The Research University, Invention, and Industry: Evidence from German History*

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December 11, 2024

Abstract

We examine the role of universities in knowledge production and industrial change using historical evidence. Political shocks drove a profound pro-science shift in German universities in the late 1700s. To study the consequences, we construct novel microdata. We find invention and manufacturing developed similarly in cities closer to and farther from universities in the 1700s and shifted towards universities and accelerated in the early 1800s. The shift in manufacturing was strongest in new and high knowledge industries and near large universities. After 1800, the adoption of mechanized technology and the number of firms winning international awards for innovation were higher near universities.

JEL Codes: O14, O18, O30, N13, R10, I25

Keywords: industrialization, invention, universities, cities

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One might define modern economic growth as the spread of a system of production, in the widest sense of the term, based upon the increased application of science…

– Kuznets (1968), *Reflections on the Economic Growth of Modern Nations*

1 Introduction

Can universities drive major changes in industrial activity? The pre-modern university focused on non-scientific knowledge and did not drive industrial activity. In contrast, the modern research university, which first developed in early 19th century Germany, is a unique producer of scientific knowledge and human capital, which are essential for modern growth. Yet surprisingly little economic research documents whether and how the modern research university promotes long-run growth and large scale transformations of the economy.

In this paper, we document that research universities were instrumental in shifting the German economy from a position of backwardness onto a path to the world frontier in technology and industry. Prior research on this industrialization process emphasizes shifts in economic activity starting in the 1840s, associated with railroads, heavy industry, and primary schooling. We assemble the first large-scale microdata covering the development of technology and manufacturing plants across German cities from 1760 to 1900, and study how changes in research universities induced modern growth, using within-Germany variation. In these novel data we find that modern universities drove a take-off in invention and industry in neighboring cities before the 1840s. These university effects precede and dominate factors emphasized in prior research. The effects we document are also not driven by endogenous university locations or differences in regional institutions. We find that historic universities, whose locations were fixed and which did not previously drive economic activity, became modern research universities and subsequently drove industrialization.

We document how universities shaped a major pivot in the development of invention and industrial activity in the early 1800s by investigating novel, disaggregated data from Germany.[1] We first show that universities sharply increased their investments supporting scientific research starting in the 1790s. We then show that levels and trends in scientific and technological discovery were similar in cities near to and far from universities before 1800, and shifted significantly towards universities after 1800. We next study evidence on

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[1] We use "Germany" and "German" as short-hands and study 2,254 historically German-speaking cities.

manufacturing plants at the city and city-by-sector level. We document that manufacturing developed similarly in cities nearer to and farther from universities in the 1700s, and shifted towards universities and accelerated in the early 1800s. The increase in manufacturing around universities was concentrated in new and knowledge intensive industries. In addition, we find that firms in cities near universities were more likely to adopt mechanized production technologies and to win international prizes for industrial innovation.

Exogenous political shocks drove the changes in universities whose consequences we study. The French Revolution (1789) famously led to the development of a ground-breaking, pro-science and pro-research model for university education in Germany (Palmer 2014; Blackbourn 2003; Rüegg 2004a; McClelland 2008; Van Bommel 2015). McClelland (2019; p. 6) observes, "the inertia of most of the traditional faculties could not be broken until the increasingly powerful waves of change emanating from France after 1789 placed the 'German university' before a potential inundation." The number of scientific research collections at German universities doubled after the French Revolution and before the Napoleonic invasion of 1805, leaping off prior trends (Section 2.2). Scientific and technical activities at universities expanded, including mechanical institutes designed to promote spillovers into local industries (Ziche 2001).[2] By the mid-1800s, the excellence of German universities and their superiority in the sciences were recognized internationally.[3] Before the French Revolution, German universities focused on theology and law and enrollments were stagnant (Turner 1975).

Economic theory predicts that geographic shifts in knowledge production will generate spillovers that transform the nature and location of industrial activity (Marshall 1920; Audretsch and Feldman 1996). We motivate our study with a new stylized fact: scientific and technological discovery followed similar trends in cities close to and far from German universities before 1800, and then accelerated and shifted spatially towards universities after 1800, as shown in Figure 1. This evidence and economic theory lead us to test four hypotheses. First, we expect to find industrial activity increasing around universities. For this relationship to be causal, it should hold where university locations were predetermined and did not previously confer economic advantage. Further, if research universities supplied

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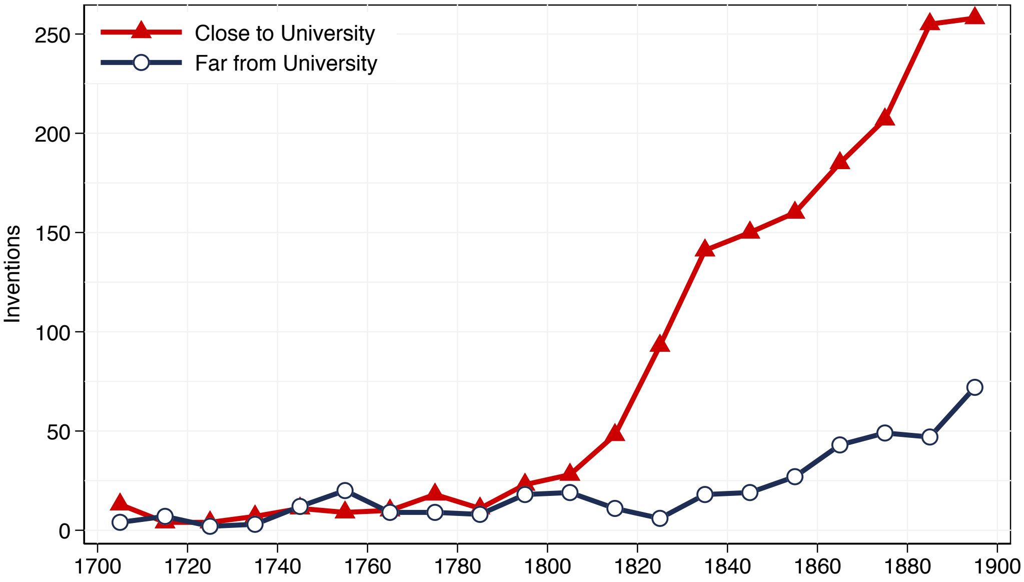
[2] We distinguish the effects of universities from other institutional and economic changes precipitated by the French Revolution, which varied across regions and cities in a different manner, as detailed below.

[3] In other countries, the research university was adopted endogenously in the later 1800s in response to developments observed in and around universities in Germany (Arnold 1868; Urquiola 2020).

Figure 1: The Pattern of Scientific and Technological Discovery



Graph plots data on major scientific and technological discoveries from Darmstaedter, du Bois-Reymond, and Schaefer (1908), across 2,254 German cities recorded in Keyser (1939-1974). Cities "Close to University" and "Far from University" are those below or above median distance in a given decade. See Section 3 below.

new economically useful knowledge and human capital, we would expect larger universities to generate larger spillovers and for cities near universities to differentially expand "new manufacturing," in industries previously not present. Second, we expect that these increases in industrial activity will also be concentrated in knowledge intensive sectors. Third, we expect that technological change will increase most around universities. Fourth, we expect to find universities associated with high quality industrial innovation after 1800.

We first test whether industrial activity increased around universities after 1800. We use distance to university to measure the spillover effects of universities on manufacturing. We find that cities near universities enjoyed no advantage or differential positive trend in manufacturing in the 1700s, and that manufacturing expanded significantly in cities near universities in the early 1800s. This "research university effect" confirms our first hypothesis. Our analysis rests on novel evidence on the establishment of manufacturing plants across every city in historic Germany from 1760 through 1899, which covers periods before census data are available.[4]

We argue that the research university effect was causal. A causal interpretation invites

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[4] We collect data on manufacturing activity (establishments) at the city-industry-time level as recorded in the *Deutsches Städtebuch*, an encyclopedia of 2,000+ historic cities. Our data strongly predict the number of factories and number of workers in two-digit industrial sectors when census coverage begins in the mid-1800s.

several identification questions. A first question is whether our findings could be driven by endogenous university locations. However, the research university effect is not driven by exposure to new universities or changes in locations. A second question concerns underlying trends. We find no differential positive trends in industrial or pre-industrial activity near universities before the reforms we study. A third question is whether time-varying regional factors could account for the research university effect, such as institutional changes after the French Revolution that varied across regions. However, we find universities promoted manufacturing after 1800 when we compare cities within the same political territory and controlling for time-varying factors shared by all cities in a territory. A fourth question is whether the research university effect could be explained by other factors that vary across cities *within* regions and over time, in particular the development of schooling at other levels. However, we collect detailed evidence on all schools in the cities we study and find schooling is neither a confounder nor itself a driver of manufacturing in our period. A fifth question is whether other major economic changes could explain the shift in industrial activity around universities. However, we observe the effect of universities on industry starting in the early 1800s, decades before the German customs union lowered trade barriers, railroads appeared, coal deposits became important for the location of industry, and the emergence of Germany's distinctive universal banks.

We next test mechanisms driving our main result. University size indicated both the amount of human capital produced and the quality of education (McClelland 2008). It follows that, if universities drove industrialization, we would expect larger universities to generate larger effects. In contrast, a general spread of science would not be related to university sizes. In the data, we find the university effect on industrial activity concentrated in cities near larger universities. In addition, if research universities shifted the supply of human capital and new useful knowledge, as the history suggests, we would expect universities to be particularly important for the development of new industrial activities. We test and confirm that after 1800 cities near universities differentially developed new industries which did not previously exist in a given city.

We extend our analysis to test whether the university effect was concentrated in knowledge-intensive industries, as our second hypothesis suggests. To measure the knowledge intensity of industries, we use our data on technological discovery, in which we gather evidence on inventors' educations. We classify industries as "high knowledge" and "low knowledge" based on the share of inventions used in a given two digit SIC industry made by university-educated inventors. We find that the shift in manufacturing towards universities was largely driven by high knowledge manufacturing, consistent with our hypothesis.

To test our third hypothesis, that universities promoted technological change, we examine establishment-level evidence on the adoption of mechanized production technology. Our principal source of data, the *Deutsches Städtebuch*, does not record the technology used in different establishments. We therefore construct unique evidence on firm-level mechanization in Saxony, which was the most advanced region of historic manufacturing in Germany. We observe that mechanization increased significantly faster in cities closer to universities in the first decades of the 1800s, consistent with our hypothesis.

Finally, we test whether universities were associated with the *quality* of industrial innovation measured by the development of internationally competitive products and technologies (our fourth hypothesis). We focus on competitive prizes for innovation at the first world's fair, *The Great Exhibition of the Industry of All Nations* at Crystal Palace in 1851 (see Moser 2005). We find that significantly more prizes were won by producers from German cities near universities, consistent with our hypothesis. The share of exhibits winning prizes in German cities near universities was similar to the share winning prizes in Belgium, then the most advanced industrial nation in continental Europe, whereas the share winning prizes in cities far from universities was similar to that in Spain, which was relatively backward. The data from Crystal Palace also provide cross-sectional verification of the patterns in our panel database on science and discovery, shown in Figure 1, but our panel data allow us to trace practical invention increasing within German cities near universities in the early 1800s, consistent with the dynamics in manufacturing.

The increases in industrial activity and invention near universities are likely to reflect how political shocks shifted supply-side and demand-side processes. The pro-science shift at universities increased useful knowledge. However, the patterns that we document are likely to also reflect how political shocks made universities and university-educated inventors more responsive to economic incentives. Indeed, narrative evidence indicates that changes in the late 1700s and early 1800s enabled universities to act in new ways as conduits for induced technological change, for instance through the establishment of mechanical institutes.

Our paper makes several larger contributions to the literature. First, we contribute evidence on the literature on endogenous growth. Economic theory emphasizes the importance of innovation for growth (Aghion and Howitt 1998; Romer 1994; Nelson and Phelps 1966) and empirical work indicates research universities are potentially key drivers of innovation (Jaffe 1989; Audretsch and Feldman 2004; Foray and Lissoni 2010; Kantor and Whalley 2014; Valero and Reenen 2019). Previous research identifies local spillovers from land grant universities into agricultural productivity over the medium run (Kantor and Whalley 2019) and shows patenting clustered around colleges established during the industrialization process, starting in the mid-1800s in the USA (Andrews 2023). In contrast, we show that the development of the modern research university drove a large-scale acceleration in industrial activity in the early 1800s, and link university invention to the growth of knowledge intensive industries. In prior work, Cantoni and Yuchtman (2014) document that the foundation of universities in Germany in the middle ages led to the establishment of legal institutions that supported the Commercial Revolution of the 1300s and 1400s. However, we find no differences in the level or trend of industrial, inventive, or urban construction activity associated with universities until the development of the modern research university in Germany. We thus provide evidence showing that modern research universities shaped a major pivot in development and that, as Landes (1969, p. 151) observes, scientific education may offer a "cure for technological backwardness."[5]

We also contribute to the literature on human capital and industrialization. Mokyr (2005) argues that upper tail human capital, produced outside universities, played a central role in British industrialization. Squicciarini and Voigtländer (2015) provide quantitative evidence for this mechanism, showing that fixed city-level differences in upper tail human capital explain the diffusion of the industrial revolution in France. Becker and Woessmann (2009) and Becker, Hornung, and Woessmann (2011) find that differences in local primary education affected economic structure in Germany after 1840. In contrast, we provide evidence on how political shocks led to the creation of modern research universities, increasing the supply of upper tail human capital, and driving industrialization starting in the early 1800s.

Our analysis documents how shocks to politics and culture are transmitted into changes

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[5] Prior studies find universities shaped the development of science in the Renaissance (Dittmar 2019) and the pre-industrial allocation of talent (de la Croix et al. 2022), but made limited direct contributions to innovation and industry in the English Industrial Revolution (Mitch 1999).

in the path of growth. Our historical analysis supports Kuznets' (1968; p. 103) observation that "modern economic development was partly preceded by and partly accompanied by these shifts in the structure of social values, which had an independent existence... at critical junctures." Our quantitative findings reflect how shocks to culture were transmitted through elite education to shape innovation and development, in the spirit of Mokyr (2016). Further, we document the role of the research university in promoting capitalist industrialization in the absence of political liberalization (Kuczynski 1961; Blackbourn and Eley 1984; Davidson 2012). Indeed, the German path famously involved a "revolution of the mind" but not liberal democracy (Palmer 2014; Blackbourn 2003).

Lastly, our study also contributes to a classic debate about catch-up industrialization. The predominant view is that industrialization in Germany took off with a growth spurt in the 1840s, driven by railroads and coal-based heavy industry (Gerschenkron 1962; Fremdling 1977; Pollard 1990; Pierenkemper and Tilly 2004). Against this view, some scholars argue that industrialization was a more continuous process, induced by deeper historical developments (Tilly and Kopsidis 2020; Kopsidis and Bromley 2016). Our evidence reveals a shift toward industrialization, centered around research universities, in the early 1800s. Our findings point to a substantially new view of the industrialization process.

2 The Historical Process

In this section, we review the research on German industrialization, including the paucity of evidence before 1840, which has limited study of the research university as a factor driving industrialization. We then discuss the pro-scientific shift at German universities. Finally, to clarify our analysis of spillovers, we provide evidence on the nature of university locations.

2.1 Industrialization in Germany

The timing and nature of the industrialization process in Germany are subject to debate.

An influential body of research dating back to Sombart (1909), Schumpeter (1939), and Gerschenkron (1962) argues that the key shift towards industrialization occurred in a "big spurt" in the 1840s and 1850s. This literature points to the importance of railroads, heavy industry, and large scale banking (see Hoffmann 1963; Tipton 1976; Fremdling 1977; Pollard 1990; Guinnane 2002; Hornung 2015). Thus Becker, Hornung, and Woessmann (2011) argue that Germany was "pre-industrial" in the first decades of the 1800s.[6]

A second strand of literature emphasizes the gradual and continuous nature of the industrialization process. Kaufhold (1986) and Ogilvie (1996) present evidence indicating that industrialization was part of a longer-run economic transformation. Building on this scholarship, Tilly and Kopsidis (2020) and Kopsidis and Bromley (2016) argue that the growth of heavy industry and urbanization after the mid-1800s reflected and was caused by very gradual, prior processes of economic and institutional development. Pfister (2022) provides evidence that is consistent with this view, but identifies a pivot towards gradual real wage growth starting in the late 1810s, following the shifts we study.

A third strand of the literature argues that significant, and in some sense revolutionary, shifts towards industrialization took place in the late 1700s and early 1800s. The mechanization of textiles in Germany increased rapidly in the early 1800s (König 1899; Meerwein 1914; Forberger 1958; 1982; Kirchhain 1973). Similarly, the adoption and development of steam engines in Germany starting in the late 1700s is considered as an indicator of significant economic change (Engelsing 1968, p. 73; Kuczynski 1961, p. 24, 87).[7]

The role of universities in German industrialization is ambiguous and, we argue, understudied. While research universities developed in the early 1800s, as we detail below, the leading view among historians is that that higher education and scientific training became economically important after 1850, when they provided human capital and innovations for a process driven by the development of railroads and heavy industry (Landes 1969; pp. 151, 187). However, almost all prior research using quantitative methods to investigate the development of industrial or inventive activity studies data from periods after the 1840s, when the first industrial censuses appear and richer patent data are available.[8] Indeed, as Tilly

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[6] Indeed, a large share of the population was employed in agriculture into the late 1800s (Kopsidis and Bromley 2016). Meaningful productivity comparisons begin in the 1870s and indicate German manufacturing had not caught up with British manufacturing at that time (e.g. Broadberry and Burhop 2010).

[7] Henderson (1956; p. 202) also argues that the origins of German industrialization date from the late 1700s, highlighting blast furnaces, foundries, and engineering works established in the later 1700s. Mottek (1960) argues that a preparatory period starting in the 1780s with the adoption of steam engines and spinning machines set the stage for industrial transition after 1834, when the German customs union was formed.

[8] Panel data from industrial censuses begin with the Prussian census of 1849. In earlier periods, existing data on industry are fragmentary and research has studied unique cross-sectional evidence, notably Hornung's (2014) analysis of Prussian textile plants in 1802. Prior quantitative research on invention is largely restricted to the patent record (Streb, Baten, and Yin 2006; Donges and Selgert 2019). However, patent data also do not permit the temporal and spatial comparisons we explore around the reform of universities. Prussia passed the first patent law in Germany in 1815; patent systems in other territories were set up at substantially later dates and under different rules; an agreement harmonizing patent systems was adopted in 1842 (Donges and

(1991; p. 177) observed more generally, most analytic narratives of German industrialization remain based on study of heavy industry and railroads, but not on quantitative evidence from other sectors or the pre-1840 period, when universities were transformed.[9]

While our analysis focuses on shifts in universities precipitated by the French Revolution, the shock we study may also have influenced development through other channels. The Napoleonic invasion of Germany led to legal reforms in some regions, including the abolition of guilds and occupational restrictions starting in the 1790s.[10] The Napoleonic wars also disturbed trade, raising effective protection against British imports of cotton textiles (Juhász 2018) and disturbing input supplies, with unclear net effects (Crouzet 1964; p. 579). Our analysis below thus studies how universities shaped invention and industrialization *within* political territories and thus across cities exposed to similar institutional change and shocks.

2.2 The Shift to Science and Technology in Universities

German universities moved to promote science and technology in the period we study, and "the sciences underwent a revolutionary change" (Turner 1987; p. 56). In the 1700s, universities focused on theology and law; in the 1800s, German research universities emerged as world leaders in science and technology (McClelland 2019; Turner 1975).

University investments in scientific research collections provide a unique measure of institutionalized university support for scientific research. Figure 2 shows that the number of scientific research collections at German universities began increasing sharply around 1789/1790, and shifted from a low underlying trend to a higher growth path between 1790 and 1820. These shifts were shared across universities and reflect such examples as the technology collection at Göttingen (1789) and the chemistry collection at Leipzig (1805).

The timing of this shift in the development of research infrastructure is significant. The increase in research collections began during the French Revolution (1789) and pre-dates the Napoleonic invasion of Germany (1805) and subsequent foundation of the university of Berlin

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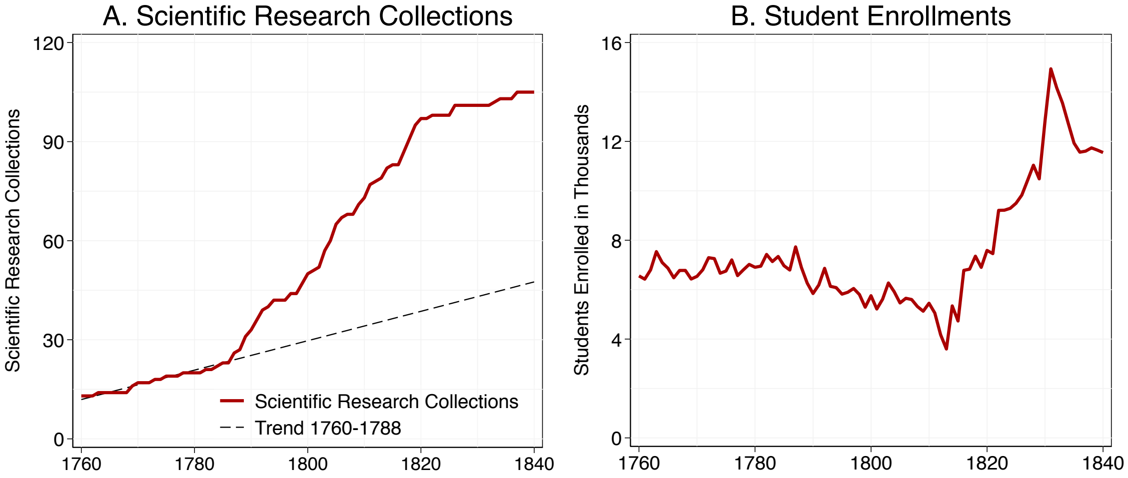
Selgert 2019; p. 61-3). Moser's (2005) study of patented and non-patented innovation examines evidence from the 1851 World's Fair and 1876 Centennial Exhibition, and is also situated in the mid-1800s.

[9] Scholars have for some time pointed to the potential underestimation of development pre-1850. Tilly (2001; p. 157) notes that, "the implications could be far-reaching: Germany's relative backwardness in the so-called 'take-off' period of industrialisation was quite likely significantly less."

[10] Acemoglu et al. (2011) find these reforms led to greater urbanization after 1850 in more affected Western regions. However, guilds were not eliminated in the leading industrial region of Saxony until the late 1800s.

Figure 2: Scientific Research Collections and Enrollments at Universities



Panel A plots the number of scientific research collections at German universities, measured by the number of: technological model, chemistry, physics, mineral, and zoology research collections; observatories; and botanical gardens. Panel B plots annual data on the number of students enrolled at German universities. Data on scientific collections at universities are from Weber et al. (2013), supplemented with evidence for Breslau from Nadbyl (1861). Data on university enrollments before 1830 are from Eulenburg (1904) except for Berlin, which is recorded in Lenz (1910). Data on enrollments from 1830 forwards are from Titze (1995).

(1810), indicating that these factors did not precipitate the process we study.[11] Panel B shows university enrollments increased with a lag, after 1820, suggesting that any university effects in the early 1800s were not principally driven by increases in student numbers.

The data on research collections reflect a shift in support for the sciences, which is also documented but less systematically recorded in other sources of evidence. For example, "massive state intervention" led to the establishment of "a veritable phalanx of…scientific institutions" at Jena in 1803 (Ziche 2001; p. 152 – our translation), but these institutions were only formally recognized by new university statutes in 1821. Similarly, in 1821 the parliament of Saxony granted the university of Leipzig an annual subsidy on condition that the university maintain transparent books, indicating how budget records in the early 1800s provide problematic evidence on research expenses. Surviving evidence on syllabi and courses in the early 1800s are also fragmentary. Partly for this reason, historians have focused heavily on tracing the development of formalized research seminars and institutes with dedicated budget lines, and the formation of separate scientific departments within the "philosophy"

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[11] Narrative evidence points to the importance of changes starting around 1800. As Böhme and Vierhaus (2002; p. 165 – our translation) observe, "the natural sciences in the middle of the 18th century did not yet have the professionalism, reputation, and scientific level that only began to develop fifty years later."

faculty, all of which begin to be more systematically recorded in the late 1820s (Titze 1995).

This pro-science shift in universities involved innovations we would expect to generate local spillovers into industrial activity. Local spillovers from universities are salient today (Audretsch and Feldman 2004; Kantor and Whalley 2014), and historical transport costs were far higher, especially before railroads, suggesting a potentially large role for spillovers. Research institutes were established to promote the development and commercialization of technology, and local economic activity, such as the Physical Mechanical Institute (1802) at Jena (Ziche 2001; p. 193). Professorships in scientific subjects that generated useful knowledge were created in philosophy departments, such at the chair in Chemistry at Jena (1789) and the applied science section in the Philosophy faculty at Heidelberg (1803) (Martin 2007; Hinz 1961). Biographical evidence points to the importance of inventions developed around universities and by university graduates, which we confirm quantitatively (Section 5). Narrative evidence also indicates that university graduates established manufacturing firms and that local mechanics attended universities as non-matriculated students after 1800.[12]

Political events shifted the supply of and demand for scientific knowledge in Germany, leading to concrete changes in universities. Palmer (2014) summarizes the German response to the French Revolution as a "revolution of the mind" (see also Blackbourn 2003). On the supply-side, the French Revolution inspired pro-science intellectuals in a massive cultural shift (Whaley 2012; p. 601).[13] On the demand side, the priorities of policy makers also shifted and increasingly science and technology were viewed as important for a broader project of modernization in the context of the shifting political environment. The Napoleonic invasion of Germany further promoted the modernization of university education, which was famously advocated by Prussian Interior Minister Wilhelm von Humboldt.

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[12] Professor Johann Heinrich Voigt (1751-1823) observed local mechanics attending his mathematics and physics lecture at Jena to learn the science behind their trade, and established a "physical-mechanical" institute in 1802 to: combine university teaching and the development of instruments; promote the commercialization of technologies; and help mechanics to set up laboratories (Ziche 2001; pp. 227-229). The career of Johann Beckmann (1739-1811), Professor at Goettingen and coiner of the word "technology", also provides evidence on spillovers between universities and business. Beckmann's university lectures drew merchants and craftsmen who already had acquired business training (Marino 1995; p. 359).

[13] For example, Kant wrote his *Critique of Judgment* (Kant 1987 [1790]; p. xxix) in a period in which the French Revolution "occupied him entirely," according to his friend Reinhold Jachmann. Following Kant's intervention, "the ideal of a rigorous science experienced a spectacular upsurge" (Van Bommel 2015; pp. 12-14). Conceptually, Karl Marx (1975 [1842]; p. 213) noted that Kant's work should be considered, "the German theory of the French Revolution." See also Marcuse (1960; pp. 3-4) on how major innovations in German philosophy and intellectual life developed, "largely as a response to the challenge from France."

It is important to note that other aspects of education shifted in the period we study. Prussia enacted a major reform of primary education in 1809 in response to military defeat in 1806 (Kindleberger 1975; p. 260) and schooling more generally expanded. In our quantitative analysis, we therefore introduce controls for time-varying territory-level factors, such as educational reforms, and gather evidence on all schools established in every city, from elementary through higher technical schools.[14] To preview, we find the effects of universities hold controlling for the territory-level factors and more local variation in the development of other types of schooling. In addition to schools, "economic societies" emerged to promote the development of knowledge (Cinnirella, Hornung, and Koschnick 2022), but such societies do not account for the effects of universities on manufacturing as we detail below.

2.3 The Locations of Universities

We use historical evidence to guide our quantitative analysis and address questions concerning the potentially endogenous location of universities. Guided by the history, we study variation in university exposure due to two types of universities: exogenous historic and potentially endogenous new universities.

The *historic universities* pre-date our study period and are exogenous to the economic process we study. Historic universities in Germany were "generally located in small towns" at locations that were "already too fixed to be manipulated by the new states" in the 1800s (Segal 2018; p. 57).[15] Local rulers founded historic universities in the pre-industrial era to produce non-scientific human capital and knowledge, including bureaucrats, and for prestige. These universities developed town-specific reputations in provincial cities which helped fix their locations (Rüegg 2004b). There are 15 historic universities in our data.

Three *new universities* were established as a result of military events, but were still potentially endogenous. The university at Berlin (1809) was founded by Prussian authorities to offset the loss in 1807 of the university at Halle due to military defeat (McClelland 2008; p. 50); the university of Bonn (1818) was founded to offset the closure of the nearby university at Cologne in 1794 during the French occupation; the university of Ingolstadt was transferred

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[14] As discussed below, we also consider the role of technical "higher schools" (*Technische Hochschulen*), which were established decades into the process we study and, as a rule, in capital and not university cities (e.g. Karlsruhe in 1825, Darmstadt 1826, Munich 1827, Dresden 1828, Stuttgart 1829, and Hannover 1831).

[15] The university of Leipzig was exceptional in being in an important city in our study area.

to Landshut in 1800 after the French invasion, and to Munich in 1825.[16]

A number of universities were closed in our study period, as a result of the political shocks emanating from France, which also changed the geography of higher education. Historical research indicates that the closure of universities reflected political factors that were independent of the strength or quality of the universities (Rüegg 2004b; Turner 1987). We test and confirm that there were no significant differences in *ex ante* enrollment growth for the universities that were closed or remained open after the French Revolution (Appendix B)

Our baseline quantitative analysis shows that cities nearer to universities had no advantages, and no differences in trends, in manufacturing, invention, or urban construction before the shock of the French Revolution. To address questions about potentially endogenous locations, we show that the university effect holds when we study only the exogenous variation in university exposure due to historic universities. Our results thus are not driven by changes in university locations.

3 Data

3.1 Manufacturing

We gather information on manufacturing activity from the *Deutsches Städtebuch* (Keyser 1939-1974), an encyclopedia of German cities. The *Städtebuch* entries describe the economic development of cities, including the history of manufacturing activities and establishments. We code, date, and classify all manufacturing activities with two-digit SIC codes. The underlying observation in our data is a manufacturing "event": the opening or presence of an establishment or a specific type of manufacturing in a city-year. For example, in 1801 the *Städtebuch* records: a printing establishment (*Buchdruckerei*) in Schwabach; a machine factory (*Machinenfabrik*) in Mannheim; a wire factory (*Drahtfabrik*) in Allersberg; a paper mill (*Papiermühle*) in Hoehr-Grenzhausen; a tobacco manufacture (*Tabakfabrikation*) in Vierraden; and a textile weaving establishment (*Tuchweberei*) in Euskirchen.

Several aspects of the data are important to clarify. First, our data record the opening and in some cases presence of establishments. Second, our measure of events is a *proxy* for changes

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[16] Before the Napoleonic wars, Prussia's principle university was in Halle. The Treaty of Tilsit (1807) stripped Prussia of half its territory, including Halle, depriving it of its university (Dieterici 1836; p. 60). Bonn is 34 kilometers from Cologne. This change generated limited local shifts in exposure to a university.

in manufacturing. Third, the dating of some observations in the *Deutsches Städtebuch* is approximate, but this does not vary with proximity to universities in general or in our post period.[17] We aggregate to twenty-year periods and focus on the shifting relationship between manufacturing and proximity to universities conditional on the variation shared by all cities in a given period. Fourth, the data cover 2,254 settlements that received formal city rights. The "cities" we study thus range from very small towns to major urban centers.

Several analyses indicate that measurement error cannot plausibly account for our findings. The principal measurement concern would be that more complete records of industrial activity were kept for cities near universities after 1800, following the pro-science shift. To assess the quality of our data in this period, we test how well our measure of manufacturing explains the number of factories and workers at the two-digit industrial classification level in the first large body of administrative data, the Prussian Census of 1849 (Becker et al. 2014). Our measure of changes in manufacturing, observed over the earlier 1800s, predicts county-level industrial activity recorded in Census data in the 1840s. Indeed, we estimate elasticities close to one in almost every industry (see Appendix A). We also corroborate the pre-1800 evidence by examining evidence on historic city construction, which can be accurately dated, and find no differences in levels or trends between cities near to and far from universities over multiple centuries before the 1800s (Section 4.2).

3.2 Scientific and Technological Discovery

We construct data on scientific and technological discoveries building on Darmstaedter, du Bois-Reymond, and Schaefer's (1908) *Handbuch zur Geschichte der Naturwissenschaften und der Technik*, which catalogues major inventions and discoveries in our period. Darmstaedter's project was produced by 60+ contributors, including four Nobel Laureates. The handbook records inventions, pure science break-throughs, early technology prototypes, and the adoption or installation of commercially viable technologies.[18] The handbook describes and dates each contribution and identifies the scientists or inventors responsible.

We build our database as follows. First, we match discoveries to city locations and

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[17] Some establishments are recorded as opening "around" a given year or with even more roughly defined dates, such as "in the 19th century". We exclude the latter observations from our baseline analysis.

[18] In terms of the lexicon suggested by Joseph Schumpeter, our data include invention and innovation observations, and observations where the invention-innovation distinction is ambiguous (c.f. Rosenberg 1976).

gather information on the educational background of each scientist and inventor. To do this, we construct biographical evidence on the lives, employment, and educations of scientists and inventors from the *Deutsche Biographie*, the *World Biographical Information System*, and historical sources. Second, we distinguish between scientific discoveries and practical inventions, most of which have industrial applications. We classify the practical inventions in our data with SIC codes for the industries in which they could be used or applied. Our database comprises 1,937 major discoveries in the 2,254 cities we study 1760-1899.[19]

The variation in the education and location of individual knowledge producers in the data motivates our quantitative analysis, which tests whether invention shifted towards universities and examine how manufacturing developed in sectors more or less reliant on inventions by university-educated inventors. Examples of observations in our data are as follows. In 1801, chemist Franz Karl Achard develops inventions for beet sugar production (SIC food) in Berlin and establishes a factory in Silesia. In 1807, university-educated chemist Christian Friedrich Bucholz develops sulfur milk (SIC chemicals) at Erfurt. In 1811, Friedrich Krupp develops processes for steel and cast iron production (SIC primary metals) at Essen and he founds Krupp steel company. In 1820, the university-educated chemist and inventor Ernst August Geitner develops chromium-acid based dyes (SIC textiles) at Schneeberg, where he sets up a chemicals factory. Appendix Tables A2 and A5 provide details on the data.

The data have advantages and limitations. They provide unparalleled evidence on practical invention and basic science and cover time periods for which no consistent German patent data exist. The data can be used, as the authors of the handbook indicate, to study the development of science and technology, including "their condition in. . . changing political conditions" (Darmstaedter and du Bois-Reymond 1904; p. II – our translation). By construction, the data record major discoveries that can be attributed to individuals.

3.3 Additional Sources

We gather additional data as follows. Data on the location of universities are from Rüegg (2004a;b). We collect information on all schools opened in the cities we study, coding evidence from Keyser (1939-1974). We construct evidence on territory-level free enterprise

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[19] We focus analysis on discoveries for which location is unambiguous. Our findings are robust to flexibly incorporating observations where there is ambiguity over locations.

laws following Acemoglu et al. (2011), data on railroad connections from Kunz and Zipf (2008), and data on coal deposits from Asch (2005). We gather information on the adoption of mechanized production technologies from Forberger (1982) and on exhibits and prizes at the Crystal Palace World's Fair as described below. For details on all data see Appendix A.

4 Universities and Manufacturing

4.1 Stylized Facts

Table 1 summarizes the key stylized facts in our analysis. The primary fact is that cities near universities had no advantage in new manufacturing before 1800 and that new manufacturing increased and shifted towards universities after 1800 (columns 1 and 2).

Table 1: Universities and the Development of New Manufacturing

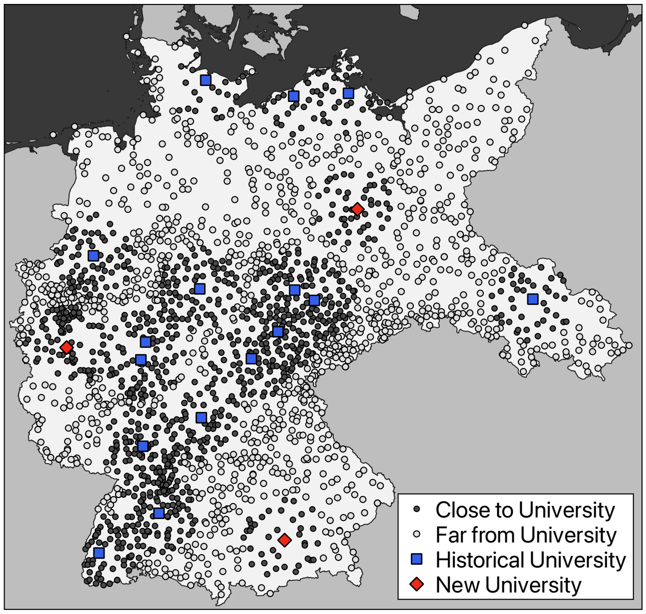
	(1)	(2)	(3)	(4)
	Data on All Cities All the Variation in Exposure		Cities Exposed to Historic Universities Predetermined Exposure	
Period	In Cities Close to University	In Cities Far from University	In Cities Close to University	In Cities Far from University
1760-1799	159	208	122	149
1800-1859	1,407	1,008	1,053	634
1860-1899	798	694	581	491

This table reports the number of new manufacturing events in cities recorded in the *Deutsches Städtebuch* (Keyser 1939-1974). Cities "close" to and "far" from to a university defined as below or above median distance. Columns 1 and 2 examine all 2,254 cities and define "close" and "far" using distance to a university in the 1800s. Columns 3 and 4 restrict to 1,686 cities with predetermined (unchanging) exposure due to historical universities, which were thus either close or far in both the 1700s and 1800s (see Appendix A).

This pattern is not explained by endogenous university locations. When we examine cities with predetermined and unchanging exposure to *historical* universities, we find a similar increase in manufacturing around universities after 1800 (columns 3 and 4). The university effect thus holds for cities in areas untouched by university openings or closures. This indicates the importance of the pro-science changes in historical universities.

The differential shift in new manufacturing towards universities is particularly pronounced in the period between 1800 and 1859. This core period begins with major shocks to politics and universities and closes when the costs of transportation fell significantly due to the development of railroads (Fremdling and Hohorst 1979; Wrigley 1961). The growth advantage of cities near universities declines after 1860. To be clear, the manufacturing events we study proxy for *growth* in manufacturing activity. Cumulatively, the events we

Figure 3: University and City Locations



Map shows 2,254 cities recorded in the *Deutsches Städtebuch* (Keyser 1939-1974). Cities "close to" and "far from" a university are below or above median distance to a university in the 1800s. "Historical University" indicates predetermined universities. The "New University" locations are Bonn, Berlin, and Munich.

observe over the first half of the 1800s predict the stock of factories and the number of workers recorded by the 1849 Prussian Census at the county-by-industry level, with almost unit elasticities, as we show in Appendix A.

Figure 3 maps the comparison between towns "close to" and "far from" universities in the 1800s. This comparison invites questions about: (1) pre-trends, (2) confounding factors, and (3) flexible measures of geographic spillovers. We address these questions and document the robustness of the stylized facts in our quantitative analysis.

4.2 Quantitative Analysis

A. Research Designs. To test our first hypothesis, that manufacturing increased differentially around universities after 1800, we estimate regression models of the form:

$$manufacturing_{it} = \sum_{s} \beta_s (university_i \times time_s) + \theta_i + \delta_t + \epsilon_{it} \qquad (1)$$

The outcomes we study are the number of manufacturing events in a city-time-period, with time measured in twenty year periods, and an indicator for any manufacturing, which captures the extensive margin of economic activity. The treatment variable $university_i$ is a time-invariant indicator for cities close to universities, defined as below median distance, which is approximately 60 kilometers. The θ_i and δ_t are city and time fixed effects.

We first document the shift in manufacturing towards universities after 1800, and show this shift is not driven by pre-trends, in Subsection B. We rule out the possibility that endogenous university locations drive our finding in Subsection C. We test and show that our results hold within regions and within territory-×-time cells, which absorb regional institutional variation, in Subsection D. We show the university effect holds controlling for potential within-region, city-level confounders, such as prior manufacturing and differences in schooling in Subsection E. To test the mechanism, we show that the university effect is driven by larger universities in Subsection F. We confirm the relationship between manufacturing and proximity to universities using linear and flexible measures of distance in Subsection G.

B. Baseline Analysis. Figure 4 presents baseline estimates of the shift in manufacturing towards universities after 1800. We study shifts over two longer periods suggested by historical research, 1800-1859 and 1860-1899, indicated by shaded boxes. To clarify the underlying variation, we also report flexible period-by-period estimates. We focus on shifts in manufacturing around universities active in the 1800s (Panel A).

We find that the number of manufacturing events and the probability of any manufacturing increased differentially in cities nearer to universities after 1800, consistent with our hypothesis. We confirm that the growth advantage of cities near universities declines after 1860, as discussed above.

There was no trend in manufacturing towards universities before 1800, as our flexible model estimates show. If anything, there was a slight pre-trend away from universities. We further test for and find no evidence of differential pre-trends in urban construction, which is a core indicator of longer-run pre-industrial development, as shown in Subsection H below.

We take steps to ensure that inference is not biased by spatial autocorrelation. We estimate standard errors allowing for arbitrary forms of spatial correlation following Conley (1999). Our core results are not contingent on the distance over which we allow for spatial autocorrelation (see Appendix C for details).[20] Below we also introduce a rich set of control

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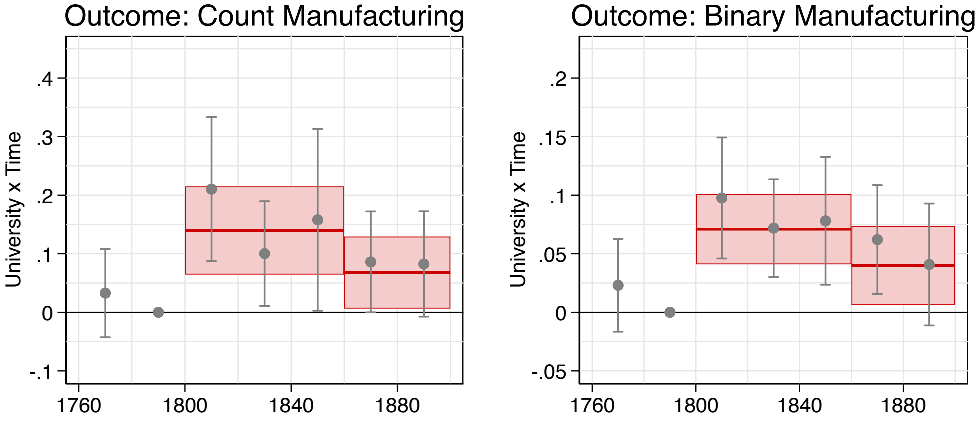
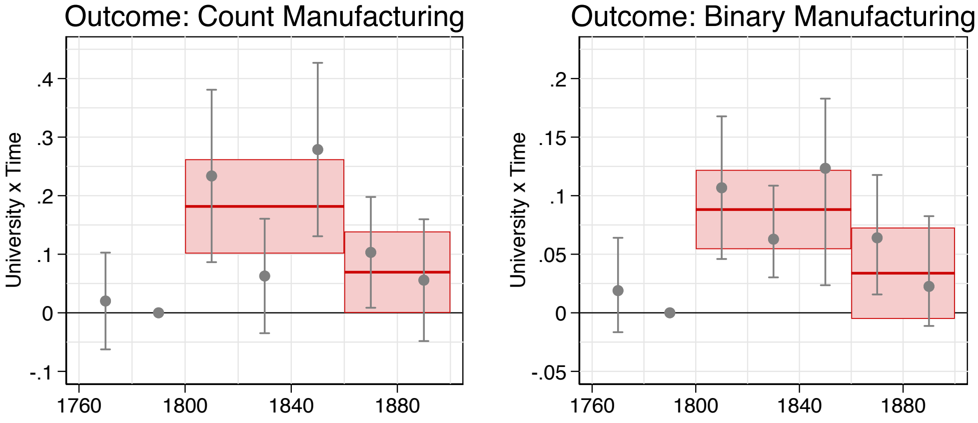
[20] Inference also holds accounting for potential serial correlation following Bertrand, Duflo, and Mullainathan (2004) and is not driven by spatial noise, as we show in Appendix C.

Figure 4: Universities and New Manufacturing

A. All Cities



B. Cities with Pre-Determined Exposure Due to Historic Universities



This figure presents regression estimates in which the outcomes are the count of manufacturing events (mean 0.27) and an indicator for any manufacturing events in a city-period (mean 0.17). The treatment variables are interactions between an indicator for cities close to universities in the 1800s and time period indicators. The university exposure indicator ("University") is 1 for cities below median distance to a university in the 1800s. Panel A examines all cities (n=2,254). Panel B restricts analysis to cities whose university exposure did not change between the late 1700s and the 1800s (n=1,686). Each graph reports estimates from two regressions. The first regression estimates the response of manufacturing to universities in two post periods: 1800-1859 and 1860-1899, relative to the reference period 1760-1799. These estimates and 95% confidence intervals are represented by shaded boxes. The second regression estimates a flexible model in which "University" is interacted with time period indicators, with 1780-1799 the reference period. All models include city and time fixed effects. Standard errors and 95% confidence intervals estimated following Conley (1999) allow for arbitrary spatial correlation within 25 km (see Appendix C for estimates examining a range of distances).

variables that vary across space and time and absorb underlying spatial correlation.

C. Ruling Out the Endogenous Selection of University Locations. It is natural to wonder whether changes in university locations in the early 1800s were endogenous and could explain why manufacturing clustered around universities after 1800.

To test whether endogenous university locations could explain our results, we restrict the analysis to cities exposed to fixed *historic* universities, whose predetermined locations were not endogenous to the industrial processes we study. We find that the university effect holds and is in fact slightly *stronger* for cities that were not exposed to potentially endogenous changes in university locations. Our findings are thus not driven by the opening of universities at Berlin and Munich or by the closure of other universities. This result also highlights the broad-based nature of the economic process we study. We confirm that new universities were associated with no differential shifts in manufacturing in Appendix B.

We further find that the estimated university effect is similar but slightly weaker when we study exposure to historic university locations as of the 1780s as in an intent-to-treat analysis. Our estimates here are significant, but slightly smaller in magnitude, reflecting dilution due to the "non-compliance" caused by university closures and openings (see Appendix B).[21]

D. Time-Varying Regional Factors. A second natural question is whether time-varying regional factors could be confounders that explain the university effect.

The literature emphasizes several regional development factors. First, regional variation in institutional change shaped industrialization. Acemoglu et al. (2011) document that legal changes instituted during the Napoleonic occupation of Western regions of Germany led to greater urbanization in these regions after 1850. More generally, historians suggest that German industrialization was shaped by "regionally varying, gradual institutional evolution," including schooling reforms (Tilly and Kopsidis 2020; p. 11). Second, trade shocks arising in the aftermath of the French Revolution varied regionally. Juhász (2018) finds that the Napoleonic blockade of England generated a differential increase in import protection to the French cotton spinning industry in regions nearer to England, raising the possibility of similar patterns in Germany. Third, religion and basic human capital varied regionally. Literacy was higher in Protestant regions of Germany and strongly predicts industrial activity in the late 1800s (Becker and Woessmann 2009; Becker, Hornung, and Woessmann 2011).

We address questions about the role of time-varying regional factors by investigating the relationship between universities and manufacturing both within regions and within

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[21] When we study the predictive power of university locations as of the 1780s, we include universities that closed in the 1790s and early 1800s.

territory-×-time cells. Our regional analysis assesses whether university effects are observed in regions *not* treated by the legal changes Acemoglu et al. (2011) study and in Eastern regions far from England, which were the *least* exposed to increases in effective protection from British cotton. Our analysis studying university effects controlling for factors that vary at the territory-×-time level absorbs all the variation in economic institutions studied by Acemoglu et al. (2011), controls for shifting territory-level factors such as schooling reforms, and accounts for almost all the spatial variation in the trade shocks due to the Napoleonic blockade across the 44 German territories we study, and differences in religion. We address potential residual, within territory variation below (see Subsection D).

Table 2 presents our estimates. Panel A studies studies all cities and measures university exposure based on locations in the 1800s, while Panel B restricts analysis to cities whose university exposure did not change as a result of potentially endogenous shifts in locations. Columns 1-5 study the number of manufacturing events as an outcome. Column 1 presents estimates which replicate Figure 4. Column 2 shows that in Eastern Prussia we find a somewhat larger effect in an area not treated by Napoleonic institutional reforms and not treated with large increases in protection due to the blockade.[22] Column 3 studies cities in Western Prussia, where Napoleonic institutional changes were concentrated and several universities were closed in the Napoleonic era. Here we find a slightly weaker and imprecisely estimated university effect studying the number of manufacturing events. Outside Prussia we find a significant but quantitatively somewhat smaller estimate, as shown in column 4.

The positive university effect after 1800 remains statistically and economically significant when we control for factors that vary over time at the territory-level (column 5). We study the relationship between universities and manufacturing *within* territory-×-time cells, locating cities in 44 territories comprising the German Confederation as of 1815, which we consider as time invariant regional identifiers. To clarify, for the Principality of Brunswick, our analysis compares the evolution of manufacturing in 9 towns close to and 9 far from a university, conditional on the variation shared by all cities in Brunswick in a period. In the Province of Saxony, we compare 91 towns close to and 63 far from a university. Details on the within-

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[22] We provide further evidence against the trade shock hypothesis below, showing that while the protection effects of the Napoleonic blockade were specific to cotton spinning (Juhász 2018), the university effect on German industry was highly significant in industries other than textiles. In addition, the expansion in German cotton spinning during the Napoleonic blockade was concentrated *far* from England in Saxony.

Table 2: Universities and Manufacturing by Region

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Variation Studied					Variation Studied				
	All Germany	Eastern Prussia	Western Prussia	Outside Prussia	Within Territory × Period	All Germany	Eastern Prussia	Western Prussia	Outside Prussia	Within Territory × Period
A: All Cities										
	Outcome: Count Manufacturing					Outcome: Binary Manufacturing				
University × 1800-1859	0.14***	0.19**	0.16	0.11***	0.07**	0.07***	0.10***	0.11***	0.04**	0.04***
	(0.04)	(0.08)	(0.11)	(0.04)	(0.03)	(0.02)	(0.03)	(0.04)	(0.02)	(0.01)
University × 1860-1899	0.07**	0.19***	0.02	0.02	0.04	0.04**	0.11***	0.03	-0.00	0.01
	(0.03)	(0.06)	(0.08)	(0.04)	(0.03)	(0.02)	(0.03)	(0.04)	(0.02)	(0.02)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Terrritory × Time FE	No	No	No	No	Yes	No	No	No	No	Yes
Observations	15778	3717	2408	9653	15778	15778	3717	2408	9653	15778
Mean	0.27	0.23	0.43	0.25	0.27	0.17	0.14	0.24	0.16	0.17
B: Cities With Predetermined Exposure Due to Historic Universities										
	Outcome: Count Manufacturing					Outcome: Binary Manufacturing				
University × 1800-1859	0.18***	0.30***	0.16	0.11**	0.10**	0.09***	0.14***	0.13**	0.05**	0.06***
	(0.04)	(0.10)	(0.13)	(0.05)	(0.04)	(0.02)	(0.04)	(0.05)	(0.02)	(0.02)
University × 1860-1899	0.07*	0.30***	-0.13	-0.01	0.03	0.03*	0.16***	-0.07	-0.02	-0.01
	(0.04)	(0.08)	(0.13)	(0.04)	(0.04)	(0.02)	(0.04)	(0.06)	(0.03)	(0.02)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Terrritory × Time FE	No	No	No	No	Yes	No	No	No	No	Yes
Observations	11648	2779	1323	7546	11648	11648	2779	1323	7546	11648
Mean	0.26	0.21	0.43	0.26	0.26	0.16	0.14	0.25	0.16	0.16

This table reports regression estimates in which the outcome is the count of manufacturing events (columns 1-5) or a binary indicator for manufacturing events (columns 6-10) at the town-×-time-period level. The unit of observation is a town-period: 2254 towns examined in 20-year time periods, 1760 to 1899. "University × 1800-1859" and "University × 1860-1899" interact an indicator for towns close to a university with indicators the 1800-1859 and 1860-1899 periods, respectively. In Panel A, "University" is defined as below median distance to universities operating in the 1800s. Panel B restricts to cities with no change in "University" from the 1700s through the 1800s. All regressions include city fixed effects. The "Territory × Time" fixed effects in column 6 interact indicators for 44 territories, defined as of 1815, with time period indicators. Columns 2-5 examine subsets of the data relative to the set of towns in Prussia as of 1849. Standard errors allow for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

territory variation are provided in Appendix A. The comparisons in column 5 thus control for changes in territory-level legal regimes, educational reforms, and trade shocks.

Our findings are somewhat stronger when we study the extensive margin of manufacturing (Panel A, columns 6-10). We find that universities are systematically associated with a higher probability of their being manufacturing events in a city-period. This positive effect is statistically significant in all regions and concentrated in the 1800-1859 period.

These findings are not driven by the endogenous selection of new university locations. Our estimates for the 1800-1859 period are larger when we restrict analysis to cities for which "university treatment" did not change over our period (Panel B). We confirm that new universities did not lead to differential increases in manufacturing in Appendix B.

E. Factors Varying Within Regions and Over Time. Given that the university effect is not explained by time-varying regional factors, it is important consider other factors that vary within regions and over time. Prior research emphasizes four factors with the potential to be locally-varying confounders. First, the prior development of proto-industrial *early manufacturing* varied across cities and potentially influenced the development of manufacturing in the 1800s (Kopsidis and Bromley 2016; Kreidte, Medick, and Schlumbohm 1977). Second, *railroads* promoted manufacturing in ways that varied locally (Fremdling 1977; see also Hornung 2014). Third, proximity to *coal* deposits became a factor for industrial activity in Germany, particularly after 1840 as coal-using technology diffused (Wrigley 1961). Fourth, *schooling* was a potential factor in local development (Lundgreen 1975).[23]

We account for and study these factors as follows. *(1) Early manufacturing*: we gather data on city-level manufacturing before 1760 from the *Städtebuch* and test whether cities with such early manufacturing enjoyed an increase in growth after 1800. *(2) Railroads*: we measure and control for railroad connections period-by-period with a binary variable for cities on railway lines. *(3) Coal*: we classify cities close to or far from coal deposits, measured as above or below median distance, and test whether cities close to coal enjoyed developmental advantages after 1800 or after 1840. *(4) Schooling*: we construct a measure of local schooling by coding information on all schools in the cities we study, period-by-period, but focus on the role of "higher schools," which provided advanced training outside the

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[23] The diffusion of knowledge was also promoted by "economic societies," which were set up in some cities (Cinnirella, Hornung, and Koschnick 2022). However, the university effects we estimate hold controlling for economic societies, which were not themselves correlated with shifts in manufacturing. See Appendix B.

university system. Higher schools include *Gymnasia*, *Gewerbeschulen* (technical schools), *Lyzeen* (Lyceum), and *Realschulen*.[24] We focus on higher schools because they were unique in having a strong relationship with manufacturing over the first half of the 1800s. To clarify and preview, we find that the establishment of elementary, middle, and continuing education schools have little explanatory power for the development of manufacturing until the late 1800s and are not confounders in our analysis.[25] We provide details in Appendix **??**.

To clarify our findings relative to the literature, we also consider the role of territory-level "free enterprise" (*Gewerbefreiheit*) laws, which spread in a staggered manner across the territories of the German Confederation, and shaped urbanization after 1850 (Acemoglu et al. 2011). The effects of these institutions can be estimated when we study variation *across* territories, but are absorbed in analyses with territory-×-time fixed effects. No significant institutional changes that varied within territories over the post-1800 period were systematically related to distance to universities, to the best of our knowledge.[26]

Table 3 presents our estimates. The estimated post-1800 effects of universities hold virtually unchanged when we account for differences in early manufacturing, proximity to coal, exposure to free enterprise laws, railroad connections, and the presence of higher schools (Table 3 column 1 compares to Table 2 column 1). The estimates on these factors are, however, significant and in several instances similar in magnitude to the university effect.

To examine the timing of the relationships shaping manufacturing more closely, we restrict our analysis to periods before 1840 (column 2). Over this period, before railways were developed, the impact of universities is almost unchanged, while the association between free enterprise laws and manufacturing declines and is only borderline statistically significant.[27] A history of early manufactures was strongly associated with manufacturing in this pre-railroad period, consistent with continuities in development operating alongside the university effect.

We extend our analysis to consider the timing of the relationship between higher schools and manufacturing (column 3). We introduce leads and lags for higher schools. We find

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[24] Our results are also robust to controlling for the presence *Technische Hochschulen*, which were established starting in the 1820s and evolved only in the late 1800s to became Germany's "technical universities."

[25] Prior research documents a positive relationship between elementary education, literacy, and manufacturing in late 1800s Germany (Becker, Hornung, and Woessmann 2011; Becker and Woessmann 2009). We find elementary and middle schools do explain manufacturing *after* the mid-1800s (Appendix **??**).

[26] The university effect is also observed in territories which had no "free enterprise" laws (Appendix D).

[27] We consider the period to 1839 to be the pre-railroad era. The first railway construction in Germany dates from the late 1830s. Our results are robust to restricting to years before any railroads were built.

Table 3: Universities and Other Factors Varying Within Regions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Count of Manufacturing Events						Outcome: Binary	
	In All Industries				Non-Textile	New	In All Industries	
	1760-1899	1760-1839	1760-1839	1760-1839	1760-1839	1760-1839	1760-1839	1760-1839
University × 1800-1859	0.14^{***}	0.13^{***}	0.13^{***}	0.07^{**}	0.06^{**}	0.06^{**}	0.07^{***}	0.05^{***}
	(0.04)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.01)	(0.01)
University × 1860-1899	0.06^{**}							
	(0.03)							
Free Enterprise Law	0.10^{***}	0.07^{*}	0.07^{*}				0.01	
	(0.03)	(0.04)	(0.04)				(0.01)	
Early Manufactures × Post-1800	0.15^{***}	0.20^{***}	0.20^{***}	0.18^{**}	0.14^{**}	0.09	0.04	0.03
	(0.05)	(0.07)	(0.07)	(0.07)	(0.06)	(0.06)	(0.02)	(0.02)
Coal × Post-1840	0.13^{***}							
	(0.05)							
Coal × Post-1800	-0.03	-0.02	-0.02	-0.08^{*}	-0.07^{*}	-0.08^{*}	0.03^{**}	-0.00
	(0.04)	(0.04)	(0.04)	(0.05)	(0.04)	(0.04)	(0.01)	(0.02)
Railroad Connection	0.24^{***}							
	(0.06)							
Higher School	0.18^{***}	0.20^{***}	0.11	0.11	0.06	0.09	0.05^{*}	0.04
	(0.04)	(0.07)	(0.09)	(0.09)	(0.08)	(0.08)	(0.03)	(0.03)
Higher School: Lead			0.14^{**}	0.13^{**}	0.12^{**}	0.12^{**}	0.05^{**}	0.05^{**}
			(0.07)	(0.07)	(0.06)	(0.06)	(0.02)	(0.02)
Higher School: Lag			0.09	0.09	0.10	0.09	0.02	0.02
			(0.10)	(0.10)	(0.08)	(0.09)	(0.04)	(0.04)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	No	No	No	Yes	No
Territory-×-Time FE	No	No	No	. Yes	Yes	Yes	No	Yes
Observations	15778	9016	9016	9016	9016	9016	9016	9016
Mean Outcome	0.27	0.19	0.19	0.19	0.13	0.17	0.12	0.12

This table reports regression estimates with variables defined as above. Columns 1-4 study all manufacturing measured in counts. Columns 5 and 6 study counts of manufacturing in non-textiles and new industries, respectively, with new industries defined as those industries in which a given city had no pre-1760 manufacturing. Columns 7-8 study a binary outcome for any manufacturing in all industries. "Railroad Connection" and "Free Enterprise Law" are indicators constructed from Kunz and Zipf (2008) and coded following Acemoglu et al. (2011), respectively. "Early Manufactures × Post-1800" interacts an indicator for post-1800 periods and an indicator for pre-1760 manufacturing activity. "Coal × Post-1840" and "Coal × Post-1800" interact an indicator for proximity to coal fields with time period indicators constructed from Asch (2005). "Higher School" is an indicator measuring the presence of secondary schools. Territory-×-Time fixed effects as in Table 2. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Conley (1999). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

that the university effect is stable and only *future* higher schools have a strong, statistically significant relationship with current manufacturing. This indicates that higher schools were established after manufacturing increased and the endogeneity of schooling. However, as territory-level educational reforms were passed starting in Prussia in 1809, it natural to question whether the university effect holds controlling for territory-by-time variation.

When we study the within-territory variation, the university effect remains highly significant and large relative to the mean, but declines in magnitude to 0.07 (column 4).

These findings indicate the importance of universities and the limited role of basic education in the process we study. Given that our research design controls for time-varying territory-level factors (such as educational reforms) and the establishment of city-level schools, for schooling to account for our results the quality of or returns to schooling would have to differentially increase near universities in the early 1800s. While unobserved shifts in school quality could theoretically provide a *channel* for the university effect, this is not a plausible explanation because reforms targeting the quality of education developed with substantial lags. Thus Prussia, which famously implemented early education reforms, required teacher certification starting 1810 and made final exams (*Abitur*) universal in 1812, but experienced a school construction boom between 1820 and 1835 (Meisenzahl 2015; p. 311), and phased reforms in over the 1820s and 1830s (Rang-Dudzik 1981).[28] The cohorts impacted by changes in schooling in Prussia emerged to influence invention and industry in decades after 1840. In our quantitative data, we find that elementary and middle schools do not explain manufacturing before the mid-1800s and do so afterwards. See Appendix **??**.

We next investigate the mechanisms driving our result. We first test and find the university effect is strongly present in non-textile industries, within-territory (column 5). This indicates that the spatial effects of the Napoleonic blockade, which Juhász (2018) finds were specific to the cotton industry, do not explain our findings.[29] We next test whether the university effect on manufacturing after 1800 was concentrated in "new" industries, defined as activities in two-digit SIC industries in which that city had no manufacturing before

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[28] For example, core provisions of the 1816 reform of Prussian grammar schools was not compulsory, and teachers were required to have passed science exams only starting in 1831 (Rang-Dudzik 1981; p. 219-21).

[29] Juhász (2018) effectively uses "distance to England" to estimate the impact of the Napoleonic blockade across French districts. Our *within*-territory analyses absorb almost all geographic variation. The university effect we find outside textiles further indicates that the blockade cannot plausibly explain our results.

1760.[30] When we study the development of new manufacturing industries, the post-1800 university effect remains almost unchanged. This implies that the university effect is almost entirely accounted for by new industries (compare column 6 with column 4). In contrast, the effect of "early manufacturing" on new industries is approximately half the size of the effect for all industries. Thus while universities and early manufacturing both explain patterns of change after 1800, in relative terms universities explain new activities more than old.

Finally, we study a binary measure recording whether there is any manufacturing in a city-time-period. We find that university exposure strongly predicts the presence of manufacturing after 1800 (columns 7 and 8), whereas early manufacturing is not a significant factor, indicating the importance of universities for the extensive margin of manufacturing activity. We again find that manufacturing precedes the establishment of higher schools.

Other historical features of cities do not account for the increase in manufacturing near universities post-1800. For example, we test whether the potentially time-varying implications of "free imperial city" status, location on trade routes, and city population sizes are confounders. We find they are not confounders and that the university effect is robust.[31]

F. Heterogeneity. Heterogeneity in the quality and influence of universities provides a test of the mechanism. The size of enrollments indicated the influence and quality of historic German universities (McClelland 2008). We therefore test whether the university effect after 1800 was greater near large universities. We re-estimate our model with two measures of treatment: being near a "large" or a "small" university. We measure size by enrollments 1800-1830 defining large as the top 7 and small the bottom 8.[32] We focus on cities whose nearest university was neither Berlin nor Munich, as these opened after 1810.

Figure 5 shows that manufacturing increased more after 1800 in cities close to large universities. Cities exposed to large universities experienced 0.16 more manufacturing events 1800-1859 than cities far from universities. In contrast, cities near smaller universities

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[30] For a city with no historical textile industry, activities in textiles are "new"; such activities are not new in cities with textiles before 1760. At the two digit SIC level, almost no industries are globally "new" in our period. We study the relationship between universities and technical change within textiles in Section 6.1.

[31] Consistent population data are not available for all cities. We therefore test whether population size is consequential conditional on being observed and/or when it crosses thresholds.

[32] Relative enrollments were generally stable, however Tübingen experienced outsized enrollment growth and established a scientific instrument collection in 1802 and chair in technology in 1818 (Decker-Hauff and Fichtner 1977; p. 116), suggesting enrollments in part proxy for "compliance" with the shift to science.

Figure 5: University Size and Shifts in Manufacturing

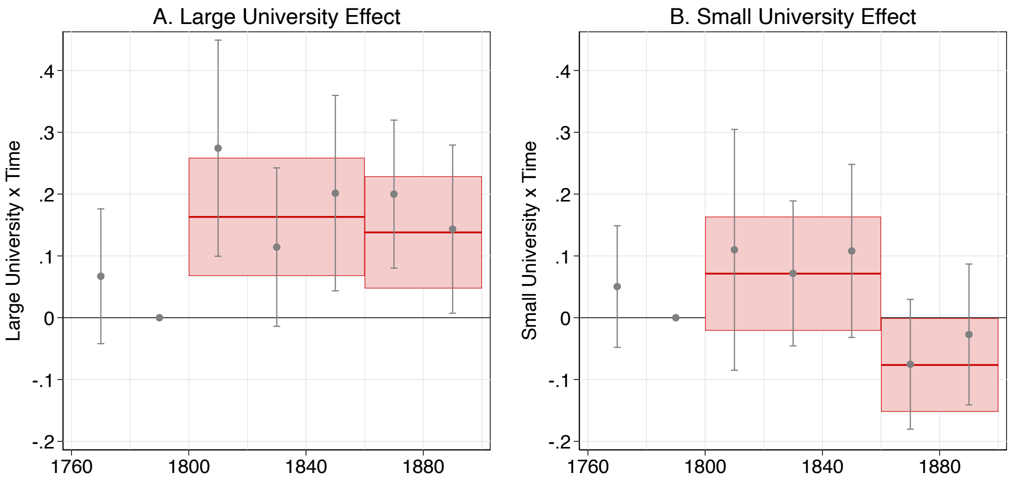

Figure presents regression estimates of spillovers from large and small universities. The baseline regression model is adjusted to include separate interactions between both (A) an indicator for cities near a "Large University" and time indicators and (B) cities near a "Small University" and time indicators. The reference period is 1760-1799 in the model with two post periods (boxes) and 1780-1799 in the flexible model (bars). Panel A plots large university estimates. Panel B plots small university estimates. This analysis restricts to 1,623 cities ($n = 11,361$) for which the nearest university was neither Berlin nor Munich, which opened in 1810 and 1826, respectively. "Large" designates the 7 largest universities (Göttingen, Halle, Heidelberg, Jena, Leipzig, Tübingen, and Würzburg) and "Small" the 8 smallest (Breslau, Erlangen, Freiburg, Giessen, Greifswald, Kiel, Marburg, and Rostock). Graph shows 95% confidence intervals estimated with standard errors allowing for arbitrary spatial correlation within 25 kilometers following Conley (1999).

experienced only 0.07 more manufacturing events and this effect is not statistically significant. For 1800-1859 the difference between the large and small university effects is significant at the 90% level. By the late 1800s, the difference is highly significant.[33]

While we find that high quality, larger universities differentially promoted manufacturing, the role of heterogeneity on other observable dimensions is more ambiguous. We find some limited advantage in scientific research collections and in invention for large universities after 1800, however these differences are relatively modest before the mid-1800s.[34] We also test for and find no evidence that effects of university exposure varied with the initial population size of the exposed cities, suggesting limited interactions with local demand-side factors.[35]

G. Flexible Estimates of the Role of Distance. Our baseline analysis comparing

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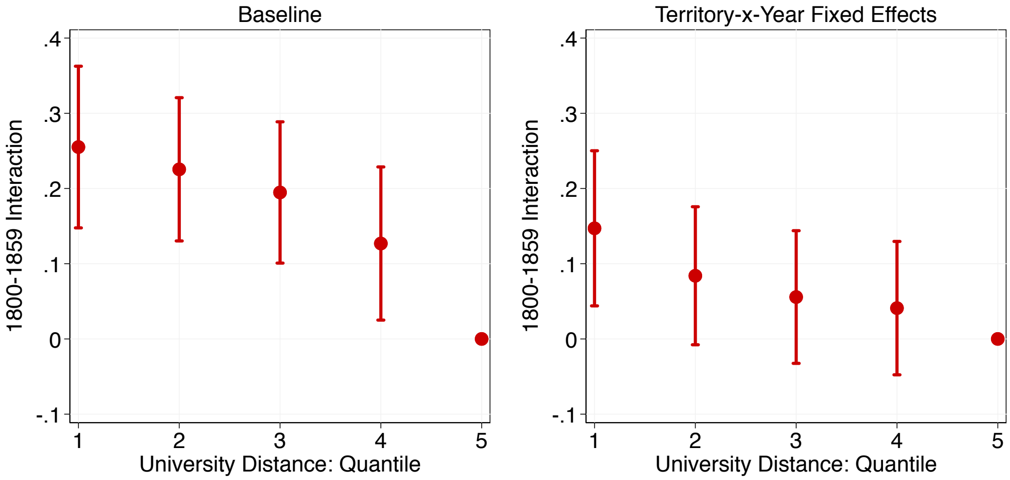
[33] Because our outcome measures *new* manufacturing, the differential positive (growth) effect observed near small universities 1800-1859 is offset by the differential negative (growth) effect 1860-99.

[34] In unreported results, we find these differences become statistically significant after 1850.

[35] While population data are not consistently observed for smaller cities, we are able to test whether the university effect shifts when population crosses various thresholds. We find no evidence of such shifts.

Figure 6: Distance to a University and Shifts in Manufacturing



Regression estimates in which the outcome is manufacturing events in a city-period. Figure plots estimates on interactions between an indicator for the period 1800-1859 and for a given city's distance quintile (1 closest, 5 farthest). Left panel corresponds to Table 2, Panel A column 1 (baseline estimate: 0.14). Right panel corresponds to Table 2, Panel A column 5 (fixed effects estimate: 0.07). Estimates include interactions between indicators for distance quantiles and the 1860-1899 period and city fixed effects. Left panel includes year effects. Conley (1999) standard errors allow for arbitrary spatial correlation within 25 kilometers.

cities close to and far from a university enables us to directly compare the "university effect" to that of other factors. However, it is natural to question how spillovers varied with distance more flexibly or reflected exposure to universities more generally.

We first extend our analysis to examine how manufacturing shifted after 1800 for cities in different quantiles of distance distribution. Figure 6 presents estimates on the interactions between an indicator for the 1800-1859 period and indicators for distance quintiles. Panel A corresponds to our baseline model (Table 2, column 1) and shows the post-1800 shift in manufacturing declined in distance.[36] We observe a similar, but muted pattern when we study effects within territories (Panel B corresponds to Table 2, column 5). This evidence indicates that the "close" and "far" heuristic reflects an underlying spatial gradient.

In fact, analysis of the relationship between manufacturing and linear distance to a university in kilometers supports our baseline estimates. We find a 60 kilometer reduction in distance, equal to median distance, is associated with a 0.13 increase in the count of manufacturing events 1800-1859, which is similar to Figure 4 (Panel A). See Appendix B.

It is natural to question whether manufacturing responded to distant universities and

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[36] Mean distance to a university for quantiles 1, 2, 3, 4, and 5 are: 23, 45, 62, 82 and 132 km, respectively.

Table 4: Test for Pre-Trends in Urban Construction

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Urban Construction Projects							
	1400-1799		1500-1799		1600-1799		1700-1799	
University × Trend	-0.002	-0.002	0.004	0.004	-0.011	-0.011	0.018	0.018
	(0.007)	(0.006)	(0.011)	(0.009)	(0.022)	(0.018)	(0.078)	(0.049)
University	0.012		0.009		0.007		0.021	
	(0.013)		(0.014)		(0.014)		(0.042)	
Observations	44820	44820	33615	33615	22410	22410	11205	11205
Mean Outcome	0.286	0.286	0.317	0.317	0.356	0.356	0.411	0.411
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City Fixed Effects	No	Yes	No	Yes	No	Yes	No	Yes

This table reports regression estimates examining the number of major construction events in a city-period of 20 years. "University" is an indicator for cities below median distance to a university in the 1800s and "Trend" is a linear time trend measured in 100-year units. Construction data are from Cantoni, Dittmar, and Yuchtman (2018) and Keyser (1939-1974). Headers indicate the time frame studied. Standard errors estimated allowing for arbitrary spatial correlation within 25 kilometers following Conley (1999).

more global measures of exposure. We find our estimate holds conditional on distance weighted exposure to all universities and that measures of overall exposure have no relationship to industrial activity conditional on our near university effect (Appendix B).[37]

H. Testing for Pre-Trends in Pre-Industrial Development. While our analysis shows that cities near universities enjoyed no positive pre-trends in industrial activity, Cantoni and Yuchtman (2014; p. 848) find new universities promoted market institutions over the "narrow window" between 1386 and 1406. This raises the question of whether universities were associated with trends in pre-industrial outcomes over longer time horizons. City construction is a core indicator of pre-industrial development and rich data on major projects are observed across cities in our data over long time horizons (Cantoni, Dittmar, and Yuchtman 2018). We therefore test whether cities near universities enjoyed any differential pre-trend in construction in a fixed effects regression model. Table 4 shows universities were associated with no significant differences in prior trends or levels of construction over the four centuries before 1800.

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[37] We also find that cities close to more than one university had no significant manufacturing advantage after 1800 over cities near just one. Results hold considering universities close to but outside our study area.

5 High and Low Knowledge Manufacturing

Theory and history motivate our second testable hypothesis: that the economic shifts towards universities were most pronounced in knowledge intensive industries.

To test this hypothesis, we study the relationship between universities and knowledge intensive manufacturing. We measure industries as more or less knowledge intensive using our data on discovery. We classify all practical inventions in our data on discoveries by (1) the industry using the invention and (2) whether or not the inventor was university educated.[38] We define "high knowledge" industries as those in which university educated inventors account for 50% of inventions 1760-1860.[39]

We extend our baseline analysis to study how universities were associated with shifts in manufacturing in higher and lower knowledge industries. We examine three manufacturing outcomes: high knowledge manufacturing; low knowledge manufacturing; and net high knowledge manufacturing, defined as the difference between high and low knowledge manufacturing. We also directly test whether practical inventions with industrial applications shifted spatially towards cities near universities in our panel data after 1800.

Figure 7 presents our findings on the relationship between universities and knowledge intensive manufacturing. Panel I shows that universities were associated with significant increases in manufacturing in high knowledge industries after 1800 (graph A). We observe smaller positive shifts in low knowledge manufacturing that decay over time (graph B). We also find that university exposure positively predicts the difference or wedge in the expansion of high and low knowledge manufacturing after 1800 (graph C). We observe no pre-trends in high knowledge manufacturing towards universities before the post-1800 shifts.

Panel II clarifies the underlying pattern of invention. Our regression estimates document that cities near universities had no advantages in practical invention before 1800 and that invention shifted significantly towards universities after 1800 (Graph D). This connects back to the motivation for our study, our finding that a broad measure of science and discovery expanded near universities after 1800 (Figure 1). We now formally confirm that universities

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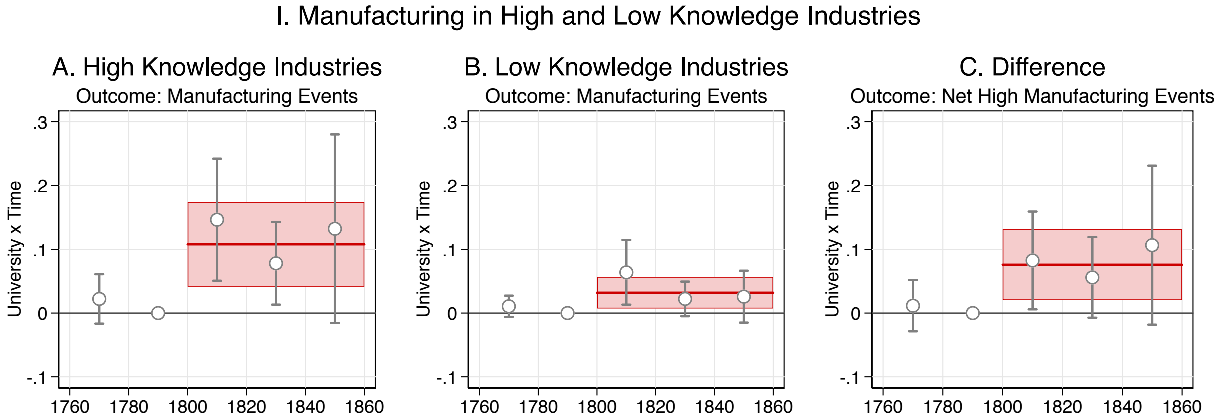
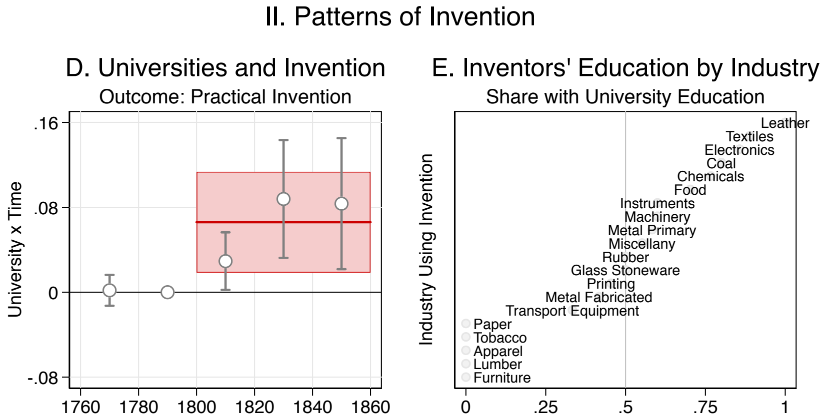
[38] We distinguish inventions, with industrial applications, from pure scientific discoveries (see Section 3).

[39] Practical inventions and manufacturing activities are classified at the two-digit SIC level. Inventions are classified by the industry using them. Thus chemical dyes are classified as used in the textile industry. See Section 3. Our findings below are robust to alternate categorizations of "high" and "low" knowledge industries, including when we classify all industries with university-educated inventors as high knowledge.

Figure 7: Universities and the Knowledge Intensity of Manufacturing


I. Manufacturing in High and Low Knowledge Industries


II. Patterns of Invention

Panel I presents regression estimates examining manufacturing 1760-1859. The outcomes are counts of manufacturing events in city-periods: (A) in "High Knowledge" industries; (B) in "Low Knowledge" industries; and (C) net high knowledge manufacturing. Each graph presents estimates from two regressions. The first estimates the relationship between manufacturing and interactions between university exposure and time fixed effects, relative to the 1780-1799 reference period. The second estimates the relationship between manufacturing and an interaction between university exposure and an indicator for the post-1800 period. University exposure is measured with an indicator for cities close to universities in the 1800s. Graphs present 95% confidence intervals estimated using standard errors allow for spatial correlation over 25 km following Conley (1999). Panel II presents evidence on practical invention 1760-1859. Graph D presents regression estimates of the relationship between practical invention and university exposure. The outcome is the number of practical inventions in a city-period. The estimating models and confidence intervals are as in Panel I. Graph E shows the variation across industries in the share of inventions made by university educated inventors, which is used to classify industries as high or low knowledge in the analyses in Panel I.

were associated with a differential expansion of economically useful knowledge in the early 1800s. Graph E shows the variation across industries in the share of inventions by university educated inventors, which we use to classify industries as "high" or "low" knowledge.

To interpret the estimates in Figure 7 several observations are important. First, the differential shift towards universities in high knowledge manufacturing may reflect supply and demand side dynamics. In particular, the shifts in manufacturing that we observe are likely to reflect how universities and university-educated inventors were differentially able to respond to economic incentives after the shocks of the late 1700s. Indeed, the inventions we study and use to classify industries are themselves, in part, endogenous outcomes in this larger post-shock context. Here the causal process that we study has parallels with the economic role of universities in the United States. Rosenberg (2000) observes that the political shock of WWII promoted science and technology in US universities and thus made it possible for universities to respond to demand in new ways as conduits for induced technological change. In Germany, political shocks similarly promoted science in the universities in the early 1800s, thereby enabling universities to respond to demand in new ways.[40]

Second, our measure of knowledge intensity based on the pattern of invention may proxy for a broader set of knowledge-related spillovers from universities. Historical evidence indicates that universities contributed directly to the transmission of knowledge about best practices and to the training of mechanics starting in the early 1800s (Ziche 2001). Universities were thus likely to increase the local flow of small "tweaking" improvements in products and processes that are not observed in our data on major inventions. The observed shifts in high knowledge manufacturing industries can be expected to also reflect these processes, which involved both knowledge and human capital.

6 Technological Change and the Quality of Innovation

Our central claim is that the profound pro-science shift in German universities in the early 1800s drove economic development. To further assess this claim, we test our third and fourth hypotheses: that universities promoted both significant technological change in manufacturing and the quality of industrial innovation. To test these hypotheses, we expand our analysis beyond the evidence in the *Deutsches Städtebuch* both out of necessity and to document how the economic process is observed in interlocking bodies of independent data.

To study the pattern of technological change, we examine establishment-level data on a key dimension of technological change in the early 1800s, the adoption of mechanized

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[40] There are contrasts between U.S. universities in the 1900s and German universities in the 1800s. The pro-science shift in U.S. universities coincided with a major expansion of state financial support. German universities in the 19th century delivered remarkable scientific and technological advances on modest budgets, but research funding requirements in the 19th century were comparatively modest (McClelland 2008).

production techniques. To study the quality of industrial innovation, we examine evidence on competitive awards won by German firms exhibiting products and process technologies at the first World's Fair, the Crystal Palace Exhibition of 1851.

6.1 Technological Change

It is natural to wonder whether universities were associated with the adoption of *advanced* technology, given the central role of technological change in the industrialization process (Landes 1969). The mechanization of manufacturing was one of the most fundamental technological advances in our period. However, the *Deutsches Städtebuch* does not provide systematic information or clear indications on the technology used in manufacturing.[41]

To study the relationship between universities and technological change we collect detailed information on the technologies used by individual firms. We examine data gathered by Forberger (1982), which provide virtually comprehensive evidence on manufacturing establishments in Saxony. These data enable us to study, "factories and workshops on the path to manufacturing in the first phase of the Industrial Revolution (1800-1830)" (Forberger 1982; Bd. 1, p. 509 – our translation).[42] Over the period covered by the data, Saxony emerged as Germany's leading industrial region (Tilly and Kopsidis 2020; Pollard 1981). The first mechanized textile plant was established in Saxony in 1799-1800 (Meerwein 1914, p. 20; see also Pollard 1981). Mechanization then diffused rapidly. Factories in Saxony accounted for 14% of spindles installed in Germany textiles in 1800, 52% of spindles in 1810, and over 72% in 1815 (Appendix D; Kirchhain 1973; Forberger 1982).

To document the pattern of mechanization, we classify factories as mechanized or not. We classify 233 factories established in the early 1800s in cities in Saxony, using the categorization of factories (*Art der Fabrik*) provided by Forberger (1982). For example, "factory cotton machine spinning" (*Baumwollmaschinespinnerei*) is *mechanized* and "cotton spinning" (*Baumwollspinnerei*) is *not mechanized*. We note that our classification provides a *proxy* measure of technology choice, as some establishments combined mechanized and non-mechanized production processes. Appendix A provides details on the data.

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[41] Historical designations for manufacturing are ambiguous. For example, the words *Fabrik* and *Manufaktur* do not distinguish "factory" and pre-industrial "manufactory." See Freudenberger and Redlich (1964).

[42] In the original, Forberger (1982) writes: "Fabriken und der auf dem Wege zur fabrikatorischen Fertigung befindlichen Werkstätten in der ersten Phase der Industriellen Revolution (1800-1830)..."

Table 5: Universities and Mechanization

	(1)	(2)	(3)	(4)	(5)	(6)
	Mechanized Firms		Other Firms		Share Mechanized	
University	1.90***	1.35**	0.55	-0.24	0.37**	0.35*
	(0.64)	(0.55)	(0.66)	(0.69)	(0.17)	(0.18)
Prior Manufacturing Trends		Yes		Yes		Yes
Observations	164	164	164	164	38	38
Mean	1.17	1.17	0.25	0.25	0.82	0.82

This table reports regression estimates examining the mechanization of establishments set up in cities in Saxony between 1800 and 1830. The outcome in columns 1 and 2 is the number of firms in a city using mechanized technology and in columns 3 and 4 is the number of non-mechanized firms. These regressions are estimated across 164 cities with Poisson regressions. The outcome in columns 5 and 6 is the share of firms in a city using mechanized technology, estimated with OLS, in cities with manufacturing establishments. "University" is an indicator for cities below median distance to a university. "Prior Manufacturing Trends" indicates that models control independently for the number of manufacturing plants established in a given city: before 1700; 1700-1749; and 1750-1799. Heteroskedasticity robust standard errors in parentheses. Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively. Appendix D reports Conley (1999) standard errors. Data are from Forberger (1982; 1958).

We find that mechanized manufacturing concentrated in cities closer to universities in the early 1800s, conditional on prior manufacturing trends, consistent with our hypothesis. Table 5 presents cross-sectional regression estimates examining manufacturing across cities in Saxony closer to and farther from a university. We observe a significantly higher number of mechanized factories in cities close to universities (column 1). This relationship remains large and statistically significant when we control flexibly for pre-1800 manufacturing period-by-period to absorb underlying pre-trends and shifts (column 2). In contrast, we find a weak and insignificant relationship between universities and non-mechanized manufacturies (columns 3 and 4). In cities with manufacturing in the 1800-1830 period, we find that share of firms adopting mechanized technologies was higher in cities closer to universities (columns 5 and 6). These findings are not driven by unusual cities such as Chemnitz, and hold when we allow for arbitrary spatial correlation or study rural manufacturing (see Appendix D).

To interpret this evidence several observations are important. First, when we examine the evidence on manufacturing from the *Städtebuch* we find similar shifts towards universities in Saxony and other regions (see Appendix D), but the pattern of mechanization in Saxony may be in part region specific. Second, the larger impact of mechanization in the early 1800s unfolded gradually and via indirect channels, including the development of mechanics' workshops (Wolff 1979). Third, while Saxony was a leading industrial region within Germany, the factory system diffused more slowly in Saxony than in industrial regions of England, which points to the significance of a range of forces shaping industrialization.

6.2 The Quality of Innovation

We now test our fourth hypothesis, that universities fostered high quality innovations that took German industry towards or pushed out the world technology frontier.

To study the quality of innovation within Germany, we examine evidence on exhibits and prizes for innovation at the first world's fair, *The Great Exhibition of the Industry of All Nations* at Crystal Palace, London in 1851. We construct data on innovation in historic Germany from the original exhibition catalogue (Royal Commission 1851), following Moser (2005). We record the cities in which exhibiting firms were based and categorize as "high quality" exhibits that received a Council Medal, Prize Medal, or Honourable Mention. We also record whether the catalogue categorizes high quality exhibits as materials, machinery, or manufactures. Of 1,418 exhibits from German cities, 32% are thus classified as high quality. Across all countries, 30% of exhibits received such awards (Moser 2005; p. 1219).

Within Germany, the quality of innovations at the world's fair varies with exposure to universities. In cities below median distance to a university, 38% of exhibits were high quality. In cities above median distance, 24% were high quality. Within Germany, the 50% of cities thus closer to universities account for 58% of total and 69% of high quality exhibits. However, these differences could reflect pre-1789 variation in the level or trend of invention.

To test our hypothesis and control for underlying differences, we estimate regressions: $exhibits_i = \alpha + \beta uni_i + \gamma X_i + u_i$. The outcome is the number of exhibits from city i of a given quality and uni is an indicator for cities close to universities. To absorb pre-1789 differences in levels and trends of technical change, we control separately for the number of scientific and technological discoveries in each of the (1) 1760s, (2) 1770s, and (3) 1780s.

We present our estimates in Table 6. Proximity to a university has a modest and statistically insignificant association with total exhibits (Panel A, column 1). In contrast, high quality innovations were a significant 60 percent (0.48 log points) higher in cities near universities conditional on pre-1789 patterns of science and technology (column 2). Proximity to universities was most strongly associated with award-winning exhibits of machinery and materials and less strongly associated with high quality new manufactures (columns 3-5), when we disaggregate high quality exhibits using the exhibition's classification. These results are consistent with the hypothesis that universities promoted advanced innovation.

Table 6: The Quality of Industrial Innovation

	(1)	(2)	(3)	(4)	(5)
	Outcome: Number of Exhibits at First World's Fair				
	Total Exhibits	High Quality Exhibits	High Quality Exhibits By Type		
			Materials	Machines	Manufactures
A. University Effect					
University Close	0.07	0.48**	0.94***	1.07***	0.29
	(0.18)	(0.24)	(0.27)	(0.40)	(0.24)
Prior Invention Trends	Yes	Yes	Yes	Yes	Yes
B. Scientific and Technological Discoveries					
Discoveries 1830-1849	0.29**	0.34***	0.44***	0.43***	0.69***
	(0.12)	(0.11)	(0.08)	(0.16)	(0.11)
Prior Invention Trends	Yes	Yes	Yes	Yes	Yes
Observations	2254	2254	2254	2254	2254

Table reports Poisson regression estimates in which the outcome is the number of exhibits from a given German city in the Crystal Palace Exhibition of 1851 (Royal Commission 1851). "University" is an indicator for cities below median distance to a university. "Discoveries 1830-49" is the number scientific and technological discoveries in a city recorded in Darmstaedter, du Bois-Reymond, and Schaefer (1908). The outcome in column 1 is the total number of exhibits. The outcomes in columns 2-5 are the number of "High Quality" exhibits, defined as those awarded a Council Medal, Prize Medal, Honourable Mention, or money prize. "Prior Invention Trends" indicates separate controls for the number of Darmstaedter discoveries in a city in each of 1760-69, 1770-79, and 1780-89. Robust standard errors clustered by region in the *Städtebuch*.

The fact that firms in cities close to universities produced internationally competitive innovations suggests that universities were instrumental in the process that took German industry to the world technology frontier. Indeed, we find German cities near universities producing internationally recognized innovations in machines and materials already by the mid-1800s. These findings are consistent with historical evidence indicating that universities were promoting advanced innovation at the beginning of the railroad era and in fields besides chemicals and heavy industry, which are often framed as the key sectors of German industrialization in the late 1800s (see Appendix **??**).

The Crystal Palace data also confirm and point to the value of our separately collected data on science and invention. Table 6, Panel B shows that the number of Crystal Palace exhibits from a city varies in the cross-section with the measure of scientific and technological discovery we construct in our panel database. However, our measure varies across time and space, and in our data we find that there were no pre-trends towards universities before 1800 and that invention shifts significantly towards universities after 1800 (Figures 1 and 7).

7 Conclusion

Universities are widely viewed as core institutions promoting knowledge, industrial innovation, and growth. However, prior research provides limited evidence on the relationship between universities and large scale shifts in economic activity.

Our analysis examines historical evidence from Germany, where the research university first arose, and points to a substantially new view of the industrialization process. We collect and analyze new microdata on science, invention, and manufacturing. In the data, we find that universities drove a pivotal transformation in the German economy starting in the early 1800s. Invention and industry shifted towards universities and accelerated decades before the introduction of railroads and the growth of coal-based industry, which became important in the 1840s. By the mid-1800s, German universities were fostering industrial innovations that were winning competitive international prizes. The spatial and temporal patterns we uncover indicate that universities played a leading role in the process through which Germany industrialized and embarked on a path towards the world frontier in science-based industry.

The economic process we document reflected political shocks. The French Revolution and Napoleonic invasion led to cultural and institutional changes and reshaped German universities, promoting science and ultimately a model of the university as a center of research that has since diffused internationally. German history thus provides a model of how political and cultural change that shifts the orientation of higher education towards science and technology can shape development.

While we trace these dynamics over the 1800s, the convulsions in German society in the 20th century – resulting from war, inflation, and the rise of Fascism – point to the potential fragility of science-based growth and to the underlying importance of the political economy environment in the process we study. We focus on the period before Fascist politics and war delivered lasting negative shocks to German universities (Waldinger 2016). Both the positive economic shifts that we document and these later developments reflect an important instance of a transition to modern growth without democratization.

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Online Appendix

A Data

A.1 Sources and summary statistics

Manufacturing. We construct data on city-level manufacturing from the *Deutsches Städtebuch* (Keyser 1939-1974), recording the timing and sector of manufacturing "events" as described in the main text. The *Deutschtes Städtebuch* is a historic encyclopedia of settlements in German-speaking Europe that acquired city rights. Our analysis focuses on 2,254 cities examined in Cantoni and Yuchtman (2014), mapped in Figure 3. We examine corroborating evidence on county-level manufacturing from the 1849 Prussian Census from Becker et al. (2014), described in Section A.2 below.

Universities. We construct data on the location and dates of operation of universities from Rüegg (2004a;b). We consider the following universities. The surviving historical universities that remained open through 1820 are: Breslau, Erlangen, Freiburg, Giessen, Göttingen, Greifswald, Halle, Heidelberg, Ingolstadt, Jena, Kiel, Leipzig, Marburg, Rostock, Tübingen, and Würzburg. The universities that opened include: Berlin, München, and Bonn. The universities that closed include: Altdorf, Bamberg, Duisburg, Erfurt, Frankfurt, Fulda, Helmstedt, Herborn, Köln, Mainz, Paderborn, and Wittenberg.

Schools. We gather evidence on all schools founded in the cities we study from the *Deutsches Städtebuch* (Keyser 1939-1974). Our main analysis focuses on "higher schools," that is secondary schools including: *Gymnasia*, *Lyzeen* (*Lyzeum*), *Realschulen*, and *Gewerbeschulen* (technical schools). Our findings are robust to extending our analysis to consider, and control for, the potential differential impact of vocational schools, middle schools, and elementary schools as shown in Appendix **??**.

Railroads. We construct measures of city-level railway connections based on the spatial development of the railroad network, using GIS maps from Kunz and Zipf (2008).

Coal Deposits. We record whether cities are near coal deposits using geological evidence from, "The 1:5 Million International Geological Map for Europe and Adjacent Areas" prepared by Die Bundesanstalt für Geowissenschaften und Rohstoffe (Asch 2005).

Free Enterprise Laws. Territorial-level data on the passage of "free enterprise laws" (*Gewerbefreiheit*) are coded following Acemoglu et al. (2011) and Kopsidis and Bromley (2016). Additional territories are coded based on information in Braun (1860).

Territories. We assign cities to 44 historic territories of the German Union (*Deutscher Bund*), as constituted in 1815.

Scientific and Technological Discovery. We gather evidence on scientific breakthroughs and inventions from Darmstaedter, du Bois-Reymond, and Schaefer (1908). We match inventions and discoveries to town locations by constructing evidence on the lives and employment of inventors from the *Deutsche Biographie*, the *World Biographical Information System* and historical sources. We also construct data on the educational backgrounds of all scientists and inventors, recording whether or not they were university-educated.

Technology Adoption in Saxony. Data on factories, workshops, and the adoption of mechanized production technologies in Saxony between 1800 and 1830 are from Forberger (1982). We rely on Forberger (1958) for evidence on manufacturing in Saxony before 1800.

Exhibits and Prizes at the 1851 World's Fair. Data on German exhibits at *The Great Exhibition of the Industry of All Nations* at Crystal Palace, London are collected from the original exhibition catalogue (Royal Commission 1851).

* * *

Table A1 presents summary statistics on the city-level panel dataset we use to examine manufacturing in Sections 4 and 5. Table A2 presents summary statistics on the database of scientific break-throughs and inventions building on Darmstaedter, du Bois-Reymond, and Schaefer (1908) that we examine in Section 5. Table A3 presents summary statistics on the city-level cross-sectional dataset we use to examine technological change in Saxony (Section 6.1). Table A4 presents summary statistics on the cross-sectional city-level dataset on industrial innovations exhibited at the 1851 Crystal Palace exhibition (Section 6.2).

Table A5 provides an illustrative examples of our data building on Darmstaedter, du Bois-Reymond, and Schaefer (1908) that we examine in Section 5.

Table A1: Summary Statistics on Manufacturing

	Mean	S. D.
Count Manufacturing	0.271	0.919
Any Manufacturing	0.170	0.428
High Knowledge Manufacturing	0.206	0.729
Low Knowledge Manufacturing	0.065	0.332
University 1845	0.500	0.500
Railroad Connection	0.046	0.209
Free Enterprise Law	0.360	0.480
Early Manufacturing	0.132	0.338
Coal × Post-1840	0.214	0.410
Coal × Post-1800	0.357	0.479
Higher School Lead	0.211	0.408
Higher School	0.190	0.392
Higher School Lag	0.148	0.355
Observations	15778	

"Count Manufacturing" is the count of manufacturing events in a city-period of twenty years. "Any Manufacturing" is an indicator for any manufacturing. "University 1845" and "University 1785" are time-invariant indicators for cities that were below median distance to a university active in these decades. "Railroad Connection" is an indicator for railroad connections in a city-period. "Free Enterprise Law" is an indicator for cities in territories that had passed *Gewerbefreiheit* legislation. "Early Manufacturing" is an indicator for the presence of pre-1760 manufacturing in a city. "Coal" is an indicator for cities below median distance to coal deposits. "Higher School" is an indicator for cities in which a higher school was or had been established.

Table A2: Summary Statistics on Knowledge Intensity and Invention

	Mean	S.D.
Scientific Discovery	0.388	0.487
Technological Discovery	0.744	0.436
University Education of Scientist or Inventor	0.801	0.400
Observations	1119	

This table summarizes the data on scientific and technological discovery used to classify manufacturing industries as "High Knowledge" and "Low Knowledge," based on the educational backgrounds of inventors producing technological discoveries. These data cover the period 1760-1860. The underlying observations are constructed from Darmstaedter, du Bois-Reymond, and Schaefer (1908). Our analysis first determines which individual discoveries were made in the 2,254 cities we study and then classifies observations as indicated in this table. "Scientific Discovery" is an indicator that takes the value of 1 for observations that are or involve basic scientific discoveries. "Technological Discovery" is an indicator for observations that are inventions or innovations with practical applications, including in manufacturing. "University Education of Scientist or Inventor" is an indicator that takes the value of 1 for discoveries where the scientists or inventor has a university education.

Table A3: Summary Statistics on Technology Adoption in Saxony

	Mean	S.D.
Number of Mechanized Firms	1.171	5.356
Number of Non-mechanized Firms	0.250	1.093
Share of Mechanized Firms	0.822	0.315
University	0.500	0.502
Manufacturing pre-1700	0.091	0.493
Manufacturing 1700-1749	0.134	0.622
Manufacturing 1750-1799	0.732	3.161
Observations	164	

This table summarizes the cross-sectional data on the adoption of mechanized technologies 1800-1830 by firms in cities in Saxony. "Number of Mechanized Firms" and "Number of Non-Mechanized Firms" are the number of such firms in a given city 1800-1830. "Share of Mechanized Firms" is the share of firms that are mechanized, which is observed only in cities with any firms. "University" is an indicator for cities below median distance to a university in 1785. "Manufacturing pre-1700," "Manufacturing 1700-1749," and "Manufacturing 1750-1799" are the number of manufacturing firms (establishments) observed in these periods. Data on mechanization post-1800 and on pre-1800 manufacturing are from Forberger (1982) and Forberger (1958), respectively.

Table A4: Summary Statistics on Innovations at Crystal Palace in 1851

	Mean	S.D.
Total Number of Exhibits	0.629	5.120
High Quality Exhibits	0.197	1.968
Low Quality Exhibits	0.432	3.468
High Quality in Materials	0.035	0.274
High Quality in Machines	0.023	0.367
High Quality in Manufactures	0.133	1.383
University	0.500	0.500
Scientific and Technological Discoveries 1830-1849	0.116	1.750
Observations	2254	

This table summarizes cross-sectional data on innovations exhibited at *The Great Exhibition of the Industry of All Nations* at Crystal Palace in 1851. "Total Number of Exhibits" is the total number of exhibits at Crystal Palace from a given city. "High Quality Exhibits' is the number of exhibits receiving an award, as described in the text. "Low Quality Exhibits" is the number of exhibits not receiving an award. High quality exhibits in "Materials," "Machines," and "Manufactures" are the number of high quality (award-winning) exhibits in each category, as recorded in the original catalogue. These data are coded from Royal Commission (1851). "University" is an indicator for cities below median distance to a university in 1845. "Scientific and Technological Discoveries 1830-1849" is the number of observations in a given city recorded in Darmstaedter, du Bois-Reymond, and Schaefer (1908).

Table A5: Examples of Individual Inventions and Discoveries

Subject Classification	Year	Town	Industry	University	Note
Beet sugar production (*Rübenzuckerfrabrikation*)	1801	Berlin	Food	1	Inventor Franz Karl Achard builds first sugar factory in Konary, Silesia.
Sulfurmilk (*Sulfurmilch*)	1807	Erfurt	Chemicals	1	Inventor Christian Friedrich Bucholz published 100+ papers on chemicals and production.
Galvanic series (*Spannungsreihe der Metalle*)	1808	Halle	Metals	1	Galvanic series are used to determine galvanic reaction, the principle upon which batteries are based.
Steel and cast iron production (*Stahl- und Flusseisenbereitung*)	1811	Essen	Metals	0	Inventor Friedrich Krupp founds the Krupp steel company in same year.
Reproduction of pictorial representation (*Reproduktion von bildlichen Darstellungen*)	1815	Magdeburg	Printing	0	Significantly reduced costs of reproducing pictures.
Production of artificial mineral waters (*Fabrikation der künstlichen Mineralwässer*)	1817	Dresden	Food	1	Inventor Friedrich A. A. Struve's business flourished, was knighted for achievements.
Chromium-acid based dyes (*Chromsaure Salze zum Färben*)	1820	Schneeberg	Textiles	1	Inventor Ernst August Geitner built chemical factory in 1810 and commercialized many inventions.
Chain blower (*Kettengebläse mit Wasserliderung*)	1820	Kassel	Mining	0	Inventor Carl Anton Henschel was mostly self-taught and his company Henschel & Sohn produced equipment starting in 1817.
Platin catalysts and lighter (*Platinkatalysatoren und -feuerzeug*)	1824	Jena	Misc	1	Inventor Johann Wolfgang Döbereiner taught in a colloquium in practical chemistry at the university of Jena in 1820. He was also instrumental in building a sugar factory and a ethanoic acid factory.
Ammonian and ammonium compounds (*Ammoniak oder Ammoniumverbindungen*)	1828	Giessen	Chemicals	1	The third invention by Justus von Liebig in our data. Liebig owned a private institute for pharmacy and an equipment workshop to supplement his income between 1827 and 1833.
Leukol, rosoleic and carbolic acid (*Leukol, Carbolsäure and Rosolsäure*)	1834	Oranienburg	Chemicals	1	Inventor Friedlieb Ferdinand Runge professor of technology in Breslau before leaving academia in 1832 to work as industrial chemist at Chemischen Etablissement Dr. Hempel (Chemische Produkten-Fabrik Oranienburg).
Cork borer (*Korkbohrer*)	1838	Koblenz	Equipment	1	Inventor Karl Friedrich Mohr also co-founded a local chamber of commerce and later invested in the chemical industry.
Self-interrupting pointer telegraph (*Zeigertelegraphen mit Selbstunterbrechung*)	1846	Berlin	Equipment	1	This is the first of many inventions by Werner von Siemens in our database.

"Subject Classification" is the hand-coded classification of the subject of the invention and scientific discovery. "Year" is the year of the invention or discovery as per Darmstaedter, du Bois-Reymond, and Schaefer (1908). "Town" is the location of the invention or discovery, coded from historical and biographical sources. "Industry" is our classification of the industry that used the given invention or break-through. "University" column records whether the inventor had a university education.

A.2 Manufacturing in *Städtebuch* and in administrative data

To document the variation in the measure of manufacturing we construct from the *Deutsches Städtebuch*, and to verify what these data capture, we compare them to the first large scale administrative data on manufacturing in Germany, the Prussian census of 1849. We specifically examine how our measure of manufacturing is correlated with county-level data on the number of factories and the number of workers in different types of manufacturing activity in the 1849 census.

We compare our data on manufacturing to the census data on a industry-by-industry basis. We estimate cross-sectional regressions: $man_i^c = \alpha + \beta man_i^s + \epsilon_i$, where man_i^c is manufacturing activity in the 1849 Prussian Census, measured by either the number of factories or by the number of workers in a given two-digit industry in county i. Similarly, man_i^s is the number of manufacturing events in the same industry in county i recorded in the *Städtebuch* between 1820 and 1839.[43] To estimate these relationships, we aggregate our city-level data to the level of their respective Prussian counties (the mean Prussian county comprises 3.5 *Städtebuch* cities). We aggregate manufacturing events to the industry level, following the two-digit SIC coding for manufacturing activity but combining all metal-related manufacturing in a single industry. We estimate negative binomial regressions.

Table A6 documents the correlation between our measure of manufacturing and the number of factories and workers in a given industry. For most sectors the correlation is highly significant and the estimates are close to, and not statistically different from, unit elasticities. It should be noted, however, that the outcome measures the number of active factories or workers in 1849, whereas our *proxy* measure of manufacturing from the *Städtebuch* measures the opening and, in some cases, the presence of factories in earlier periods. We exclude the 1840s from the *Städtebuch* measure because for some cities data recorded for "the 1840s" in fact reflect the Census itself. By restricting our analysis to factories established in the 20 years before the 1840s, we ensure we do not regress information from the Census on itself, but this also implies that here our measure does not capture variation in industrial activity dating from the 1840s. Of the industries in question, transportation equipment expanded relatively dramatically in the 1840s, with the build out of the railroads, which in

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[43] We examine the period before 1840 to capture how the *flows* of plant openings recorded before the 1840s in the *Deutsche Städtebuch* captures the *stock* of factories (and number of workers employed) in the 1840s.

part explains the high elasticity estimate for this industry.

Table A6: Evidence on Manufacturing by Industry

	(1)	(2)	(3)	(4)
	Factories in 1849 Census in Given Industry		Workers in 1849 Census in Given Industry	
Manufacturing Industry	β	Std. Err.	β	Std. Err.
Food	1.01***	(0.30)	1.69***	(0.33)
Tobacco	1.04**	(0.46)	1.50***	(0.53)
Textiles	0.54***	(0.17)	0.94***	(0.24)
Paper	1.18***	(0.40)	1.35**	(0.60)
Chemicals	1.38***	(0.28)	1.42***	(0.34)
Leather	0.51	(0.68)	1.03*	(0.61)
Glass	0.81	(0.73)	0.65	(0.65)
Metals	0.62*	(0.33)	1.09***	(0.32)
Machines	1.90**	(0.95)	1.85**	(0.79)
Transport Equipment	3.43***	(0.47)	3.24***	(0.39)

This table reports regression estimates in which the outcome is either the number of factories (columns 1-2) or the number of workers (columns 3-4) in a given industry and county in the 1849 Prussian census. Each row presents estimates from industry-specific binomial regressions: $man_i^c = \alpha + \beta man_i^s + \epsilon_i$. The outcome is the number of workers or number of factories recorded in 1849 Prussian Census (Becker et al. 2014). The independent variable is the measure of manufacturing events in a given industry recorded in the *Deutsches Städtebuch* (Keyser 1939-1974) from 1820 through 1839. City-level data constructed from Keyser (1939-1974) are aggregated to the county-level for 229 historical Prussian counties within the coverage of the *Deutsches Städtebuch*. Standard errors clustered by administrative district (*Regierungsbezirk*). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

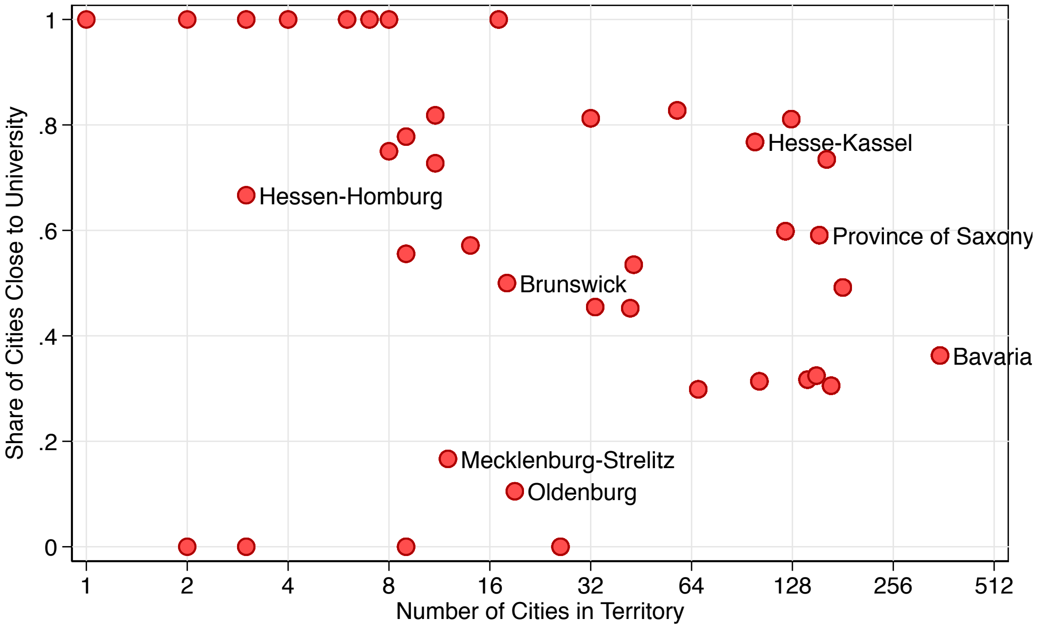
A.3 Territories within historic Germany

Several of our analyses study the relationship between university exposure and manufacturing within territory-×-time cells (see Table 2 and Table 3). To clarify the variation we study, we present evidence on the within-territory variation.

Figure A1 plots territory-level evidence on the the share of cities close to a university against the number of cities in a given territory.

Table A7 presents evidence on the distribution of cities across territories, and illustrates the within-territory variation in the number cities were located close to and far from universities. Table A7 distinguishes between cities located closer to and farther from universities in the 1800s, defined as being above or below median distance to a university in the 1840s. We note that these territorial definitions are as of 1815. This accounts for the

Figure A1: Variation in University Exposure within Territories



This graph summarizes the variation in university exposure within 44 territories of the German Bund as of 1815. The horizontal axis records the number of cities in a territory. The vertical axis records the share of these cities that were close to universities, defined as below median distance, in the 1800s.

small difference between number of cities in Saxony listed in Table A7 and examined in our analysis of mechanization in Saxony in Table 5.

B Universities and Manufacturing

This appendix provides further analysis on the relationship between universities and manufacturing. In particular, the analysis re-examines how proximity to universities was related to development using a more flexible approach to geographic distance and offers additional evidence relating to the potential endogeneity of university locations.

First, to clarify the pattern of spillovers, we provide further evidence on geographic proximity to universities and the development of manufacturing. We do this by studying the implications of distance both (A) more flexibly and (B) in a linear framework.

Second, we provide evidence on the relationship between new universities – founded in the early 1800s – and the development of manufacturing after 1800. We show that new universities were not associated with any differential shift in manufacturing.

Third, we examine the relationship between manufacturing and proximity to historical

Table A7: Cities and Proximity to Universities by Territory

	Cities by Proximity to University in 1800s		
Territory	Number Far From	Number Close To	Total Cities
Anhalt-Bernburg	2	7	9
Anhalt-Dessau	2	6	8
Anhalt-Köthen	0	4	4
Baden	24	103	127
Bavaria	227	126	353
Brandenburg	102	49	151
Brunswick	9	9	18
Free City	4	5	9
Hannover	70	32	102
Hesse-Darmstadt	10	48	58
Hesse-Kassel	23	76	99
Hessen-Homburg	1	2	3
Hohenzollern-Hechingen	0	1	1
Hohenzollern-Sigmaringen	0	6	6
Lauenburg	3	0	3
Lippe-Detmold	9	0	9
Lübeck	2	0	2
Mark	19	14	33
Mecklenburg-Schwerin	20	23	43
Mecklenburg-Strelitz	10	2	12
Oldenburg	17	2	19
Poland	26	0	26
Pomerania	47	20	67
Province of Saxony	63	91	154
Reuß ältere Linie (Reuß-Greiz)	0	3	3
Reuß-Ebersdorf	0	2	2
Reuß-Gera	0	4	4
Reuß-Lobenstein	0	1	1
Reuß-Schleiz	0	3	3
Rhineland	92	89	181
Sachsen-Coburg-Saalfeld	2	9	11
Sachsen-Gotha-Altenburg	0	17	17
Sachsen-Hildburghausen	0	6	6
Sachsen-Meiningen	0	7	7
Sachsen-Weimar-Eisenach	6	26	32
Saxony	117	50	167
Schaumburg-Lippe	3	0	3
Schleswig-Holstein	23	19	42
Schwarzburg-Rudolstadt	0	8	8
Schwarzburg-Sondershausen	3	8	11
Silesia	91	51	142
Waldeck	6	8	14
Westphalia	49	73	122
Württemberg	45	117	162

universities active in the late 1700s, before the political shocks initiated by the French Revolution. This analysis shows that historical university exposure predicts subsequent manufacturing activity and how the closure of universities attenuates these effects.

Fourth, we use evidence on student enrollment trends as indicators of university quality to examine whether the closure of historic universities was selective. We find that the universities that were closed over the period we study did not exhibit any differential enrollment trends before the political shocks of the late 1700s, which led to the closures.

Fifth, we use data on urban construction to further test whether cities closer to universities enjoyed development advantages before 1800. We test and confirm that university locations were not associated with differences in pre-industrial development, as measured by construction.

Sixth, we examine the relationship between universities and manufacturing controlling for the spatial location of "economic societies" which were established in some cities in the late 1700s to promote the diffusion of knowledge. This analysis shows that our estimated university effects hold controlling for the location of economic societies, which in theory could represent a confounding factor also shaping manufacturing.

B.1 Distance to Universities and Shifts in Manufacturing

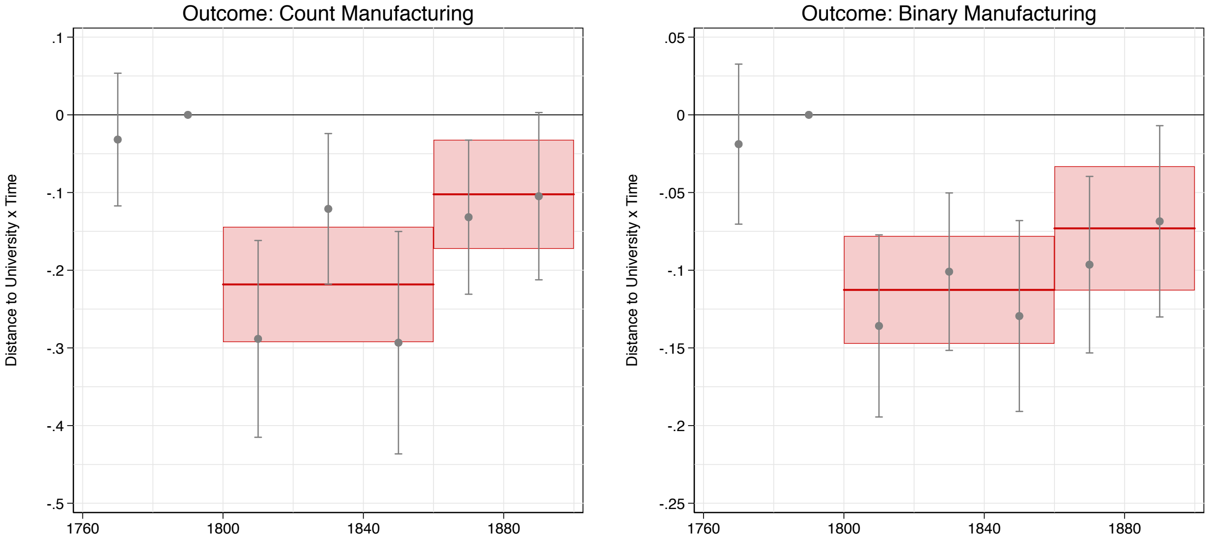
Our analysis focuses on the binary distinction between cities close to and far from a university, but also examines the role of distance more flexibly and uncovers an approximately linear pattern (Figure 6). In this section, we further consider the pattern of spatial spillovers.

First, to clarify the economic process, we examine the relationship between manufacturing and distance to the nearest university measured in kilometers. As in our baseline analysis, we examine interactions between university exposure and time period indicators. We now measure university exposure by the distance to the nearest university.

Figure B1 presents our estimates examining distance linearly and compares Figure 4 (Panel A) in the main text. We find no significant relationship between distance and manufacturing before 1800. After 1800, cities far from universities are at a large and significant disadvantage in manufacturing. Consistent with our baseline estimates in the main text, the shift is largest 1800-1859 but is also observed 1860-1899.

To clarify magnitudes, we present estimates measuring distance in 100 kilometer units. Thus in Figure B1, the left hand panel examines the count of manufacturing and shows that a further 100 kilometers distance was associated with a -0.22 shift (decline) in manufacturing 1800-1859. Equivalently, our estimates indicate that a 60 kilometer *reduction* in distance to a university is associated with a 0.13 *increase* in the count of manufacturing events. The magnitudes of these estimates compare to our baseline estimates in which cities "close" to a university, defined as those below median distance and thus within 60 kilometers, enjoyed a 0.14 increase in the count of manufacturing events (see Figure 4 and Table 2 in the main text). These shifts also compare to the mean count outcome of 0.27.

Figure B1: Distance to Universities and Manufacturing



This graph presents regression estimates in which the outcome is manufacturing events in a city-time-period. The figure plots estimates on the interactions between distance to a university, measured in 100 kilometer units, and time period indicators. Each graph reports estimates from two regressions which correspond to the specifications in Figure 4. The first regression estimates the response of manufacturing to universities in two post periods: 1800-1859 and 1860-1899, relative to the reference period 1760-1799. These estimates and 95% confidence intervals are represented by shaded boxes. The second regression estimates a flexible model in which "University" is interacted with time period indicators, with 1780-1799 the reference period. All models include city and time fixed effects. Standard errors and 95% confidence intervals estimated following Conley (1999) allow for arbitrary spatial correlation within 25 km.

These comparisons between cities closer to and farther from a university uncover significant shifts in economic activity, but do not exhaust the possible pattern of spatial spillovers. In particular, it is theoretically possible that there were spatial spillovers associated with distance to universities in general, including less proximate ones, or simply to

Table B1: Exposure to Additional Universities

	(1)	(2)	(3)
	Outcome: Count Manufacturing		
University x 1800-59	0.14***	0.11***	0.11*
	(0.04)	(0.04)	(0.06)
University x 1860-99	0.07**	0.05	0.08
	(0.03)	(0.04)	(0.05)
Inverse Distance to all Universities x 1800-59		757.13	
		(555.85)	
Inverse Distance to all Universities x 1860-99		489.35	
		(566.94)	
Count of Universities Close x 1800-59			0.03
			(0.04)
Count of Universities Close x 1860-99			-0.01
			(0.04)
Observations	15778	15778	15778
City and Time Period FE	Yes	Yes	Yes

This table reports regression estimates examining the count of manufacturing events between 1760 and 1899. Column 1 presents our baseline estimates. Column 2 controls for the sum of inverse distances to all universities interacted with time period indicators. Column 3 controls for the total number of universities that are "close" to a given city, defined as within 60 kilometers. Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following Conley (1999).

being near multiple universities. To study this question, we expand our analysis to include a measure of inverse distance to all universities and a measure counting the number of nearby universities. We find that these alternate measures of exposure have no significant relationship to shifts in shifts in manufacturing activity and that our baseline binary measure of exposure is broadly robust to including these measures. See Table B1.

B.2 New Universities and Manufacturing

Because new universities were established in the period we study, it is natural to ask whether new universities had a more pronounced relationship with manufacturing, which might be the case if the new locations were endogenous.

To address this question, we examine the heterogeneity in the university effect across historic and new universities. We specifically test whether cities close to new universities experienced any differential shifts in manufacturing over and above those common across all cities near to universities. We extend our baseline analysis, reported in Figure 4 (Panel A), by including in the estimating model interactions between indicators for cities close to new universities and indicators for time periods. We use these interactions to estimate the incremental shift in manufacturing explained by exposure to new universities. The variation we study here arises from 284 cities which became "close" to universities in the early 1800s due to shifts in university locations, including the foundation of the universities at Berlin and Munich. As before, we define cities below median distance to a university as "close."

Table B2 shows that cities near new universities enjoyed no clear advantages over those near historic universities. Between 1800 and 1859, our estimates indicate virtually zero difference in manufacturing in cities near new universities compared to cities near pre-existing universities. Over the 1860-1899 period, there is some modest evidence that manufacturing increased more in cities near the new universities. This effect is statistically insignificant when we examine the count of manufacturing events (Column 1) and weakly significant when we examine the binary outcome recording whether any manufacturing is observed (Column 2). This evidence indicates that the development of manufacturing around new universities proceeded in manner similar to that observed around pre-existing universities. This, in turn, casts some doubt on the idea that the new universities at Berlin and Munich were unique and potentially endogenous drivers of development.

B.3 Pre-existing Universities and Manufacturing

Our main analysis shows that the university effect on manufacturing after 1800 is not driven by potentially endogenous changes in university locations. In particular, we find that that the estimated university effect is strong and stable when we restrict the analysis to cities whose university exposure was fixed over our study period and arose due to the location of pre-existing historic universities.

Differences in exposure to universities as they existed *before* the French Revolution provide another lens through which we can examine shifts in manufacturing and offer comparisons akin to intention-to-treat analysis.

Figure B2 presents estimates that extend the analysis to study how exposure to pre-1789 universities explains manufacturing. We find that cities closer to pre-1789 universities experienced a positive shift in manufacturing after 1800 (Panel A), but that the estimated shift is quantitatively smaller than the shift we estimate when we restrict our analysis to

Table B2: New Universities and Manufacturing

	(1) Manufacturing Count	(2) Manufacturing Binary
University × 1800-1859	0.14***	0.07***
	(0.04)	(0.02)
University × 1860-1899	0.06*	0.03
	(0.03)	(0.02)
New University × 1800-1859	0.01	-0.00
	(0.06)	(0.02)
New University × 1860-1899	0.04	0.04*
	(0.05)	(0.02)
City and Time Period FE	Yes	Yes
Observations	15778	15778

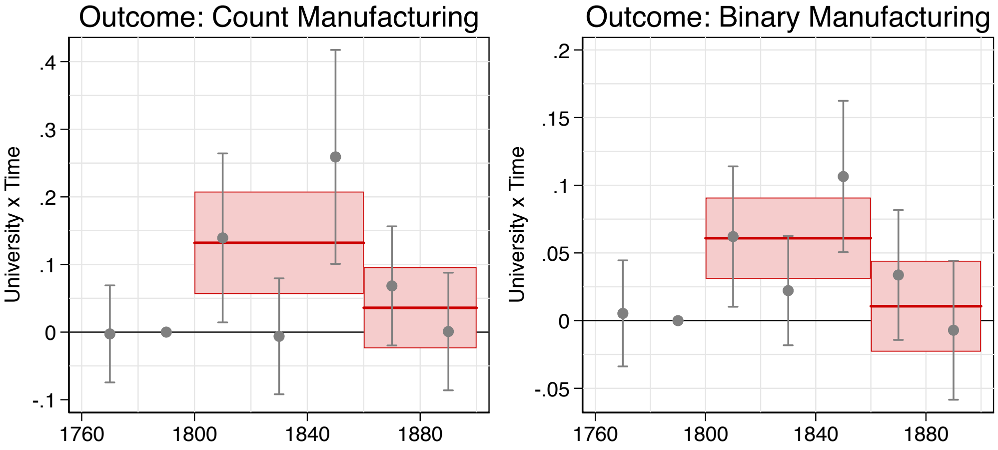
This table reports regression estimates examining the count and presence of manufacturing events between 1760 and 1899. "University × 1800-1859" interacts an indicator for cities below median distance to a university in the 1800s with an indicator for the 1800-1859 period. "University × 1860-1899" interacts an indicator for cities below median distance to a university in the 1800s with an indicator for the 1860-1899 period. "New University × 1800-1859" and "New University × 1860-1899" interact indicators for cities that became close to a university due to the founding of new university. The estimated models include and city and time fixed effects and correspond to Figure 4, Panel A (equivalently, Table 2, columns 1 and 6). Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999).

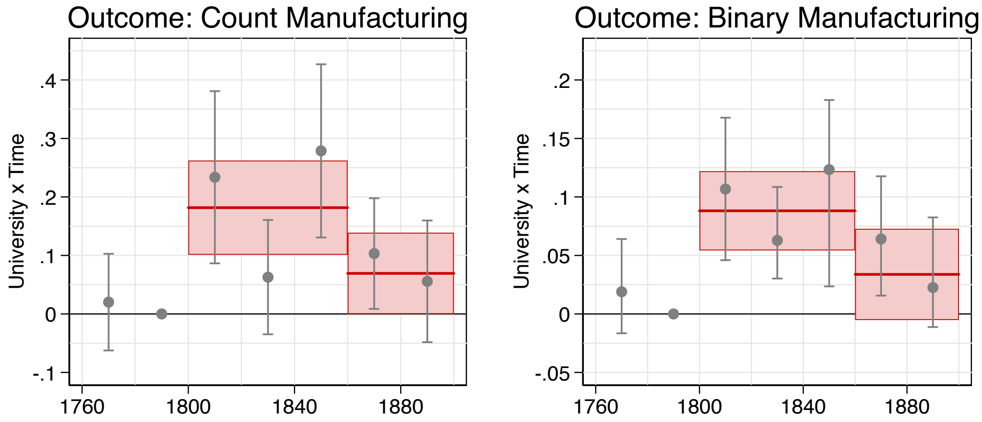
cities for which university exposure did not change over this period (shown in Panel B). For example, for the count outcome we estimate a positive shift of 0.13 for cities close to universities in the 1700s (Panel A, left graph) and a positive shift of 0.18 for cities whose university exposure did not change (Panel B, left graph). The differences we observe reflect the fact that some pre-1789 universities closed and some new universities opened, making pre-1789 locations a noisy measure of actual university exposure after 1800. More formally, when we use proximity to 1780s university locations as a measure of exposure, our estimates are diluted by "non-compliance" resulting from subsequent changes in university locations.

B.4 University Closures and Prior Enrollment Trends

The fact that some universities closed during the period of political change running from the French Revolution through the Napoleonic era raises a natural question: were the universities that closed better or worse, or more or less dynamic, than those that survived?

Figure B2: Manufacturing and University Exposure Before and After Political Shocks


A. All Cities - Exposure to University in 1700s


B. Cities with No Change in University Exposure

This figure presents regression estimates that extend our baseline analysis. Panels A studies how exposure to historic universities, active in the 1780s, explains shifts in manufacturing activity. Panel B replicates the corresponding panels in Figure 4. Panels A examines all cities (n=2,254). Panel B restricts analysis to cities whose university exposure did not change between the late 1700s and the 1800s (n=1,686). The models include city and time fixed effects as in the main text. Standard errors and 95% confidence intervals estimated following Conley (1999) allow for arbitrary spatial correlation within 25 km.

Enrollment patterns provide important indications of university quality, as they reflect the historic competitiveness of the German university system and the geographic mobility of students and faculty (Eulenburg 1904; Rüegg 2004a; Turner 1975). We therefore assemble university-year level data on enrollments from Eulenburg (1904) and test whether enrollments evolved similarly at universities that were and were not closed during the era of the French

Revolution and Napoleonic invasion. We estimate:

$$enroll_{it} = \alpha_i + \delta_{decade} + \sum_{s=1700}^{1780} \beta_s (decade_s \times survive_i) + \epsilon_{it} \tag{2}$$

Here *enroll* is the number of students enrolled at university i in year t, the α are university fixed effects, the δ are decade fixed effects. The β_s estimate variation in enrollment specific to surviving universities in each decade. We measure the surviving universities with a time invariant indicator (*survive*) for universities that survived to 1820.

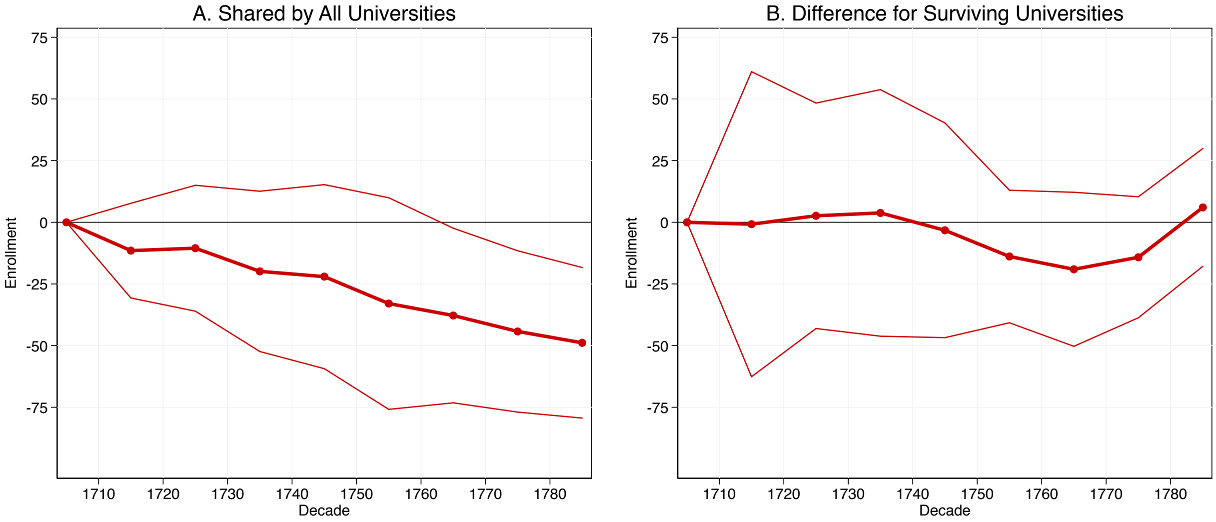
Figure B3 plots our estimates and shows that there was a secular decline in enrollments for all universities (Panel A) and no significant shifts in enrollments for universities that survived the politically-driven closures of the late 1700s and early 1800s (Panel B). This evidence is consistent with the view that university closures were driven by political events and did not, for example, lead to the selective closure of weaker institutions. This evidence is also consistent with view that German university education was in a long-running decline before the political shocks of the late 1700s (Turner 1975).

B.5 The Role of Universities and Economic Societies

To assess the role of universities, it is important to also consider other organizational changes related to the diffusion of knowledge. Notably, a number of "economic societies" were established in the late 1700s, animated by englightenment ideas concerning progress and technology. Cinnirella, Hornung, and Koschnick (2022) indicate that economic societies contributed to the diffusion of useful knowledge, and notably find that patenting was higher in cities exposed to these societies in the period after 1870. The natural question for our study is whether exposure to these economic societies, which were established in 16 cities in our data in the very late 1700s, may be correlated with university exposure and account for some component of the university effect.

To examine the role of economic societies, we extend our analysis. We test (1) whether the university effect estimates change when we account for cities' exposure to economic societies and (2) whether manufacturing increased more after 1800 in cities exposed to economic societies. We measure exposure to economic societies with an indicator variable for cities

Figure B3: University Enrollment Dynamics Before the French Revolution



This graph plots regression estimates examining enrollments at German universities. Graphs report estimates from equation (2), in which the outcome is the number of students enrolled in a university-year. Panel A plots decade fixed effects. Panel B plots parameter estimates on the interaction between (i) decade fixed effects and (ii) an indicator for universities that survived the French Revolution and Napoleonic invasion and were not closed. Graphs present point estimates and 95 percent confidence intervals. Data on enrollments at the university-year level are from Eulenburg (1904). The surviving universities that remained open through 1820 are: Breslau, Erlangen, Freiburg, Giessen, Göttingen, Greifswald, Halle, Heidelberg, Ingolstadt, Jena, Kiel, Königsberg, Leipzig, Marburg, Paderborn, Rostock, Tübingen, and Würzburg. The universities closed by 1820 are: Altdorf, Bamberg, Duisburg, Erfurt, Frankfurt, Fulda, Helmstedt, Herborn, Köln, Mainz, Strassburg, and Wittenberg.

close to cities housing such societies. We define cities within 50 kilometers of a society's home base as exposed in our baseline analysis. However, we obtain similar results when we examine other distance thresholds and when we measure exposure using the membership size of different societies rather than a binary measure of exposure.

Table B3 reports our results. Columns 1-3 examine the number of manufacturing events in a city-period. Column 1 reports our baseline results (as in Table 2). Column 2 reports results examining proximity to economic societies. Column 3 presents estimates examining exposure to universities and economic societies. Columns 4-6 present parallel results examining the binary outcome recording whether any manufacturing is observed in a city-period.

We find that the university effects hold controlling for exposure to economic societies and that exposure to economic societies does not explain variation in industrial activity.

Table B3: Universities, Economic Societies, and Manufacturing

	(1)	(2)	(3)	(4)	(5)	(6)
	Manufacturing Count			Manufacturing Binary		
University × 1800-1859	0.14^{***}		0.14^{***}	0.07^{***}		0.07^{***}
	(0.04)		(0.04)	(0.02)		(0.02)
University × 1860-1899	0.07^{**}		0.07^{**}	0.04^{**}		0.04^{**}
	(0.03)		(0.03)	(0.02)		(0.02)
Economic Society × 1800-1859		0.00	-0.02		0.02	0.00
		(0.04)	(0.04)		(0.02)	(0.02)
Economic Society × 1860-1899		0.01	-0.00		-0.01	-0.02
		(0.04)	(0.04)		(0.02)	(0.02)
City and Time Period Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15778	15778	15778	15778	15778	15778

This table reports regression estimates examining the count and binary presence of manufacturing events between 1760 and 1899. "University × 1800-1859" interacts an indicator for cities below median distance to a university in the 1800s with an indicator for the 1800-1859 period. "University × 1860-1899" interacts an indicator for cities below median distance to a university in the 1800s with an indicator for the 1860-1899 period. "Economic Society × 1800-1859" and "Economic Society × 1860-1899" interact indicators for cities near economic societies, defined as within 50 km. Data on location of economic societies are from Cinnirella, Hornung, and Koschnick (2022). The estimated models include and city and time fixed effects and correspond to Figure 4, Panel A (equivalently, Table 2, columns 1 and 6). Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999).

C Inference and Spatial Autocorrelation

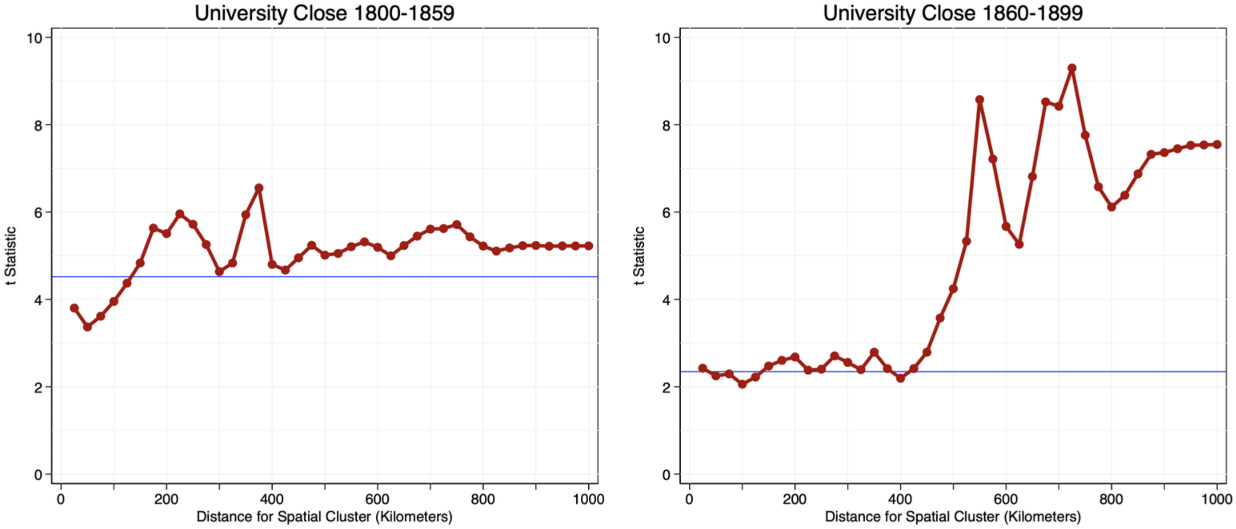
C.1 Sensitivity of Standard Error Estimates

Our baseline analysis presents standard errors estimated following the methodology of Conley (1999) that allow for arbitrary spatial correlation within 25 kilometers. It is natural to wonder whether the choice of spatial cut-off is consequential for inference in our setting, and how these estimates compare to standard errors clustered at the unit (city) level.

To address this question, we re-estimate our baseline model varying the cut-offs for spatial correlation in the error structure. We re-estimate the model in Table 2 (column 1) varying the cut-off from 25 to 1,000 kilometers. Figure C1 plots the estimated t-statistics against the corresponding distance cut-off and shows we reject the null hypothesis of no shift in manufacturing for locations near universities across all distances. The estimated t-statistics are smallest (standard errors are largest) when we consider autocorrelation under

100 kilometers. In this region, Conley (1999) t-statistics are smaller than those obtained clustering at the unit level (shown by horizontal line in graph). But for all distances we estimate t-statistics over 3.0 on the interaction "University × 1800-1859" (left-hand graph).

Figure C1: Inference Varying the Distance of Spatial Correlation



This graph presents the t-statistics on our baseline estimates Table 2, column 1 as we vary the threshold for spatial autocorrelation. The t-statistics are estimated allowing for arbitrary spatial correlation following Conley (1999). The horizontal (blue) lines indicate the corresponding t-statistics estimated by clustering standard errors at the city-level.

C.2 Placebo University Locations

To further assess inference in settings characterized by spatial correlation, we can compare our baseline results to the distribution of estimates we obtain when we construct artificial spatially correlated data. We study the observed manufacturing outcome as it relates to placebo spatial data. We construct the placebo data by [1] assigning "artificial universities" to locations and [2] determining which cities were close to these placebo universities, defined by below median distance as in our baseline analysis. To do this, we randomly assign 19 artificial universities to locations in our data. We implement this in our baseline by assigning artificial universities to different 0.25×0.25 degree grid cells (approximately 27 kilometer by 27 kilometer cells).[44]

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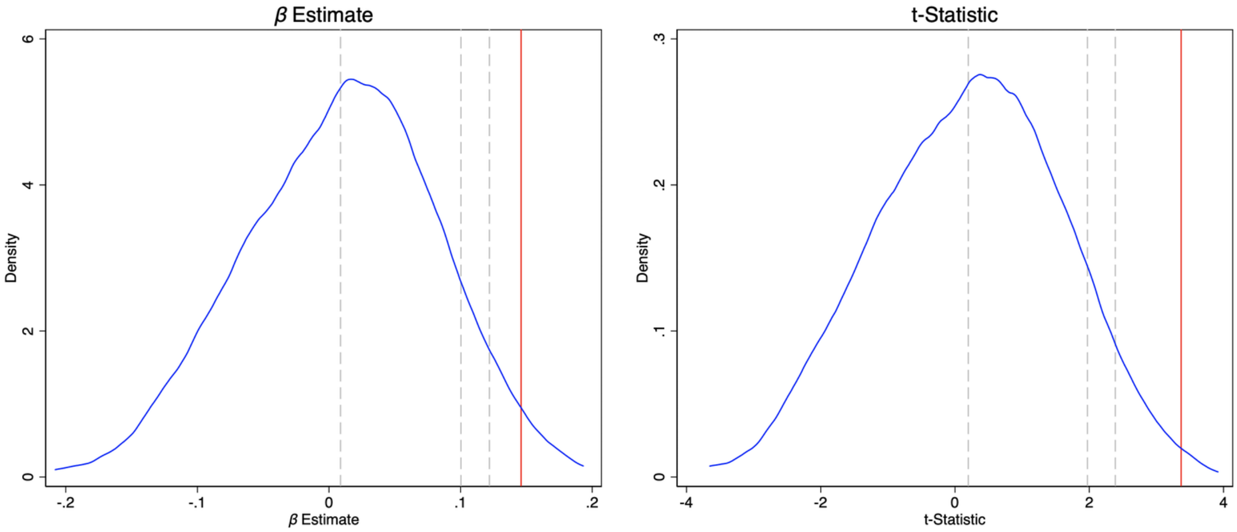
[44] Note that in our data many such grid cells contain multiple cities. Randomization at the level of the city generates "artificial university" locations that are relatively more concentrated in the most densely urbanized

We illustrate our findings by re-estimating the baseline regression specification in Table 2 (column 1) using placebo artificial universities to define university exposure. Figure C2 presents the distribution of parameter estimates we obtain for "University × 1800-1859" over 1,000 draws of random spatial data, and compares this to our estimate when we examine the true historical data. Figure C2 shows that the $\hat{\beta}$ and t-statistics we estimate in the historical data are found far less than 5% of the time in the artificial placebo data.

Figure C2: Distribution of Placebo Regression Estimates



This graph presents the distribution of estimates from placebo (spatial noise) regressions examining city-level manufacturing. The figure presents the distribution of estimates of the parameter on "Period 1800-1859 × University Close" (Table 2, column 1). The estimates are obtained from 1,000 draws of random spatial data assigning "placebo universities" to 0.5×0.5 degree grid cells and then calculating which cities are above and below median distance to the placebo universities. The vertical dashed lines indicate the mean, 90th percentile, and 95th percentile of the distribution of placebo estimates. The t-statistics are estimated allowing for arbitrary spatial correlation within a range of 25 kilometers following Conley (1999). The solid vertical (red) lines indicate our estimates with the historical data (Table 2, column 1).

C.3 Serial Correlation

Inference in differences-in-differences designs can also be threatened by the presence of serial correlation in the data. Bertrand, Duflo, and Mullainathan (2004) show that one way to address potential problems due to serial correlation is to collapse panel data into two periods,

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areas of historic Germany than actual universities were. However, even in this case our estimates are not consistent with a spatial noise falsification.

a pre-period before and a post-period after the introduction of treatment.

We follow this approach using our data from 1760 through 1839. We thus examine the pre-period 1760-1799 and the post-period 1800-1839. We then test whether manufacturing shifted differentially in the post period for cities near to universities.

Our results support our baseline analyses. Table C1 shows we find highly significant effects of universities on manufacturing after 1800, consistent with our baseline findings.

Table C1: Universities and Manufacturing in Pre-Post Comparison

	(1)	(2)	(3)	(4)
	Manufacturing Count		Manufacturing Binary	
University × Post 1800	0.14^{***}	0.08^{***}	0.06^{***}	0.04^{***}
	(0.03)	(0.03)	(0.01)	(0.01)
Time fixed effects	Yes	No	Yes	No
Territory × time fixed effects	No	Yes	No	Yes
Observations	4508	4508	4508	4508

This table reports regression estimates examining the count and presence of manufacturing events over the period 1760-1839. The outcome is manufacturing at the city-time-period level. The "Pre" period is 1760-1799. The "Post" period is 1800-1839. "University × Post 1800" interacts an indicator for cities below median distance to a university with an indicator for the post-1800 period. All estimates include city fixed effects. The "Territory × time fixed effects" interact indicators for territories with time period fixed effects. Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999).

D Case Study Evidence on Industrialization in Saxony

D.1 Historical Background and Comparison to Other Regions

Prior research indicates that mechanized technologies diffused in the textile industry across Germany starting around 1800 and that Saxony was overwhelmingly the leading region in this process (Tilly and Kopsidis 2020; Forberger 1982; Pollard 1981; Kirchhain 1973).

This evidence naturally invites a question about our analysis of manufacturing: was the university effect different in Saxony than in other parts of Germany? To consider this question, we test whether there was any difference in the post-1800 shift in manufacturing for cities near to universities if they were in Saxony as opposed to other regions. We extend the analysis in Table 3 (main text) to test whether in the post-1800 period university exposure is incrementally more or less predictive of manufacturing in Saxony. Table D1 reports our results and shows that we observe no difference between the university effect in Germany and the university effect in Saxony in the data on manufacturing.

Table D1: Universities and Manufacturing in All Germany and in Saxony

	(1) Manufacturing Count	(2) Manufacturing Binary
University × Post 1800	0.13^{***}	0.07^{***}
	(0.04)	(0.02)
University × Post 1800 × Saxony	-0.02	-0.00
	(0.12)	(0.06)
Time-varying controls	Yes	Yes
Observations	9016	9016

This table reports regression estimates examining the count and presence of manufacturing events over the period 1760-1839. "University × Post 1800" interacts an indicator for cities below median distance to a university with an indicator for the post-1800 period. "University × Post 1800 × Saxony" introduces as a further interaction an indicator variable for cities in Saxony. The estimates include time-varying controls, and city and time fixed effects. Table D1 Column 1 corresponds to Table 3 Column 2 in the main text. Table D1 Column 2 estimates the same model but examines the binary outcome measure. Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999).

D.2 Quantitative Analysis of Mechanization in Saxony

In this section we present several additional pieces of evidence on mechanization in Saxony.

Sensitivity of baseline results. The historical literature indicates that within Saxony manufacturing was concentrated in specific cities and notably in Chemnitz. It is natural, therefore, to wonder whether our results are driven by the number and technology choices of firms in Chemnitz or other leading cities. To examine this question, we re-examine the evidence first excluding Chemnitz from the analysis and then restricting the our analysis to cities with fewer than 10 establishments. As shown in Table D2, our findings when we restrict the sample in these ways are very similar to our baseline estimates (in Table 5).

Spatial correlation. Second, we present estimates of standard errors that account for arbitrary spatial correlation across different distance horizons. Table **??** presents OLS estimates corresponding to our baseline estimates in Table 5 in the main text. We estimate standard errors that allow for arbitary spatial correlation over 10, 25, 50, and 100 kilometers.

Table D2: Mechanization and Universities Outside the Largest Cities

	(1)	(2)	(3)	(4)
	Data: Exclude Chemnitz		Data: Cities with < 10 Firms	
	Outcome: Number of Firms		Outcome: Number of Firms	
	Mechanized	Other	Mechanized	Other
University Close	1.43***	0.01	1.63***	-0.27
	(0.55)	(0.59)	(0.38)	(0.67)
Observations	163	163	158	158

This table reports regression estimates examining the number of firms established in a city in a decade. Columns 1-2 exclude the city of Chemnitz from the analyses. Columns 3-4 restrict the analyses to cities with fewer than 10 factories and workshops established. The outcomes measure the number firms using mechanized or other (non-mechanized) technology established in a given decade. "University Close" is an indicator for cities below median distance to a university. These regressions are estimated with negative binomial regression. Heteroskedasticity robust standard errors in parentheses. Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively. Data are coded from Forberger (1982).

Table D3: Mechanization and Universities with Potential Spatial Correlation

	(1)	(2)
	Outcome: Number of Firms in City	
	Mechanized	Other
University Close	1.73	0.13
Standard errors		
Robust standard errors	0.83	0.17
Spatial standard errors 10 KM	0.83	0.17
Spatial standard errors 25 KM	0.77	0.12
Spatial standard errors 50 KM	0.66	0.11
Observations	164	164

This table reports regression estimates examining the number of firms established in a city 1800-1830. The outcomes measure the number firms using mechanized or other (non-mechanized) technology. "University Close" is an indicator for cities below median distance to a university. These regressions are estimated with OLS. Table reports heteroskedasticity robust standard errors, followed by standard errors allowing for arbitrary spatial correlation within 10, 25, and 50 kilometers following the methodology of Conley (1999). Data are coded from Forberger (1982).

E Historical Changes in and Around Universities

Timing of Shifts in Research and Science. The narrative evidence strongly indicates that the development of scientific and technical research shifted and accelerated around 1800. Thus Böhme and Vierhaus (2002; p. 165 – our translation) observe that, "the natural sciences in the middle of the 18th century did not yet have the professionalism, reputation, and scientific level that only began to develop fifty years later."

Significantly, pioneering developments in research infrastructure date from the late 1700s. For example, at Göttingen, scientific teaching and display collections of the Academic Museum, Botanical Garden, Observatory, Chemical Laboratory, and Physical Cabinet made Göttingen a center of science at the end of the 1700s (Böhme and Vierhaus 2002).

In what follows, we provide evidence on these changes across fields of knowledge and as they related to aspects of university structure and organization.

Chemistry. The first professorships of chemistry were established starting in the late 1700s and early 1800s. In 1789, a professorship in chemistry was established at Jena; additional professorships in chemistry were established at Erlangen in 1796 and 1807 and at Göttingen in 1810 (see Schwedt 2002; p. 85). Significantly, these professorships were established in the philosophy faculty, which was in the process of being elevated as the center of scientific research (*Wissenschaft*) and *pre-date* the foundation of the university of Berlin. There was some variation across universities in these processes. For example, chemistry remained within the medical faculty at Leipzig until 1830 (Krause 2003; p. 101-102), but the first chemistry lab at Leipzig university was set up in 1804/5. At Jena, a chemical laboratory – which was the predecessor to the chemistry institute – was established in 1811 on the top floor of the Duke's palace. The chemistry institute was established in 1816, at Goethe's initiative, and given new set-up in 1828 (Schwedt 2002; p. 91).

Technology. A prominent example of how changes in universities promoted economically useful knowledge is the establishment of the Physical-Mechanical Institute (*Physikalisch-mechanische Anstalt*) at Jena in 1802. The institute was set up by mathematics professor Johann Heinrich Voigt and had as its explicit mission to promote scientific knowledge inside and outside the university, including in the private sector: "In 1802, Voigt noted deficiencies in training. Among his students there were two groups of listeners whose interests he could not do justice to in his lectures: mechanics who wanted to learn the scientific basics of their profession, and 'normal' students, who wanted to learn more about instruments." (Ziche 2001; p. 227 – our translation)

Significantly, Johann Heinrich Voigt observed that he was unable to satisfy young mechanics, who were not enrolled as matriculated students but had been attending university lectures to acquire scientific and mathematical knowledge for their professional work:

> “Neither have I been able to satisfy any other class of participants in my lectures according to their wishes. These were not actual students, but young people who had learned practical mechanics and optics in so-called laboratories, but who had not had the opportunity to acquire the necessary scientific, mathematical-physical knowledge, knowledge which the heads of the most of the important laboratories in Germany have not had. These young people would therefore wish to go to the university for half a year or a year, to hear the lectures that are relevant to their art, but at the same time have the opportunity to continue their profession.” (cited in Ziche 2001; p. 228 – our translation)

The Physikalisch-Mechanische Anstalt that Voigt established had three objectives (cited in Ziche 2001; p. 229 – our translation):

> “1) So that young mechanics, who attend to university, have the opportunity to use the appropriate laboratory under specific conditions, so that they are not idle. 2) so that other students who want to have classes in practical mechanics such as glass sanding, wood turning, etc. have the opportunity [to take these classes] 3) so that when needed for math-physics lectures, new instruments can be bought and existing instruments can be modified and improved, supervised by the corresponding chair.

Notably, the institute was expressly designed to foster catch up with the technology progress in England. To achieve this goal, the institute hired three specialists: one scientific research manager, one marketing and sales manager, and one mechanic, who would supply teachers with instruments and mentor students.

Another example of university-based changes designed to promote economic catch-up and local spillovers is the establishment of the first chair in mineralogy and technology at Göttingen in 1811 (Schlotter 1994; p. 186). This position was established to promote local economic development and the investigation of local resources.

Mathematics. The historical evidence suggests that mathematical research promoted technological innovation both directly and through spillovers. An example of a mathematics professor having a direct positive impact on technical knowledge is Abraham Gotthelp Kästner at Göttingen, who published influential text book that on mechanics and thermodynamics in 1799. However, we also observe important connections between basic scientific research, including by mathematicians, and technological break-throughs. For example, the research Carl Friedrich Gauß and Wilhelm Weber conducted on electricity and magnetism in the early 1800s led as a “*by-product*” to the discovery of the electrical telegraph (Schlotter 1994; p. 144).

Structure. Innovation in the structure of scientific research at universities involved, among other factors, the development of quasi-autonomous institutes and bodies outside the pre-existing faculties. For example, the chemical laboratory and botanical gardens formed at Jena in the 1780s were established outside the existing university faculties, by "extraordinary professors" who received their own funding and equipment and played a critical role in the development of research in the early decades of the 1800s (Ziche 2001; p. 140).[45]

Quasi-independent institutes were established more broadly. For instance, the first institute established within the university of Marbug was the "State Economy Institute" (*Staatswirtschaftlichen Instituts*) founded in 1789, which offered lectures in economics, mining and metallurgy, forestry and agriculture, technology, chemistry, mathematics, physics, and statistics – among other subjects (Hermelink and Kaehler 1927; p. 451-2). More generally, the establishment of seminars transformed the nature of research conducted at universities, in particular by providing settings in teachers and students were able to collaborate in the 19th century (Krause 2003; p. 103-4).

Pro-science changes also reshaped the pre-existing faculties. Before the 1800s, the arts (philosophy) faculty ranked below the law, medicine, and theology faculties in importance and prestige. Over the first decades of the 1800s, scientific research was transferred to and consolidated in the arts faculties, which became centers of science. For instance, the university of Leipzig reorganized its faculty in 1809. In 1819, a new organization of training for Saxony pharmacists was introduced and "the first chemical laboratory of the university was established on the Pleißenburg in 1804/05" (Krause 2003; pp. 100-101). In 1821, Sachsen state parliament (Landtag) granted the university annual subsidy of 2,000 Reichsthaler on condition that it maintain transparent books. As these changes were consolidated, the value of a strong and well-staffed university gained traction (Hermelink and Kaehler 1927; p. 419).

F Schooling and Manufacturing

The Role of Schools. Our main analysis shows that the estimated relationship between universities and manufacturing holds accounting for presence of *higher schools*. It is natural to wonder whether the findings shift when we account for different levels and types of

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[45] Extraordinary professors were not appointed with chairs, in contrast with ordinary (full) professors.

schooling and the *number* of schools and not simply the *presence* of schools. More generally, the relationships between the expansion of different types of schooling and industrial activity are themselves of economic interest and clarify our findings regarding universities.

Expanded Investigation. To measure the provision of education on different margins, we gather evidence on the establishment and operation of elementary schools, middle schools, trade schools, and technical colleges across all cities in our data. We classify schools as follows. We record and classify as "lower schools" all elementary schools (*Elementarschulen*), as well as a small number of "work schools" (*Arbeitsschulen*) and "charity schools" (*Armenschulen*). We separately record and classify all "middle schools" (*Mittelschulen*). We classify as "vocational schools" all vocational schools proper (*Berufsschulen*) as well as "advanced training" and "continuing education" schools (*Fortbildungsschulen*). We exclude from our analysis a small number of military schools (*Militärschulen*), music schools (*Musikschulen*), "seasonal schools" (*Saisonschulen*), and "special education" schools (*Hilfsschulen*). We also record where and when "Technical Higher Schools" (*Technische Hochschulen*), which were forerunners of later "technical universities," were established. Our findings (below) are robust to alternate categorizations and the inclusion of all types of schools. The first *Technische Hochschulen* were established in the 1820s, as discussed in Section 2.2 (main text).

Quantitative Analysis. We extend our baseline quantitative analysis as follows.

We first examine how the presence of different types of schools was related to manufacturing in Table **??**. Column 1 of Table **??** replicates the estimates in the main text for the 1760-1899 period (Table 3, Column 1). Our estimates of the relationship between universities and manufacturing hold almost unchanged when we separately control for the presence of lower, middle, and vocational schools and proximity to *Technische Hochschulen* (Table **??**, Column 2). Our estimates of the university effect are stable even as we find a significant relationship between the presence of middle schools and vocational schools and manufacturing outcomes when we study evidence including the late 1800s. Over this period, we find no positive relationship between manufacturing and proximity to *Technische Hochshulen*, which we measure with an indicator for cities within 50 kilometers of such a school. Our results are similar using other measures of distance to such technical schools.

We next focus on manufacturing between 1760 and 1839, before the build out of the railroad network. Column 3 replicates the estimates in the main text. Column 4 shows that these estimates again hold almost unchanged when we separately control for lower, middle, and vocational schools and *Technische Hochschulen*. Over the period through 1839 we find no large or statistically significant relationship between middle schools and vocational schools and manufacturing. This confirms that over the key period in which universities drove an early positive shift in industrial activity the presence of schools at lower levels had a relatively weak and more diffuse relationship to economic development. Over this period, we find a positive, weakly significant relationship between manufacturing *Technische Hochshulen*.

A natural question is whether manufacturing may have shifted with the *number* of schools in a city, which might reflect the intensity of educational provision or other time-varying factors. We therefore expand our analysis to account for the numbers of different types of schools. As shown in Table **??**, our key findings are unchanged when we account for the number of different schools in a city (Columns 5 and 6). As in our baseline analysis examining the *presence* of schools, we find that only the *number* of higher schools had a significant relationship with manufacturing in the pre-1840 (column 8). Controlling for the number of schools at different levels, we find no significant relationship between manufacturing and proximity to *Technische Hochschulen*.

Several observations on the findings are worth noting. The pattern we document, in which university exposure is a robust predictor of manufacturing after 1800, holds controlling for different aggregations and disaggregations of the data on schools. In addition, the fact that proximity to *Technische Hochschulen* is not a strong explanatory factor warrants further study, but may be interpreted in light of the following. First, over the pre-1840 (pre-railroad) period, there is a positive if diffuse relationship between manufacturing and proximity to these technical institutions. Second, the very first of these institutions were only established in the 1820s, so exposure was limited in the pre-railroad era. Third, broadly speaking our results suggest that the pattern of local economic spillovers associated with knowledge production was strongest before the railroad era. This may help explain why technical higher schools, which developed most strongly in the later 1800s, were not so clearly associated with *local* shifts in manufacturing.

Table F1: Universities, Schools, and Manufacturing

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Count of Manufacturing Events				Outcome: Count of Manufacturing Events			
	Controls: Binary Measures of Local Schooling				Controls: Counts of Local Schools			
	1760-1899		1760-1839		1760-1899		1760-1839	
	Baseline	All Schools	Baseline	All Schools				
University × 1800-1859	0.14***	0.13***	0.13***	0.13***	0.14***	0.14***	0.13***	0.13***
	(0.04)	(0.04)	(0.03)	(0.03)	(0.04)	(0.04)	(0.03)	(0.03)
University × 1860-1899	0.06*	0.06*			0.06*	0.06*		
	(0.03)	(0.03)			(0.03)	(0.03)		
Higher School	0.18***	0.15***	0.20***	0.18**	0.09***	0.05***	0.08**	0.06*
	(0.04)	(0.04)	(0.07)	(0.07)	(0.02)	(0.02)	(0.04)	(0.04)
Lower School		0.03		0.06		0.03**		0.01
		(0.03)		(0.04)		(0.02)		(0.02)
Middle School		0.07**		0.06		0.00		0.07
		(0.03)		(0.06)		(0.02)		(0.06)
Vocational School		0.08**		0.03		0.04**		0.01
		(0.03)		(0.07)		(0.02)		(0.03)
Technische Hochschule		-0.03		0.06*		-0.04		0.04
		(0.06)		(0.04)		(0.06)		(0.04)
City and Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time-Varying Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15778	15778	9016	9016	15778	15778	9016	9016

This table reports regression estimates with variables defined as in the main text. “Higher School”, “Lower School”, “Middle School” and “Vocational School” variables are city-level indicators in columns 1-4 and city-level counts in columns 5-8. “Technische Hochschule” is an indicator for cities within 50 kilometers of such an institution in a given period. The time-varying control variables are as in the main text: “Railroad Connection” and “Free Enterprise Law” indicators constructed from Kunz and Zipf (2008) and coded following Acemoglu et al. (2011), respectively; “Early Manufactures × Post-1800”; and “Coal × Post-1840”; and “Coal × Post-1800”. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Conley (1999). Statistical significance at the 90, 95, and 99 percent confidence level denoted “*”, “**”, and “***”, respectively.

G French Revolution

G.1 Challenge and Critiques

The main criticism is simple — we never convincingly document or substantiate the claim that the French Revolution drove the changes in universities.

- Our previous analysis argued that the *common shock* of the French Revolution had spatially varying consequences, because it was transmitted through universities.
- Our argument relied entirely on the *timing* of (1) the French Revolution and the (2) shifts in (2.1) time series on 'research collections', (2.2) the spatial pattern of innovation as per Darmstaedter, and (2.3) the spatial pattern of industry.
- One referee suggests *cultural* processes, in particular the Enlightenment, could account for the timing and geography of the shifts in industry and innovation we document.
- More formally, our argument has two moving parts, both of which referees question:

$$treatment_{it} = \underbrace{(\text{`after the French Revolution'}_t)}_{\text{what evidence supports this claim?}} \times \underbrace{(\text{`university proximity'}_i)}_{\text{how? what is the mechanism?}}$$

Referees suggest we should study variation in the French Revolution shock itself.

1. Culture hypothesis: "if French Revolution delivered a pro-science cultural shock, we'd expect the 'university effect' to be bigger where the French Revolution 'hit harder'."
2. Shock to state hypothesis: "if the French Revolution delivered a shock to state organization, including consolidations of territories that 'lowered the price' of (barriers to) reforms, we would expect the 'university effect' to be bigger where the French Revolution reordered the state more."
3. Economic institutions hypothesis: "where *free enterprise laws* or Code Napoleon are passed (Acemoglu/Donges) we might see a larger university effect".

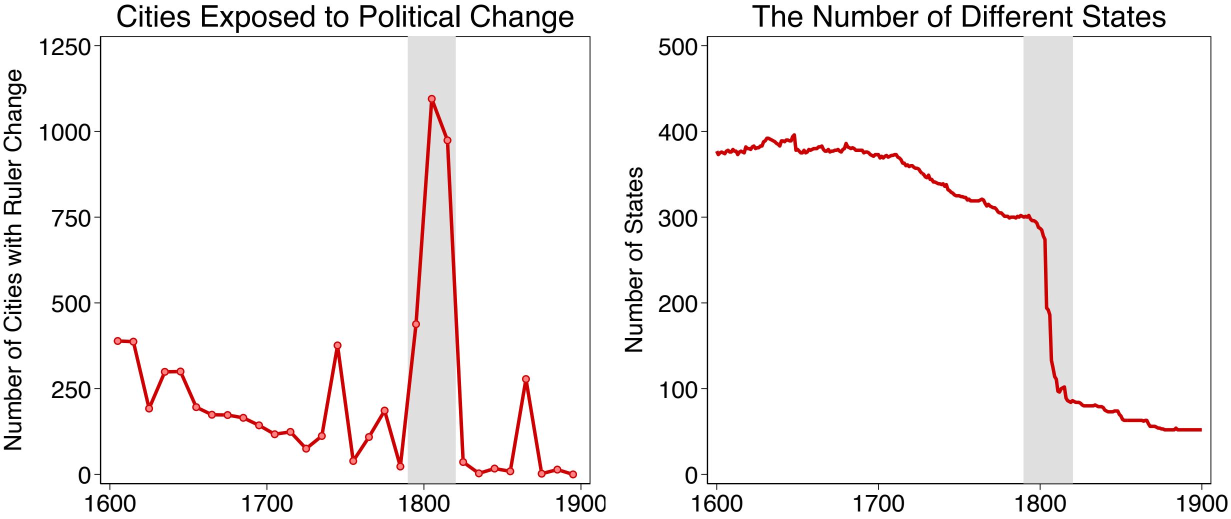
Note: none of the referees provide a clear theory or hypothesis on how or why differences in the French Revolution shock should matter. But they do seem to believe that that if it mattered, then we should verify this quantitatively and by studying 'heterogeneity'.

Further editorial note: the maintained hypothesis – “if the shock mattered, variation in the shock should map into variation in the university effect” – is not obviously correct. Because the university *system* was a competitive environment, local shocks might be transmitted, due to competition for and the geographic mobility of faculty and students. In addition, bigger shocks could be accompanied by offsetting factors.

G.2 Quantitative Analysis

First, we document that the French Revolution was associated with a major reorganization of the German state system. We measure the shock with the number of cities experiencing a change in their ruler, i.e. the state they belong to.

Figure G1: The Political Shock



Graph plots data on "ruler changes" by decade for 2,254 German cities recorded in Keyser (1939-1974). The shaded region (1790-1819) represents the shock associated with the French Revolution.

Second, we extend our baseline quantitative analysis to test whether there is a differential university effect after 1800 where the French Revolution shock was greater. We estimate models of the general form:

$$y_{it} = \beta_1(uni_i \times post_t) + \beta_2(uni_i \times post_t \times shock_i) + \theta_i + \delta_t + u_{it}$$

We explore several candidate measures of the French Revolution *shock*. We present estimates focusing on two post periods (1800-1859 and 1860-1899) as in the min text.

1. We test whether there is a differential effect for cities exposed to universities which experienced political change in their city alone 1789-1820, measured by a change in the ruler (state) governing the city in which the university was located (columns 2-3).

2. We test whether there is a differential effects for cities exposed to universities which experienced more political change in their (the universities) 'cachement area' 1789-

1820, measured by the share of cities for which university i was the closest university that experienced political change in their ruler/state (columns 4-5).

3. We test whether there is a differential effect for cities exposed to universities located in territories that grew, measured by the change in the number of cities in the territorial unit a given university i was located in between 1789 and 1820 (columns 6-7).
4. We test whether there is a differential effect for cities exposed to universities in territories acquiring economic institutions associated with the spread of the French Revolution, following Acemoglu et al. 200X (column 8).

What's open-ended here:

- What measure of 'shocks'?
- It is not clear how these measures of shocks do or do not explain *other* variables, like inventions, which universities produce inventors, or research collections – some (hazy) evidence that these measures of political shock do positively explain research collection expansions (growth) 1789-1820, but that's an exercise across like 15 universities.
- The exercise 'Δ Size' is weird because a number of universities are in the same territory post-1820. So the incremental 'treatment' is the same and we do not yet consider the fact that these are not independent pieces of information.

Table G1: The French Revolution Shock and the University Effect

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Count of Manufacturing Events							
		Shock Measure 1			Shock Measure 2			Economic
	Baseline	Change in Territory Size			1/0 Above Median Shock			Institutions
University x 1800-59	0.140***	0.077*	0.078*	-0.002	0.065	0.064	0.000	0.123***
	(0.032)	(0.040)	(0.040)	(0.040)	(0.049)	(0.049)	(0.047)	(0.038)
University x 1860-99	0.068**	0.061	0.063	0.050	0.005	0.004	-0.047	0.104**
	(0.032)	(0.040)	(0.040)	(0.046)	(0.048)	(0.048)	(0.055)	(0.051)
University x Shock x 1800-59		0.027**	0.025**	0.026**				
		(0.012)	(0.012)	(0.012)				
University x Shock x 1860-99		0.004	0.002	-0.005				
		(0.012)	(0.012)	(0.013)				
Shock x 1800-59		0.005	0.001	-0.011				
		(0.008)	(0.008)	(0.016)				
Shock x 1860-99		0.012	0.006	0.016				
		(0.009)	(0.009)	(0.018)				
University x (Shock > Median) x 1800-59					0.130**	0.116*	0.108*	
					(0.066)	(0.066)	(0.065)	
University x (Shock > Median) x 1860-99					0.118*	0.102	0.120	
					(0.066)	(0.066)	(0.073)	
(Shock > Median) x 1800-59					-0.036	-0.072*	-0.007	
					(0.043)	(0.044)	(0.086)	
(Shock > Median) x 1860-99					-0.004	-0.046	-0.122	
					(0.046)	(0.046)	(0.101)	
Uni x 1860-99 x Free Enterprise Law								-0.049
								(0.053)
Uni x 1800-59 x Free Enterprise Law								0.062
								(0.065)
City-Level Ruler Change	No	No	Yes	Yes	No	Yes	Yes	No
Free Enterprise Law	No	No	No	No	No	No	No	Yes
Territory-x-Year FE	No	No	No	Yes	No	No	Yes	No
Observations	15778	15778	15778	15778	15778	15778	15778	15778

Column 1 is our baseline estimate. Columns 2-3 test whether there was a differential effect for universities in cities that changed their ruler 1789-1820. Columns 4-5 test whether there was a differential effect for universities with cachement areas in which a larger share of cities changed their ruler 1789-1820 (measured as the share of cities for which university i was the closest that changed their ruler). Columns 6-7 test whether the effect was larger for universities in territories that became more consolidated, measured by the change in the number of cities ("Δ Size"). Column 8 tests whether the university effect was larger where economic institutions were reformed via "free enterprise laws" (Acemoglu). Models with "City-Level Ruler Change" control for variation associated with city-level ruler changes (1789-1820) interacted with time period fixed effects. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Conley (1999). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

Table G2: The French Revolution Shock and the University Effect

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Count of Manufacturing Events							
	Baseline	Change in Ruler at University		% Change in Ruler Near Uni		Δ Size of Uni Territory		Economic Institutions
Uni x 1800-59	0.14***	0.10**	0.15***	-0.05	0.02	0.06*	0.07**	0.12***
	(0.03)	(0.05)	(0.05)	(0.06)	(0.06)	(0.04)	(0.04)	(0.04)
Uni x 1860-99	0.07**	0.07	0.13***	-0.03	0.07	0.03	0.05	0.10**
	(0.03)	(0.04)	(0.04)	(0.06)	(0.06)	(0.04)	(0.04)	(0.05)
Uni x 1800-59 x Change at Uni		0.06	-0.01					
		(0.05)	(0.06)					
Uni x 1860-99 x Change at Uni		0.00	-0.10*					
		(0.05)	(0.05)					
Uni x 1800-59 x Change in Uni Area				0.27***	0.18**			
				(0.08)	(0.08)			
Uni x 1860-99 x Change in Uni Area				0.14*	-0.01			
				(0.08)	(0.08)			
Uni x 1800-59 x Δ Size of Uni Territory						0.03***	0.03***	
						(0.01)	(0.01)	
Uni x 1860-99 x Δ Size of Uni Territory						0.02**	0.01	
						(0.01)	(0.01)	
Uni x 1800-59 x Free Enterprise Law								0.06
								(0.07)
Uni x 1860-99 x Free Enterprise Law								-0.05
								(0.05)
City-Level Ruler Change	No	No	Yes	No	Yes	No	Yes	No
Free Enterprise Law	No	No	No	No	No	No	No	Yes
Observations	15778	15778	15778	15778	15778	15778	15778	15778

Column 1 is our baseline estimate. Columns 2-3 test whether there was a differential effect for universities in cities that changed their ruler 1789-1820. Columns 4-5 test whether there was a differential effect for universities with cachement areas in which a larger share of cities changed their ruler 1789-1820 (measured as the share of cities for which university i was the closest that changed their ruler). Columns 6-7 test whether the effect was larger for universities in territories that became more consolidated, measured by the change in the number of cities ("Δ Size"). Column 8 tests whether the university effect was larger where economic institutions were reformed via "free enterprise laws" (Acemoglu). Models with "City-Level Ruler Change" control for variation associated with city-level ruler changes (1789-1820) interacted with time period fixed effects. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Conley (1999). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.