is not related to the "clocks within 50 km" variable (in fact, the point estimate is negative). If it were positively related, the exclusion restriction would not hold since eclipses could simply be a proxy for nearby clocks rather than affecting the specific city in question. More generally, at the $p < 0.10$ threshold, the eclipse instrument is statistically related to only 2 of the 14 control variables and the distance to Mainz variable is related to only one control variable. This is approximately what we would expect if the data were completely random. 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]

[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 and Miller (2015) and considering a wild cluster bootstrap technique based on 100,000 replications.

Table 2: Exogeneity Tests

Dependent variable:	(1) Clock	(2) Press	(3) Clocks w/in 50km	(4) Indep. City	(5) Lay Magnate	(6) University	(7) Bishop	(8) Hansa
Eclipse	0.13***	0.05**	-0.05	0.01	0.01	-0.02	-0.13**	0.08*
	(0.03)	(0.02)	(0.05)	(0.02)	(0.04)	(0.02)	(0.04)	(0.03)
	[0.001]	[0.019]	[0.433]	[0.694]	[0.839]	[0.251]	[0.018]	[0.050]
Log(Dist. to Mainz)	0.07	-0.09	-0.02	-0.06**	0.16	-0.01	0.05	-0.00
	(0.04)	(0.03)	(0.03)	(0.01)	(0.07)	(0.02)	(0.03)	(0.03)
	[0.471]	[0.234]	[0.646]	[0.027]	[0.221]	[0.742]	[0.243]	[0.920]
Obs.	764	764	764	764	764	764	764	764
R-squared	0.35	0.30	0.17	0.42	0.24	0.10	0.28	0.29
	Water	Min Dist Witt/Zur	Log Elevation	Log Ruggedness	Roman Road	Cistercian	Log 16c Growth	Log 15c Growth
Eclipse	-0.09	0.15	0.12	-0.12	-0.06	-0.05	0.00	0.01
	(0.06)	(0.10)	(0.09)	(0.09)	(0.06)	(0.08)	(0.08)	(0.05)
	[0.350]	[0.389]	[0.283]	[0.252]	[0.664]	[0.571]	[0.964]	[0.863]
Log(Dist. to Mainz)	0.01	0.33	0.30	-0.25	-0.10	-0.12	0.10	-0.07
	(0.03)	(0.30)	(0.15)	(0.10)	(0.03)	(0.07)	(0.07)	(0.09)
	[0.815]	[0.440]	[0.115]	[0.416]	[0.131]	[0.247]	[0.340]	[0.472]
Obs.	764	764	764	764	764	764	446	257
R-squared	0.19	0.81	0.79	0.62	0.64	0.26	0.12	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 100,000 replications 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. Roman road and Cistercian variables are dummies for presence within 40km.

5 Empirical Analysis

5.1 Empirical Strategy

We test the connections between clocks, printing presses, and the Reformation using various econometric specifications. We first test whether the spread of the mechanical clock had an impact on the spread of the printing press. Because clocks were not randomly assigned to cities, we instrument for the presence of a mechanical clock with the variable $\text{Eclipse}_{i,j,1283}$. This variable is a sum of the number of times a city in nation i experienced multiple eclipses within the span of a century prior to 1283. In other words, we estimate the following set of equations (with equation (1) estimated by a linear probability model):

$$\text{Clock}_{i,j,1450} = \alpha_1 + \beta_1 \text{Eclipse}_{i,j,1283} + \gamma_1 \text{X}_{i,j,1450} + \text{D}_j + \varepsilon_1, \tag{1}$$

$$\text{Press}_{i,j,1500} = f(\alpha_2 + \beta_2 \widehat{\text{Clock}}_{i,j,1450} + \gamma_2 \text{X}_{i,j,1450} + \text{D}_j + \varepsilon_2). \tag{2}$$

$\text{Press}_{i,j,1500}$ is a dichotomous variable equaling one if town i in nation j had a press by 1500, and $\text{Clock}_{i,j,1450}$ is a dichotomous variable equaling one if town i in nation j had a clock by 1450. $\text{X}_{i,j,1450}$ is a set of city-specific covariates. D_j is a set of "nation" fixed effects as of 1500, which are more properly called regional fixed effects due to the shifting nature of borders in the early modern period.

We next turn to the three-stage equations, which test the relationship between clocks, the printing press, and the Reformation. We permit clocks to affect the spread of the printing press independently, and thus employ a three-stage technique. In these regressions, $\text{Protestant}_{i,j,t}$ is a dichotomous variable equaling one if town i in nation j adopted the Reformation by year $t \in \{1530, 1560, 1600\}$. Since these events happened sequentially—first clocks spread throughout Europe, then the printing press, then the Reformation—the main variables of concern do not suffer from reverse causation. Since omitted variables may exist, however, we employ the instruments noted above for clocks and the printing press. In other words, we estimate the following set of equations (with equations (3) and (4) estimated by a linear probability model and equation (5) estimated via probit):

$$\text{Clock}_{i,j,1450} = \alpha_3 + \beta_3 \text{Eclipse}_{i,j,1283} + \gamma_3 \text{X}_{i,j,1450} + \text{D}_j + \varepsilon_3, \tag{3}$$

$$\text{Press}_{i,j,1500} = \alpha_4 + \beta_4 \widehat{\text{Clock}}_{i,j,1450} + \delta_4 \log\left(\text{distance to Mainz}\right)_{i,j} + \gamma_4 \text{X}_{i,j,1450} + \text{D}_j + \varepsilon_4, \tag{4}$$

$$\text{Protestant}_{i,j,t} = f(\alpha_5 + \beta_5 \widehat{\text{Clock}}_{i,j,1450} + \delta_5 \widehat{\text{Press}}_{i,j,1500} + \gamma_5 \text{X}_{i,j,1450} + \text{D}_j + \varepsilon_5). \tag{5}$$

Before proceeding, there are two important issues to clarify. The first is that we estimate the first two stages using OLS (i.e., linear probability model) despite the outcome variable being dichotomous in both cases. We estimate these equations using OLS rather than a specification more suited for binary dependent variables (such as probit) because the distributional assumptions of such a specification must be correct in order for the error term to be correctly specified. This is not true of the linear probability model (LPM) (Lewbel, Dong and Yang 2012; Dong and Lewbel 2015).[15] Second, we run all of our regressions using the conditional mixed-process technique, or cmp (Roodman 2018). This technique has multi-

[15] Although Dong and Lewbel (2015) propose an alternative to LPM, they note that, unlike other functional forms, a major benefit of LPM is that "linear two stage least squares does not require the errors in the first stage regressions to satisfy any of the properties of a correctly specified model."

ple advantages over commands such as ivprobit, 2SLS, or 3SLS. For one, in the three-stage analysis cmp permits us to estimate the third stage using probit. Second, cmp permits the inclusion of data from countries where all towns chose one religion. Specifications in which probit are employed in the third-stage generally do not permit this when fixed effects are included. This is important in our context because it permits us to test of the effects of clocks on the spread of printing in those regions with only one religion. Since there is variation in the spread of clocks and the spread of printing in these regions, including these data points provides a clearer picture for the three-stage analysis. Indeed, according to Roodman (2011), the cmp estimator is "consistent for recursive systems in which all endogenous variables appear on the right-hand sides as observed ... cmp can mimic a score of built-in and user-written Stata commands. It is also appropriate for a panoply of models that previously were hard to estimate."

5.2 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.[17]

The results in column (1) indicate that the eclipse instrument is strong (F-stat = 29.29, above the threshold of 10 suggested by Staiger and Stock (1997) and Stock and Yogo (2005)).[18] The second stage results reported in column (2), which are marginal effects of a probit regression, indicate that cities with clocks were 34 percentage points more likely to adopt the printing press than cities without clocks. Column (3) indicates that these results

[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.

[17] In Appendix Tables A.2 and A.3, we show that the results are largely robust to clustering at the more local region and territory levels, which yields 44 and 210 clusters, respectively, instead of the 19 clusters used in the main results. The main differences between region, territory, and the country-level is that a region is defined as the Imperial Circle in the Holy Roman Empire, by kingdom in Spain, and in Italy many of the larger states (as of 1500) are a region. Territories break the Holy Roman Empire and France up further into local suzerainty. The two-stage results reported in Table 3 hold, although they are slightly more noisily estimated. The results in Table 5 also hold, although the results linking clocks to the press ($p = 0.16$), the press to the Reformation in 1560 ($p = 0.13$) and 1600 ($p = 0.16$) are only marginally significant when territory clusters are used. The distance to Mainz instrument becomes weaker when territory clusters are used, causing the third stage standard errors to rise.

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

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

	(1) First Stage	(2) Second Stage	(3) Second Stage
Regression Technique:	OLS	Probit	OLS
Dependent Variable:	Clock by 1450	Press by 1500	Press by 1500
Eclipse	0.13***		
	(0.02)		
Clock by 1450		0.34***	0.45**
		(0.12)	(0.18)
Mean of Dep. Var.	0.30	0.22	0.22
Politics/Trade	YES	YES	YES
Geography	YES	YES	YES
Nation Fixed Effects	YES	YES	YES
Observations	764	764	764
No. of Clusters	19	19	19
R-squared	0.34		0.29
Log (pseudo-)likelihood		-587.5	
F-stat on instrument	29.29		

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 column (2). All regressions include a constant term (not reported). Politics/trade variables include the number of cities with a clock within 50 km, independent city in 1450, calories in 1450, lay magnate in 1500, university by 1450, bishop by 1450, a Hansa dummy, a Roman roads within 40km dummy, and a Cistercian monastery within 40km dummy. Geography variables include a water dummy, minimum distance Wittenberg/Zürich, latitude, longitude, ln(elevation), ln(ruggedness). Distance to Mainz 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.

are not simply a reflection of the distributional assumptions of the probit model. A 2SLS (LPM) regression reveals that cities with a clock were 45 percentage points more likely to adopt the printing press, ceteris paribus.

Next, we see if *earlier* clock adoption mattered for subsequent press adoption. We do this in two ways. First, we create a variable "years since clock," which equals (1451 − first year of clock). We replace the clock dummy in Table 3 with the variable $ln(1 +$

years since clock).[19] We report the results in Table 4. Columns (2) and (3) report the results with the "years since clock" variable, where the second stage is probit and OLS, respectively. These results suggest that not only were towns with clocks more likely to adopt the printing press (as shown in Table 3), but *earlier* clock adopters were even more likely to adopt the press. Each log-point increase in years since a town adopted the clock is associated with 8–11 percentage points greater likelihood of ultimately adopting the printing press.

Second, we conduct an "event study", where the introduction of the public mechanical clock in the city is considered an "event" that can have a future impact on a outcome (in our case, the adoption of the printing press).[20] To do this, we reshape our data into a panel in which we consider the years 1000, 1200, 1300, 1400, and 1500 (which are the years for which we have population estimates). For this regression, we create a set of dummy variables which equal one if the year in question is two centuries prior to clock adoption (Clock_{t-200}), one century prior to clock adoption (Clock_{t-100}), the century of adoption (Clock_{t}), and one or two centuries after adoption (Clock_{t+100} and Clock_{t+200}). We control for the contemporary value of the logarithm of the city population and, following Autor (2003), the interaction of country and year. We report the results in column (4). The insignificant coefficients on the lagging values suggest there is no anticipatory response of cities with the clock in adopting the printing press, while the significant values of the leading values confirm the relationship found in columns (2) and (3). Moreover, the magnitude of the coefficients is similar to those found in Table 3. This is not surprising, since the press spread about two centuries after the initial spread of the public mechanical clock. Combined with the results reported in Table 3, these results indicate that towns that were early adopters of the clock were more likely to subsequently adopt the press.

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.

[19] In Appendix Tables A.5, we run the same analysis for the three-stage regression reported in Table 5.
[20] For more on event studies, see among others Autor (2003) and Angrist and Pischke (2009).

Table 4: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press, using a "Years Since Clock" Variable and an Event Study

	(1)	(2)	(3)	(4)
	First Stage	Second Stage	Second Stage	Event Study
Regression Technique:	OLS	Probit	OLS	OLS
Dependent Variable:	ln(1 + years since clock)	Press by 1500	Press by 1500	Press by 1500
Eclipse	0.54***			
	(0.10)			
ln(1 + years since clock)		0.08***	0.11**	
		(0.03)	(0.04)	
Clock_{t-200}				-0.07
				(0.06)
Clock_{t-100}				-0.07
				(0.07)
Clock_{t}				-0.07
				(0.10)
Clock_{t+100}				0.39**
				(0.16)
Clock_{t+200}				0.51**
				(0.22)
Mean of Dep. Var.	1.21	0.22	0.22	0.08
Politics/Trade	YES	YES	YES	NO
Geography	YES	YES	YES	NO
Nation Fixed Effects	YES	YES	YES	NO
City Fixed Effects	NO	NO	NO	YES
Year Fixed Effects	NO	NO	NO	YES
Year$x$Country Fixed Effects	NO	NO	NO	YES
Observations	764	764	764	1,734
No. of Clusters	19	19	19	32
R-squared	0.34		0.31	0.69
Log (pseudo-)likelihood		-1677.4		
F-stat on instrument	28.28			

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. City population controlled for in column (4). For more, see notes in Table 3.

5.3 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. 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 5.[21]

These results confirm most of the primary hypotheses suggested earlier in the paper. First, note that both the eclipse and distance to Mainz instruments are strong (F-stat = 29.29 and 12.27, respectively). Second, clocks once again have an economically and statistically significant effect on the adoption of the printing press (column (2)). Clock towns were 40 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.

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. Meanwhile, the clock coefficient is positive and significant in the Protestant in 1560 and 1600 regressions. Yet, this result is not robust, and we are therefore hesitant to make a causal claim. For one, the results are sensitive to the specification employed: the coefficient on clock in columns (3)–(5) is close to zero and highly insignificant when LPM is used in all three stages (see Appendix Table A.4). Moreover, when we employ an alternative definition of the eclipse instrument—multiple eclipses over a 200-year span—the coefficient on the clock variable is statistically insignificant in the Protestantism regressions (see Appendix Table A.8). Since we have no clear ex ante hypothesis regarding a direct causal link between clocks and the Reformation, we refrain from interpreting these results as causal.[22]

[21] Using OLS in equations (1) and (3) allows for arbitrary spatial clustering with a distance of 250 kilometers, as suggested by our measure of spillover. Imposing a distance linear decay in the correlation structure (using the command *acreg* proposed by Colella et al. (2019)) provides results with similar statistical significance. This is in line with the Moran tests associated with the above-mentioned equations. The $z-score$ associated with the OLS estimates of the first and second stages are 1.58 (with a p-value of 0.11) and 1.15 (with a p-value of 0.67), 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 affected by this problem. In addition, since the third stage is based on a non-linear equation, we compute the residual as the difference between the dependent variable and the prediction obtained by a probit estimate. Keeping in mind that the results are not directly comparable to the ones obtained by an OLS regression, we obtain Moran indexes for the Reformation adoption in 1530, 1560, and 1600 equal to 1.56 (with a p-value of 0.24), 3.73 (0.00), and 2.39 (0.02).

[22] Although we do not wish to push this causal story too far, there is reason to believe that a causal connection between clocks and the Reformation may exist. In particular, 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 Appendix B for a brief narrative of the link between clocks and the Dutch Reformation.

Table 5: 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	0.13***				
	(0.02)				
Log(Distance to Mainz)		-0.10***			
		(0.03)			
Clock by 1450		0.40**	-0.08	0.27*	0.35***
		(0.19)	(0.11)	(0.15)	(0.13)
Press by 1500			0.33***	0.42***	0.36**
			(0.08)	(0.15)	(0.17)
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters	19	19	19	19	19
F-stat on instrument	29.29	12.27			
Log (pseudo-)likelihood			-661.6	-679.7	-656.6

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 in miles. Politics/trade variables, geography variables, and nation fixed effects as in Table 3.

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 6, which is divided into two parts. The upper panel reports the marginal effects of the clock and press obtained from Table 5. 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.[23] The contribution of the mediated ratio is 34 percent of the effect of the printing press variable on the spread of the Reformation. The ACME is statistically significant in the "Protestant in 1530 and 1560" regressions, and it is nearly significant in the "Protestant in 1600" regression ($p = 0.110$). This indicates that there was an economically meaningful indirect effect of the mechanical clock on the early spread of the Reformation.[24]

Table 6: 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	0.40**	-0.08	0.27*	0.35***
	(0.19)	(0.11)	(0.15)	(0.13)
Press by 1500		0.33***	0.42***	0.36**
		(0.08)	(0.15)	(0.17)
		Indirect Effect		
ACME of Clock		0.13*	0.15**	0.13
		(0.07)	(0.07)	(0.08)
Contribution of Mediated				
Ratio Indirect/(Direct) (%)		34%	34%	34%
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 5. 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.

[23] Since our estimation technique is non-linear in the final stage and we have two separate instruments, we cannot consider the Stata estimation command *ivmediate* recently proposed by Dippel, Ferrara and Heblich (2020), which is designed for linear models (Dippel et al. 2020).

[24] 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)).

5.4 Robustness using German Data

In this section, we test the robustness of our results using more fine-grained data from the German-speaking lands collected from Jedin, Latourette and Martin (1970), Cantoni, Dittmar and Yuchtman (2018), Ogilvie (2019), Dittmar and Meisenzahl (2020) and maps of Talbert (2000) digitized by McCormick et al. (2019). These data have some advantages and drawbacks over the data employed in previous sections. The primary advantage is that they are more finely-grained. They include a number of smaller cities (and all control data) that are not included in Rubin (2014) or Bairoch, Batou and Pierre (1988). Second, they include three additional control variables: the number of markets, the presence of Dominican monasteries, and exposure to the plague.

However, these data also come with drawbacks. First, there were not many eclipses in the German-speaking lands in the period in question. There was one set in the 9th century and two sets in the 12th century. This limits the variation needed to obtain a strong instrument. Second, and more importantly, these data do not permit a test of the hypothesis connecting the spread of the mechanical clock and the spread of the printing press to the Reformation. The Cantoni, Dittmar and Yuchtman (2018) data do include an "ever Protestant" variable. However, in these data there are 38 "polities". Only *one* of these polities has variation in the "ever Protestant" variable, and this is not even a real polity; it is the group representing the independent cities of the HRE. This is not surprising. After the Peace of Augsburg in 1555, the cuius regio, eius religio ("whose realm, his religion") reigned in much of the Holy Roman Empire. This meant that for the small villages represented in the Cantoni, Dittmar and Yuchtman (2018) data, there would have been little choice regarding official religion. This also means that the covariates we might expect to determine religious choice—including the presence of a clock or printing press—should not have affected religious choice in these towns. It is worth noting, however, that this fact does not undermine the analyses of the previous sections. As was the case in Cantoni (2012) and Rubin (2014), these analyses focused on *larger* cities. Both independent cities and larger cities in princely territories or bishoprics were less subject to the whims of local rulers. In the case of independent cities this was because there was no local ruler (although there were town councils), and in the case of princely towns this was because religious sentiments in those towns often influenced the decision of the local ruler. The summary statistics of the German data are presented in Table 7.

Nonetheless, these data are useful for testing the first (and primary) claim made in this paper that technological agglomeration occurred in the medieval period. In Table 8 we report the results of two-stage regressions similar to those in Table 3. We begin by noting that the instrument is not strong in the German lands (F = 3.73 in column (1)). The instrument is

Table 7: Summary Statistics, data from the Holy Roman Empire

Variable	Mean	Std Error	Min	Max
	Endogenous Variables			
Clock by 1450	0.03	0.17	0	1
Press by 1517	0.02	0.13	0	1
	Control Variables			
Cities with clocks within 50 km	1.02	1.08	0	6
Zero Population dummy	0.94	0.23	0	1
Independent City	0.03	0.17	0	1
University by 1517	0.01	0.08	0	1
Bishop	0.01	0.12	0	1
Hanseatic	0.01	0.11	0	1
Log(distance to sea)	4.80	1.07	0	6.02
Markets in 1470	0.36	0.87	0	5
Roman Road within 40 km	0.35	0.48	0	1
Cistercian within 40 km	0.64	0.48	0	1
Dominican within 40 km	0.75	0.43	0	1
Total plague years	0.32	2.46	0	46
Log (distance to Mainz)	5.47	0.76	-9.05	6.87
	Instruments			
Eclipse	0.71	0.67	0	3
Eclipse (12th c only)	0.54	0.50	0	1

Notes: Total number of observations: 2,033. Data from Cantoni, Dittmar and Yuchtman (2018). We only include observations for which we have data for all covariates. Elevation dummies not reported

stronger (column (3)) when we only focus on "recent" eclipses of the 12th century (F = 5.87). With these caveats in mind, the evidence supports the conjecture that clocks were causally related to the spread of printing. We find that the presence of a clock is associated with 162–238 percentage points higher probability of having a press by 1517. Although we do not have confidence in the preciseness of these estimates—they are surely too high, likely due to weak instruments, and one of the estimates is imprecisely estimated—it is worth noting that they in the same direction as previously-reported results. With these limitations in mind, these results support the idea that technology agglomeration is one reason the printing press spread where it did.

We run another set of tests using data from Wahl (2019). These data cover the entire German-speaking lands (modern day Germany, Austria, and Switzerland). Like our data, these data are at the city level. As Wahl (2019) studies the effect of local political institutions on economic development, these data include additional control variables. These include indicators for whether the city had participative elections, guild participation in the city

Table 8: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press, data from Holy Roman Empire

	(1)	(2)	(3)	(4)
	First Stage	Second Stage	First Stage	Second Stage
Dependent Variable:	Clock by 1450	Press by 1517	Clock by 1450	Press by 1517
Eclipse	0.017*			
	(0.009)			
Eclipse (12th c only)			0.029**	
			(0.012)	
Clock by 1450		2.381***		1.624
		(0.536)		(1.158)
Mean of Dep. Var.	0.03	0.02	0.03	0.02
Politics/Trade	YES	YES	YES	YES
Geography	YES	YES	YES	YES
Regional Fixed Effects	YES	YES	YES	YES
Observations	2033	2033	2033	2033
No. of Clusters	23	23	23	23
R-squared	0.44		0.45	
Log (pseudo-)likelihood		1247.6		1247.7
F-stat on instrument	3.73		5.87	

Notes: ***p $<$ 0.01, **p $<$ 0.05, *p $<$ 0.1. Robust standard errors clustered by region in parentheses. Regressions calculated using the Stata cmp command from Roodman (2018). First stage is OLS, second stage is probit. Average marginal effects reported in columns (2) and (4). All regressions include a constant term (not reported). Politics/trade variables include the number of cities with a clock within 50 km, a zero-population dummy, independent city dummy, university by 1517, bishop dummy, a Hansa dummy, number of markets in 1470, the number of plague years, a Roman roads within 40km dummy, a Cistercian monastery within 40km dummy, and a Dominican monastery within 40km dummy. Geography variables include a log of distance to sea, distance to Mainz, and elevation dummies.

council, institutionalized burgher representation, and whether the city is a trade city. We append most of the variables we used in the regressions reported in Table 3 to these data.[25] As in the previous analysis, we focus on the clock to press relationship.[26]

Table 9: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press, cities in the German Lands

	(1)	(2)
	First Stage	Second Stage
Dependent Variable:	Clock by 1450	Press by 1500
Eclipse	0.182**	
	(0.078)	
Clock by 1450		0.496**
		(0.193)
Mean of Dep. Var.	0.45	0.29
Politics/Trade	YES	YES
Geography	YES	YES
Observations	126	126
R-squared	0.51	
Log (pseudo-)likelihood		-71.8
F-stat on instrument	5.43	

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Robust standard errors in parentheses. Regressions calculated using the Stata cmp command from Roodman (2018). First stage is OLS, second stage is probit. Average marginal effects reported in column (2). All regressions include a constant term (not reported). Politics/trade variables include number of cities within 50 km with a clock, population, urban potential and dummies for local election, guild presence, burgher representation, trade city, bishopric, lay magnate, Hansa presence, university, independent city, Cistercian monastery within 40km, Roman road, log distance to Mainz, membership in the Swiss confederation, and a dummy for towns that were part of the Austrian Imperial Circle. Geography variables include distance to river, log of elevation, log of ruggedness, agricultural suitability, latitude, and longitude.

We report the results in Table 9. Although the instrument is weak (F-stat = 5.43), the results are consistent with those found in the rest of the paper. Clock towns are 49.6 percentage points more likely to ultimately adopt the press, a number close to those found

[25] The only variables we did not append are those for which a variant are also included in Wahl (2019). These are "distance to river" instead of "water" and a Roman road dummy in place of "Roman road within 40km."

[26] We do not explore the press to Reformation connection because the distance to Mainz instrument does not work on this much smaller data set. The coefficient on distance to Mainz is positive (and highly insignificant), which undermines the third stage regression.

in Tables 3 and 5, where the point estimates on the clock coefficients are between 0.34 and 0.40. While this is a more limited sample (N = 126) than the Europe-wide sample employed in Tables 3 and 5, it supports the technology agglomeration hypothesis tested in this paper.

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 people 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 (2020) and is consistent with a large historical literature. Third, while we can not say definitively that the clock was statistically related or 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.

There are even broader implications of our findings. For one, it is possible that technology agglomeration indirectly contributed to the "Little Divergence" between northwestern Europe and the southern Europe in the 16th–18th centuries. We say indirectly because the connection is not direct—Italy (which fell behind) was among the leaders in clocks and printing, while England (which pulled ahead) was a laggard in both. However, technology agglomeration *did* help facilitate the Reformation, which for a number of reasons has long been argued to be one of the key sources of economic and political modernization, especially in England and the Dutch Republic (Weber 1905; Nexon 2009; Becker and Woessmann 2009; Becker, Pfaff and Rubin 2016; Rubin 2017). Second, our study hints at one of the consequences of Europe's political fragmentation: it permitted technological agglomeration to arise in the first place. Although our cross-sectional study cannot determine the role of political fragmentation in the spread of technology, Mokyr (1990) argues that it was key for Europe's eventual technological rise. Rulers who may have desired the suppression of technology for one reason or another would have had a difficult time doing so, since innovators and craftsmen could simply go to a nearby rival polity. In short, our findings add nuance to the broader story of Europe's economic and technological rise.

Finally, 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 (2020) 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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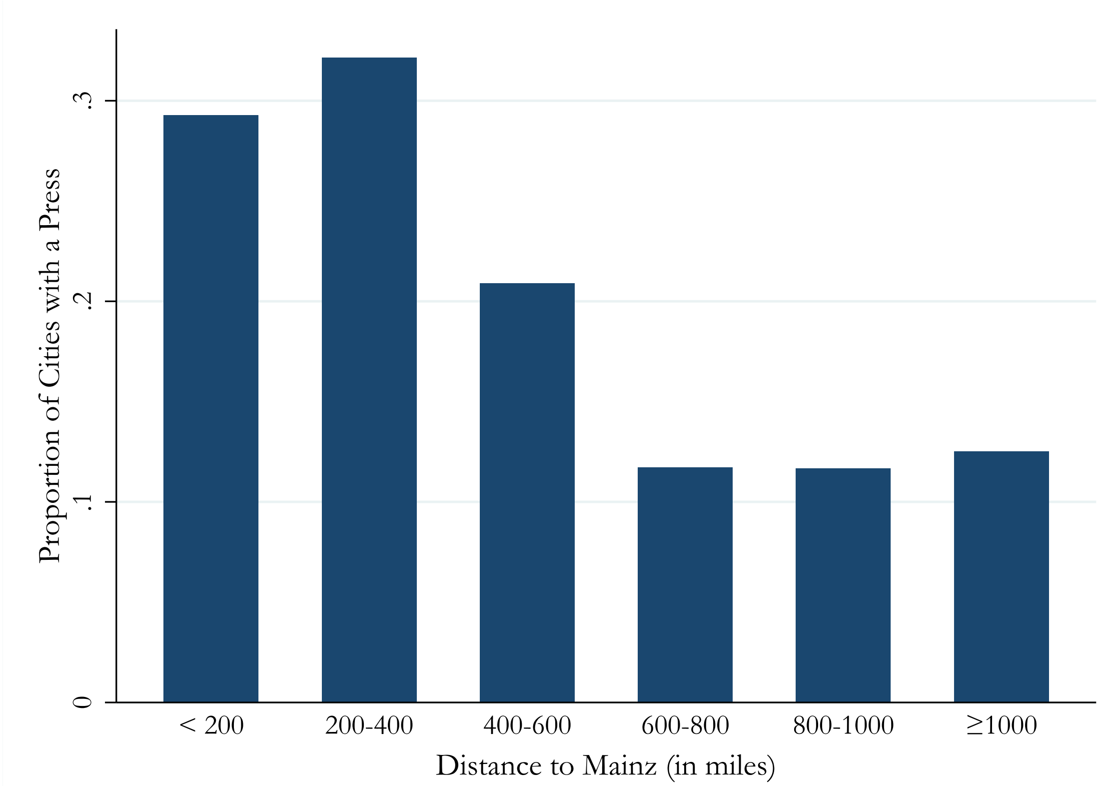
A Online Appendix

Figure A.1: Proportion of Cities with a Printing Press by 1500, by Distance to Mainz



Source: Rubin (2014).

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***	
	(0.02)	
Clock by 1450		0.47***
		(0.08)
Mean of Dep. Var.	0.30	0.22
Politics/Trade	YES	YES
Geography	YES	YES
Nation Fixed Effects	YES	YES
Observations	764	764
No. of Clusters	19	19
R-squared	0.34	
Log (pseudo-)likelihood		-588.2
F-stat on instrument	21.74	

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

Table A.2: Connecting the Spread of the Mechanical Clock to the Spread of the Printing Press, standard errors clustered by region and territory

	(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	0.13		
	(0.04)***		
	[0.04]***		
Clock by 1450		0.34	0.45
		(0.14)**	(0.27)*
		[0.12]***	[0.25]*
Mean of Dep. Var.	0.30	0.22	0.22
Politics/Trade	YES	YES	YES
Geography	YES	YES	YES
Nation Fixed Effects	YES	YES	YES
Observations	764	764	764
No. of Clusters (region)	44	44	44
No. of Clusters (territory)	210	210	210
R-squared	0.34		0.29
Log (pseudo-)likelihood		-587.5	
F-stat on instrument (region)	9.34		
F-stat on instrument (territory)	8.79		

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. Robust standard errors clustered by region in parentheses and territory in brackets. The main differences between region, territory, and the country-level is that a region is defined as the Imperial Circle in the Holy Roman Empire, by kingdom in Spain, and in Italy many of the larger states (as of 1500) are a region. Territories break the Holy Roman Empire and France up further into local suzerainty. For the rest of the variables, see notes in Table 3.

Table A.3: Connecting the Spread of the Clock and the Printing Press to the Reformation, standard errors clustered by region and territory

	(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	0.13				
	(0.04)***				
	[0.04]***				
Log(Distance to Mainz)		-0.10			
		(0.03)***			
		[0.05]**			
Clock by 1450		0.40	-0.08	0.27	0.35
		(0.29)	(0.24)	(0.25)	(0.22)
		[0.25]	[0.24]	[0.31]	[0.26]
Press by 1500			0.33	0.42	0.36
			(0.15)**	(0.27)	(0.26)
			[0.21]	[0.34]	[0.34]
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters (region)	44	44	44	44	44
No. of Clusters (territory)	210	210	210	210	210
F-stat on instrument (region)	9.34	9.76			
F-stat on instrument (territory)	8.79	3.93			
Log (pseudo-)likelihood			-661.6	-679.7	-656.6

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Robust standard errors clustered by region in parentheses and territory in brackets. The main differences between region, territory, and the country-level is that a region is defined as the Imperial Circle in the Holy Roman Empire, by kingdom in Spain, and in Italy many of the larger states (as of 1500) are a region. Territories break the Holy Roman Empire and France up further into local suzerainty. 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 in miles. Politics/trade variables, geography variables, and nation fixed effects as in Table 3.

Table A.4: Connecting the Spread of the Clock and the Printing Press to the Reformation, Linear Probability Model

	(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	0.13***				
	(0.02)				
Log(Distance to Mainz)		-0.10***			
		(0.03)			
Clock by 1450		0.40**	0.18	-0.05	-0.09
		(0.19)	(0.19)	(0.33)	(0.34)
Press by 1500			0.24	1.02**	1.18***
			(0.22)	(0.42)	(0.43)
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters	19	19	19	19	19
F-stat on instrument	29.29	12.27			

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 5.

Table A.5: Connecting the Spread of the Clock and the Printing Press to the Reformation, using a "Years Since Clock" Variable

	(1)	(2)	(3)	(4)	(5)
	First Stage	Second Stage	Third Stage		
	ln(1 + years	Press	Protestant by		
Dependent Variable:	since clock)	by 1500	1530	1560	1600
Eclipse	0.54***				
	(0.10)				
Log(Distance to Mainz)		-0.10***			
		(0.03)			
ln(1 + years since clock)		0.09**	-0.02	0.06*	0.09***
		(0.05)	(0.03)	(0.04)	(0.03)
Press by 1500			0.33***	0.42***	0.36**
			(0.09)	(0.15)	(0.16)
Mean of Dep. Var.	1.21	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters	19	19	19	19	19
F-stat on instrument	28.28	12.06			
Log (pseudo-)likelihood			-1751.1	-1768.6	-1745.6

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. See notes in Table 5.

Table A.6: Connecting the Spread of the Clock and Press to the Spread of the Reformation: Population in 1500 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	0.11***				
	(0.03)				
Log(Distance to Mainz)		-0.14***			
		(0.03)			
Clock by 1450		0.38	-0.03	0.38**	0.43***
		(0.27)	(0.14)	(0.15)	(0.12)
Press by 1500			0.27***	0.34***	0.28**
			(0.07)	(0.12)	(0.14)
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	731	731	731	731	731
No. of Clusters	19	19	19	19	19
F-stat on instrument	16.61	25.85			
Log (pseudo-)likelihood			-582.2	-600.3	-576.8

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 5. Calories in 1450 variable replaced with ln(population in 1500) variable.

Table A.7: Connecting the Spread of the Clock and Press to the Spread of the Reformation: Guild Presence 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	0.12***				
	(0.02)				
Log(Distance to Mainz)		-0.09***			
		(0.03)			
Clock by 1450		0.39*	-0.08	0.28*	0.36***
		(0.21)	(0.11)	(0.15)	(0.12)
Press by 1500			0.34***	0.43**	0.38**
			(0.09)	(0.17)	(0.18)
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Guild dummy	YES	YES	YES	YES	YES
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters	19	19	19	19	19
F-stat on instrument	43.88	11.69			
Log (pseudo-)likelihood			-640.8	-658.6	-636.1

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. See notes in Table 5. Guild dummy equals one if guilds present by 1500.

Table A.8: 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***				
	(0.02)				
Log(Distance to Mainz)		-0.10***			
		(0.03)			
Clock by 1450		0.80*	-0.08	0.20	0.32
		(0.43)	(0.25)	(0.30)	(0.25)
Press by 1500			0.34***	0.46***	0.37
			(0.08)	(0.17)	(0.23)
Mean of Dep. Var.	0.30	0.22	0.11	0.28	0.32
Politics/Trade	YES	YES	YES	YES	YES
Geography	YES	YES	YES	YES	YES
Nation Fixed Effects	YES	YES	YES	YES	YES
Observations	764	764	764	764	764
No. of Clusters	19	19	19	19	19
F-stat on instrument	21.74	9.54			
Log (pseudo-)likelihood			-662.3	-679.6	-656.3

Notes: ***p < 0.01, **p < 0.05, *p < 0.1. See notes in Table 5.

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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