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

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

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Abstract

We examine the role of universities in knowledge production and industrial change using historical evidence. Political shocks led to a profound pro-science shift in German universities around 1800. To study the consequences, we construct novel microdata. We find that 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. After 1800, the adoption of mechanized technology and the number and share of firms winning international awards for innovation were higher near universities.

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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

The research university is widely viewed as a key institution producing knowledge, but there is limited evidence showing that universities have driven major transformations in the production of useful knowledge and industrial activity. In this paper we study the economic impact of universities in 19th century Germany, where the modern research university first developed. Here history provides us with a canonical model of the potential economic role of universities and a process shaped by exogenous political shocks, originating in the French Revolution of 1789. In this setting, we observe, "the growth of teaching and research excellence in a preindustrial society" (Cassidy 1981; p. 657) and an economy shifting from a position of backwardness onto a path to the world frontier in technology and industry. However, no quantitative economics research has studied this process, reflecting in part the paucity of existing data on German industrialization before the later 1800s.

We gather novel, disaggregated data and document how universities shaped a major pivot in the development of invention and industrial activity in early 1800s Germany.[1] We first show that scientific and technological discovery shifted significantly across cities towards universities after 1800. We then study evidence on manufacturing establishments and invention 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 shift in manufacturing towards universities was most pronounced in new and knowledge intensive industries. In addition, we find that firms in cities nearer to universities were more likely to adopt mechanized production technologies and to win international prizes for industrial innovation in the 1800s.

The dynamics we study reflect exogenous political shocks. The French Revolution and the Napoleonic invasion of Germany precipitated major pro-science changes in German universities. These changes ran through universities whose locations were fixed by historical

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[1] We use "Germany" and "German" as short-hands. We analyse economic activity in 2,254 historically German-speaking cities that were in the Holy Roman Empire before 1805, the German Union (*Deutscher Bund*) after 1805, and the German Empire after 1871 and before WWI.

processes and which were not previously driving economic development. We thus analyse the role of universities in crystallizing and transmitting a key component of these political shocks which, as we show, also impacted development through other channels.[2]

Our investigation of this process is grounded in historical analysis. The French Revolution and Napoleonic invasion shifted the demand for and supply of research in Germany. In the 1700s, German universities focused on theology and law and student enrollments were in decline (Turner 1975). The French Revolution and Napoleonic invasion shifted the values of intellectual and administrative elites (Hagemann 2006; Whaley 2012; Blackbourn 2003). This led to the development of a pro-science and pro-research model for university education (Rüegg 2004a; McClelland 2008). Specifically, "the early 19th century concept of *wissenschaftliche Bildung* (scientific education) had a profound impact on the history of the German university," which was transformed into "the pre-eminent loci of research and *Bildung* (education)" (Van Bommel 2015; p. 3). Scientific and technical activities at universities expanded, including mechanical institutes that promoted spillovers into industry (Ziche 2001). These changes mark arguably one of the most important transformations in the history of the university. By the mid-1800s, the excellence of German universities and their superiority in the sciences were recognized internationally (Arnold 1868; Urquiola 2020).

We motivate our study with a new stylized fact: scientific and technological discovery increased and shifted spatially towards universities in early 1800s Germany. Figure 1 traces this shift in knowledge production in data recorded in the history of science literature.

Economic analysis predicts that such profound, geographic changes in knowledge production will transform the nature and location of economic activity, including through spillovers into industry. To study the economic consequences within Germany, we investigate interlocking bodies of novel microdata. We use the data to trace the temporal and spatial pattern of manufacturing, invention, technological change, and the quality of innovation. We distinguish changes shaped by universities from those driven by other factors, such as railroads which were built decades after shifts in knowledge production and manufacturing.

We first examine new evidence on manufacturing across every city in historic Germany from 1760 through 1899. We collect data on manufacturing activity (establishments) at the

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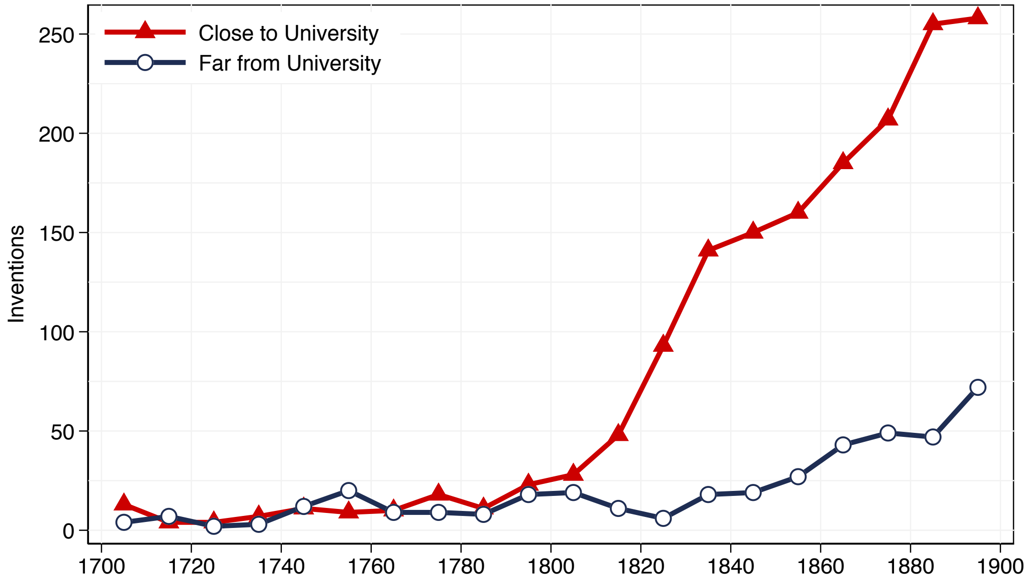
[2] The causal dynamics we study contrast with those in other countries, where the research university was adopted endogenously in the later 1800s in response to developments observed in and around universities in Germany (Arnold 1868; Urquiola 2020).

Figure 1: The Pattern of Scientific and Technological Discovery



This graph plots data on major scientific and technological discoveries from Darmstaedter, du Bois-Reymond, and Schaefer (1908), located 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.

city-industry-time level as recorded in the *Deutsches Städtebuch*, an encyclopedia of 2,000+ historic cities. Our data provide evidence on manufacturing before census data are available, and strongly predict the number of factories and number of workers in two-digit industrial sectors recorded when census coverage begins in the mid-1800s. We analyse the data using distance to university as a proxy for the effect of universities on manufacturing that accounts for spillovers. We find that cities near to universities enjoyed no advantages or differential positive trends in manufacturing in the 1700s, and that manufacturing expanded significantly in cities near universities in the early 1800s, consistent with our historical analysis.

We present several analyses which support a causal interpretation of the positive relationship between the universities and manufacturing after 1800. First, we show that our findings are not driven by potentially endogenous university locations. There are no pre-trends towards universities, and the positive shift in the relationship between universities and manufacturing after 1800 is not driven by new universities or changes in locations. Second, we show that our findings are not driven by regionally-varying factors, such as institutional changes that also shaped development (Acemoglu et al. 2011). We find that proximity to universities strongly promoted manufacturing after 1800 when we compare cities within the same political territory, controlling for time-varying factors shared within territories comprising the historic German Union. Third, we show that the university effect is also not driven by other factors varying within regions and over time. For example, we collect detailed evidence on all schools in the cities we study. We find that schooling is not a confounder. Local differences in higher level schooling do not explain the university effect, and in fact appear after shifts in manufacturing, suggesting advanced schooling was endogenous. We find no significant relationship between elementary and middle schools and manufacturing before the late 1800s. Fourth, we also use the timing of the economic changes to interpret the process. We observe the effect of universities on manufacturing starting in the early 1800s, and thus over decades before the German customs union lowered trade barriers, before railroads appeared, before coal deposits became important for the location of industry, and before the emergence of Germany's distinctive universal banks.

To investigate the economic mechanism, we examine how the university effects play out across industries. We first examine how universities were related to the expansion of manufacturing in new industries that did not previously exist in a given city. We find that universities were particularly strongly associated with the development of such new industries. We contrast the university effect on new industries with the implications of prior historical ("proto-industrial") manufacturing, which historians suggest also shaped industrial dynamism in the 1800s. Differences in prior proto-industrial development do not explain or diminish the university effects we estimate. Further, where universities explain the development of manufacturing in new sectors and on the extensive margin, earlier proto-industrial activity in a city is a strong predictor of post-1800 development in previously existing industries, but a weak predictor of manufacturing in new industries.

We next examine how the university effect varied across more and less knowledge-intensive industries. To measure the knowledge intensity of industries, we use our data on technological discovery, in which we gather historical evidence on the educational backgrounds of inventors. We classify industries as "high knowledge" and "low knowledge" based on the share of inventions used in a given industry made by university-educated inventors. We find that the shift in manufacturing towards universities was largely driven by high knowledge manufacturing. Interpretively, we emphasize that the differential increase in high knowledge manufacturing near universities is likely to reflect how political shocks shifted both exogenous (supply-side) and endogenous (demand-side) processes. In particular, the patterns that we document reflect, in part, how the shocks of the late 1700s and early 1800s made universities and university-educated inventors more responsive to economic incentives, and thus allowed them to act in new ways as conduits for induced technological change.

To study the relationship between universities and technological change directly, we examine establishment-level evidence on the adoption of mechanized production technology. Our principal source of data, the *Deutsches Städtebuch*, unfortunately 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. In these data, we observe that mechanization increased significantly faster in cities closer to universities in the first decades of the 1800s, consistent with our analysis.

Finally, we extend our investigation to study the *quality* of industrial innovation and whether universities may have promoted the development of internationally competitive products and technologies. We focus on competitive prizes for industrial innovation awarded at the first world's fair, *The Great Exhibition of the Industry of All Nations* at Crystal Palace in 1851 (see Moser 2005). Examining the exhibits from Germany, we find that significantly more competitive awards were won by producers from cities near universities. The share of exhibits winning prizes in German cities near universities was similar to the share winning prizes in Belgium, whereas the share winning prizes in cities far from universities was similar to that in Spain. The data from Crystal Palace also provide cross-sectional verification of the patterns in our main panel database on science and discovery. In the panel, however, our richer data show practical invention shifting significantly across German cities towards universities after 1800, consistent with the dynamics in manufacturing.

Our findings contribute to the literature on innovation and growth. A theoretical literature emphasizes the importance of innovation for growth (Aghion and Howitt 1998; Romer 1994; Nelson and Phelps 1966), while empirical work identifies research universities as 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 has identified local spillovers from universities into agricultural productivity (Kantor and Whalley 2019). However, the role of universities in promoting large scale shifts in invention and industrial activity has not been systematically documented.[3] We provide evidence

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[3] Prior historical studies indicate that universities shaped institutional change in medieval Europe (Cantoni

showing that universities shaped a major pivot in development and that, as Landes (1969, p. 151) observes, scientific education may offer a "cure for technological backwardness."

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) show that persistent pre-industrial differences in non-university scientific elites explain variation in the local diffusion of the industrial revolution in France. Becker and Woessmann (2009) find that the Protestant Reformation shaped local differences in primary education and economic structure in late 1800s Germany. In contrast, we document how German universities *became* centers of scientific research and invention and drivers of industrialization after major political shocks.

More generally, we provide evidence on how politics and culture feed into economic outcomes. 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 culture worked through elite education to shape innovation and development, in the spirit of Mokyr (2016). Further, we document the role of the university in promoting capitalist industrialization in a setting in which changes in political institutions were circumscribed (Kuczynski 1961; Blackbourn and Eley 1984; Davidson 2012). The German path famously involved a "revolution of the mind" but not liberal democracy (Palmer 2014; Blackbourn 2003).

Our study also speaks to a classic debate about the industrialization process in Europe. 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 far more continuous process, induced by deeper historical developments (Tilly and Kopsidis 2020; Kopsidis and Bromley 2017). Our evidence reveals an important shift toward industrialization, centered around universities, in the early 1800s. Our findings point to a substantially new view of the industrialization process.

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and Yuchtman 2014) and the development of science in the Renaissance (Dittmar 2019), but made limited direct contributions to innovation and industry in the English Industrial Revolution (Mitch 1999).

2 The Historical Process

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). Becker, Hornung, and Woessmann (2011) argue that Germany was "pre-industrial" in the first decades of the 1800s and Landes (1969; pp. 151, 187) suggests that higher education and scientific training had payoffs after 1850.[4]

A second strand of literature emphasizes the gradual and relatively continuous nature of the industrialization process. Kaufhold (1986) and Ogilvie (1996a;b) 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; 2017) 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.

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).[5]

Where the prior literature uses econometric methods to investigate the development of manufacturing or inventive activity, almost all studies consider data from periods after 1840.[6]

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[4] Indeed, a large share of the population was employed in agriculture into the late 1800s (Kopsidis and Bromley 2017). 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).

[5] 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.

[6] Quantitative research on invention is largely restricted to the patent record (Streb, Baten, and Yin 2006; Donges and Selgert 2019a;b). 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.

Thus Tilly (1991; p. 177 – emphasis in original) observes that, "the 'big spurt' view is based mainly on empirical study of German heavy industry and railroads, coupled to the leading sector theory of industrialization; it is *not* based on firm quantitative evidence covering other sectors and the *pre*-1840 period."[7]

Prior research does, however, suggest that the political shocks around the turn of the 19th century may have influenced economic dynamics through institutional, trade, and knowledge production channels. The French invasion and control of German territories led to legal reforms, including the abolition of guilds and occupational restrictions starting in the 1790s.[8] The Napoleonic wars also disturbed trade, raising effective protection against British imports (Juhász 2018) and disturbing input supplies, with unclear net effects (Crouzet 1964; p. 579). Our analysis below therefore studies how universities shaped invention and industrialization *within* political territories and thus across cities exposed to similar patterns of institutional change and similar trade shocks.

2.2 Universities, Science, and Technology

The historical shift towards scientific and technological activities at German universities is at the heart of our analysis. In the 1700s, universities focused on theology and law and saw declining enrollment (Bahti 1987; Turner 1975; Eulenburg 1904). In the 1800s, German research universities emerged as world leaders in science and technology. Turner (1987; p. 56) observes, "No proposition in the historiography of science has received more universal assent or so defied precise formulation than the claim that between 1775 and 1830 the sciences underwent a revolutionary change – a 'great transition'."

Political events shifted the supply of and demand for scientific knowledge in Germany. On the supply side, the French Revolution inspired pro-science intellectuals (Whaley 2012; p. 601). For example, Kant wrote his *Critique of Judgment* (Kant 1987 [1790]; p. xxix) over a period in which the French Revolution "occupied him entirely," according to his friend Reinhold Jachmann.[9] Following Kant's intervention, "the ideal of a rigorous science

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[7] Scholars have for some time pointed to the potential underestimation of development pre-1850 (e.g. Fremdling 1995). 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."

[8] 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.

[9] More conceptually, Karl Marx (1975 [1842]; p. 213) noted that Kant's work should be considered, "the

experienced a spectacular upsurge" (Van Bommel 2015; pp. 12-14). On the demand side, the French Revolution shifted values in a pro-science direction. Thus in 1793 Johann Kiesewetter wrote to Kant that interest in Kant's work was increasing, "since the French Revolution has stimulated a mass of such questions anew" (Kant 1999; p. 463). Palmer (2014) summarizes the German response to the French Revolution as a "revolution of the mind."

The Napoleonic invasion of Germany also promoted the modernization of university education. This involved the institutionalization of the research university ideal advocated by Prussian Interior Minister Wilhelm von Humboldt, the most influential education policy maker in German history. Subsequent developments included a shift of resources from law, medicine, and theology towards the philosophy faculty which became the main location of scientific activity; the expansion of research seminars and institutes especially in the late 1820s; and the introduction of a model combining education and research to increase knowledge. The university of Berlin is the prime example of the Humboldt model.

Table 1 provides a timeline of shifts towards science and technology that generated spillovers into industrial activity. Professorships in scientific subjects that generated useful knowledge were created in philosophy departments (Martin 2007; Hinz 1961). Research institutes were established to promote the development and commercialization of technology, such as the institute at Jena (Ziche 2001; p. 193). Complementary, biographical evidence points to the importance of inventions developed at and around universities and by university graduates, which we confirm quantitatively (Section 5). Narrative evidence also indicates that university graduates established manufacturing firms and that mechanics attended universities as non-matriculated students after 1800.[10] We observe important changes following French Revolution and before the founding of the university of Berlin.[11]

Quantitative evidence on the diffusion of scientific ideas and university enrollments

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German theory of the French Revolution." See also Marcuse (1960; pp. 3-4) on how profound innovations in German philosophy and intellectual life developed, "largely as a response to the challenge from France."

[10] Professor Johann Heinrich Voigt (1751-1823) observed 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 new instruments; promote the commercialization of technologies; and enable visiting 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).

[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."

Table 1: Changes in University Science and Technology

1789	Independent chair of chemistry established at Jena
1790	Mathematics established as section of Philosophy faculty at Giessen
1802	Natural history and physics instrument collection at Tübingen
1802	Physical Mechanical Institute established at Jena
1803	Applied sciences section established in Heidelberg Philosophy faculty
1804	Chemical laboratory established at Leipzig
1809/1810	Foundation of university at Berlin
1818	Establishment of chair of Technology at Tübingen
1820s onwards	Large scale expansion of research institutes and seminars

Sources include: 1789 Jena: Schwedt (2002; p. 86); 1790 Giessen: Baumgarten (1988; p. 118); 1802 Tübingen: Decker-Hauff and Fichtner (1977; p. 116); 1802 Jena: Ziche (2001; p. 227); 1803 Heidelberg: Hinz (1961; p. 277); Leipzig 1804: Krause (2003; pp. 100-101); Tübingen 1818: Marino (1995; p. 360); 1820s onwards institutes and seminars: Titze (1995) and Dieterici (1836).

confirms the timing of these shifts. Figure 2, Panel A shows that the German-language word for scientific inquiry (*wissenschaftliche*) rapidly diffused in German books starting in the late 1700s.[12] Panel B shows that enrollments at German universities were declining in the 1700s and began to increase in the early 1800s, after the Napoleonic wars.

The changes in German universities reflected cultural and financial support. Evidence on university budgets and resources in the early 1800s is fragmentary due to the nature of historic record-keeping. For example, historians indicate that "massive state intervention" enabled the university of Jena to survive potential crisis in 1803 and established "a veritable phalanx of…scientific institutions" (Ziche 2001; p. 152 – our translation). However, these institutions were only formally recognized by new university statutes in 1821. Similarly, in 1821 the state parliament of Saxony granted the university of Leipzig an annual subsidy on condition that the university maintain transparent books. These examples illustrate how important changes occurred in the early 1800s, before budgets record key research expenses and before formal recognition of research facilities. That said, university spending on the natural sciences remained relatively modest well into the 1800s. For example, at the university of Berlin, which emerged as a leader in research, expenses on institutes, seminars, research materials, and the library comprised 26% of the budget in 1834, with the natural

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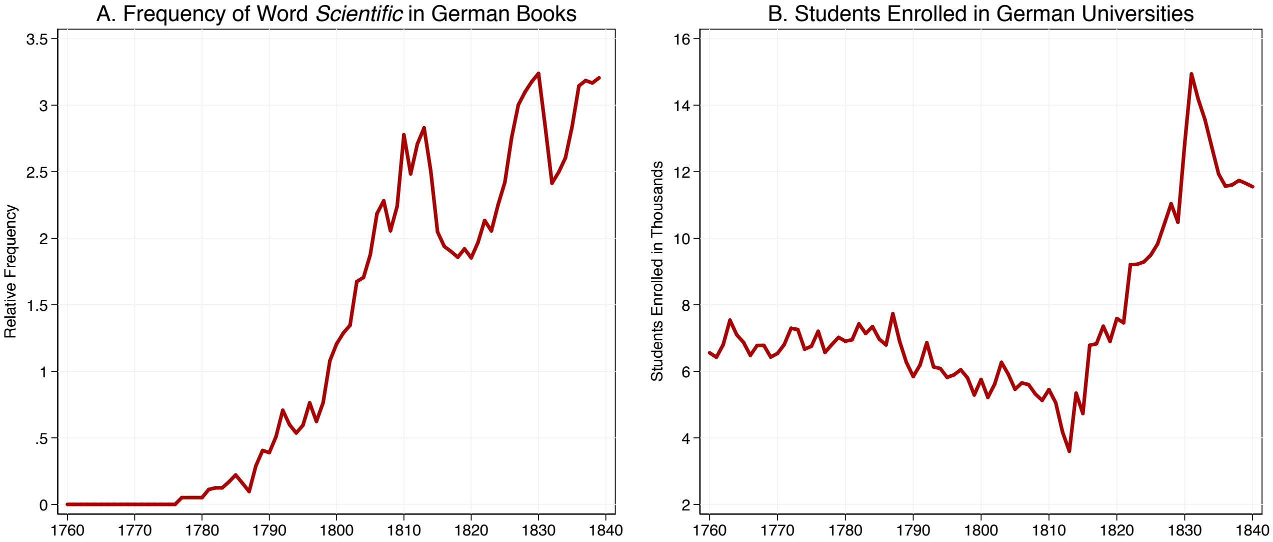
[12] *Wissenschaftliche* is typically translated as "scientific," but is a term for *systematic study* in and beyond the "natural sciences." Van Bommel (2015; p. 14) notes, "After Kant, the concept of 'fine sciences' declined rapidly. As early as 1801, August Wilhelm Schlegel (1767–1845) called the expression 'almost obsolete'. A few years later, Hegel wrote that the term 'schöne Wissenschaft' ('fine sciences') was no longer in use."

Figure 2: Scientific Ideas in Books and University Enrollments



Panel A plots the relative frequency of the word *wissenschaftliche*, calculated as the five-year moving average of the frequency of *wissenschaftliche* per million words in google's (2012) n-gram corpus of German books. Panel B plots annual data on the number of students enrolled at German universities. Data on enrollments before 1830 are from Eulenburg (1904) for all universities except Berlin. Data on pre-1830 enrollments at Berlin are from Lenz (1910). Data on enrollments from 1830 forwards are from Titze (1995).

sciences accounting for 3% of the total and a sum equal to 28 years of skilled wages.[13]

Other aspects of education also shifted over the period we study. Thus Kindleberger (1975; p. 260) observes that, "the Germans responded to defeat [in 1806] with educational reform." To study the relationship between changes in education at different levels and the industrialization process, we gather evidence on all schools established across all German cities, from elementary schools through technical and continuing education schools.[14] In our quantitative analysis, we find the effects of universities hold controlling for the development of other types of schooling.

2.3 The Locations of Universities

A key question for our analysis concerns the potentially endogenous location of universities. The historical evidence on the location of universities is therefore important in motivating the research designs in our quantitative analysis and in interpreting the data. To clarify

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[13] See Dieterici (1836; pp. 67-8). Institute budgets were lower in earlier periods (McClelland 2008; p. 204).

[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).

the variation we study it is helpful to distinguish locations with historic universities active throughout our period and locations where universities either opened or closed.

Most universities were active throughout our period at fixed locations. In Germany, these *historic universities* 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] The prestige of historic universities in small provincial towns meant they could not be shifted (Rüegg 2004b). These universities were founded in the pre-industrial age, most before 1600, and were designed to produce non-scientific human capital and knowledge.

However, French military control over German territories did lead to the opening and closure of universities. Historical evidence indicates that these changes in university locations were driven by military events. Consider the three new universities. The university at Berlin (1809) was founded by the 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; and the university of Ingolstadt was transferred to Landshut in 1800 after the French invasion, and from there to Munich in 1825.[16] Historical research also indicates that the closure of universities reflected political factors that were independent of the strength or quality of the universities (Rüegg 2004b; Turner 1987).[17] However, closures were concentrated in Western regions, and this provides one motivation for our examination of regional differences below.

The natural concern is that university locations may still have been endogenous, historical evidence on the role of political shocks notwithstanding. Our quantitative analysis addresses questions concerning the potential endogeneity of university locations in several ways. We show that cities nearer to universities had no economic advantages, and that there were no differential trends in development towards universities, before the political shocks of the French Revolution and the Napoleonic wars. We also show that our findings hold when we

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[15] The university of Leipzig was exceptional in being in an important city in our study area. The universities at Vienna and Königsberg, were also in major cities, but are outside our study area.

[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.

[17] 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).

restrict our analysis to study only the plausibly exogenous variation in university exposure shaped by historic universities open throughout our period, and thus when we take university exposure driven by changes in university locations off the table. Our findings also hold when we study exposure to universities open before the French Revolution. See Section 4 below.

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 manufacturing activity and in particular for changes in manufacturing. Third, the dating of some observations in the *Deutsches Städtebuch* is approximate.[18] We aggregate to twenty-year periods in our analysis 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.

To assess the data, we test how well our measure of manufacturing explains the number of factories and workers recorded in the Prussian Census. We study how our measure explains factories and workers at the two-digit industrial classification level recorded at the

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[18] 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.

county-level data 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 1820s and 1830s, strongly predicts the cross-sectional administrative data from the 1840s. We estimate elasticities close to one in almost every industry. We report this analysis in Appendix A.

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.[19] 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 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.[20]

Examples of observations in our data are as follows. In 1801, university-educated chemist Franz Karl Achard develops inventions for beet sugar production (SIC food) while based 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, the year 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

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[19] 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).

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

he sets up a chemicals factory. The variation in the education and location of individual knowledge producers which these examples illustrate motivates our quantitative analysis, in which we test whether invention shifted towards universities and examine how manufacturing developed in sectors more or less reliant on inventions by university-educated inventors. Appendix Tables A2 and A3 provide further 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 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 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.

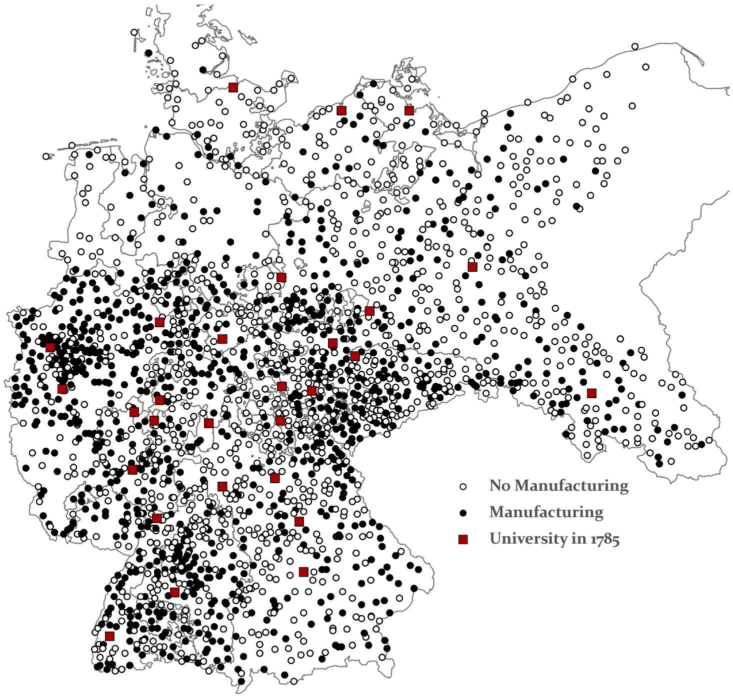
4 Universities and Manufacturing

4.1 Stylized Facts

To clarify the spatial comparisons we study, Figure 3 maps the locations of towns and universities in our analysis and the pattern of manufacturing between 1800 and 1859.

Table 2 presents the key stylized facts in our analysis. Before 1800, cities nearer to universities had no advantage in manufacturing. After 1800, manufacturing increased and shifted towards universities. The shift in manufacturing towards cities with universities is particularly pronounced in the period between 1800 and 1859. This core period begins with

Figure 3: Manufacturing in German Cities 1800-1859



This map presents evidence on manufacturing across 2,254 cities recorded in the *Deutsches Städtebuch* (Keyser 1939-1974). Cities with any manufacturing events 1800-1859 are indicated with black circular markers. Cities with no manufacturing events 1800-1859 are indicated with white circular markers. The locations of universities as of 1785 are indicated with larger square markers (shaded red in online version).

Table 2: Universities and the Development of Manufacturing

	(1)	(2)	(3)	(4)
	Any Manufacturing: Mean		Total Manufacturing: Sum	
Time Period	Close to University	Far from University	Close to University	Far from University
1760-1799	0.10	0.12	181	186
1800-1859	0.44	0.36	1427	988
1860-1899	0.30	0.30	785	708

This table reports summary statistics on manufacturing for 2,254 cities recorded in the *Deutsches Städtebuch* (Keyser 1939-1974). Towns "close" to a university are defined as those below median distance to a university in 1785. Towns "far" from a university are above median distance to the nearest university in 1785. Columns (1) and (2) report the mean of an indicator for any manufacturing events in a town-time-period. Columns (3) and (4) report the total number of manufacturing events.

major shocks to politics and universities. It closes when the costs of transportation fell significantly, after the 1850s, due to the development of railroads (Fremdling and Hohorst 1979; Wrigley 1961).

To interpret the evidence it is also important to note that the manufacturing events we study proxy for *changes* in manufacturing activity. The manufacturing events we observe cumulatively over the first half of the 1800s predict the number of workers and the number of factories recorded in the 1849 Prussian Census at the county-by-industry level, with almost unit elasticities, as we show in Appendix A.[21]

4.2 Quantitative Analysis

A. Research Designs. To investigate the relationship between universities and the development of manufacturing, we estimate regression models of the form:

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

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 confirm the relationship between manufacturing and proximity to universities using linear and flexible measures of distance in Appendix B and as discussed further below.[22]

The analysis addresses questions about the *potential endogeneity* of university locations as follows. We first estimate the relationship between universities and manufacturing using the locations of universities in the 1800s, which in a few cases could reflect the endogenous selection of locations in the early 1800s. We then restrict the analysis to cities whose university exposure did not shift due to potentially endogenous changes in universities and confirm our findings. This shows that the opening of universities at Berlin and Munich does not explain our findings.[23] We further document that new universities had no differential effects on manufacturing beyond those observed around existing universities in Appendix B.

The analysis takes steps to ensure that *inference* is not biased by spatial autocorrelation. Standard errors are estimated allowing for arbitrary forms of spatial autocorrelation,

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[21] In contrast, the manufacturing events we observe in the immediate years before the census provide a weaker and less precise prediction of the number of factories and number of workers active in the late 1840s.

[22] We find an approximately linear relationship between manufacturing outcomes and distance to a university after 1800 when we flexibly examine the variation across quantiles of the distance distribution.

[23] We also show that results are similar when we study exposure to historic university locations as of the 1780s, including several locations where universities closed in the 1790s and early 1800s (see Appendix B).

following Conley (1999). We also introduce a rich set of control variables that vary across space and time and absorb underlying spatial correlation. These include territory-by-time fixed effects for each of the 44 territories of the historic German Confederation, city-level factors that vary over time such as the number of schools and proximity to railroads, and variables absorbing the time-varying implications of initial differences in city development.[24]

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

We find that both the number of manufacturing events and the probability of any manufacturing increased differentially in cities nearer to universities after 1800. We observe these shifts when we examine exposure to universities active in the 1800s (Panel A) and when we restrict analysis to cities whose proximity to universities did not change over our period (Panel B). The flexible models show there was no trend in manufacturing towards universities before 1800. If anything, there was a slight pre-trend away from universities. The statistical significance of the estimated shift in manufacturing is not contingent on the distance over which we allow for spatial autocorrelation (see Appendix C for details).

The results show that the shift in manufacturing is not driven by potentially endogenous changes in university locations. In particular, Panel B shows that the university effect is observed when we exclude local spillovers from new universities. We confirm that new universities were associated with no differential shifts in manufacturing in Appendix B. We do, however, observe that the university effect over the 1800-1859 period is slightly smaller across all cities (Panel A) than across cities for which university exposure does not change (Panel B). This is consistent with new universities generating spillovers that develop only over time. But given that the shifts in the locations of universities varied across regions, these patterns also point to the potential importance of regional differences, and of the within-region variation, in university exposure and industrialization.

Our baseline results are supported by estimates examining the relationship between manufacturing and distance to a university in kilometers. We find a 60 kilometer reduction

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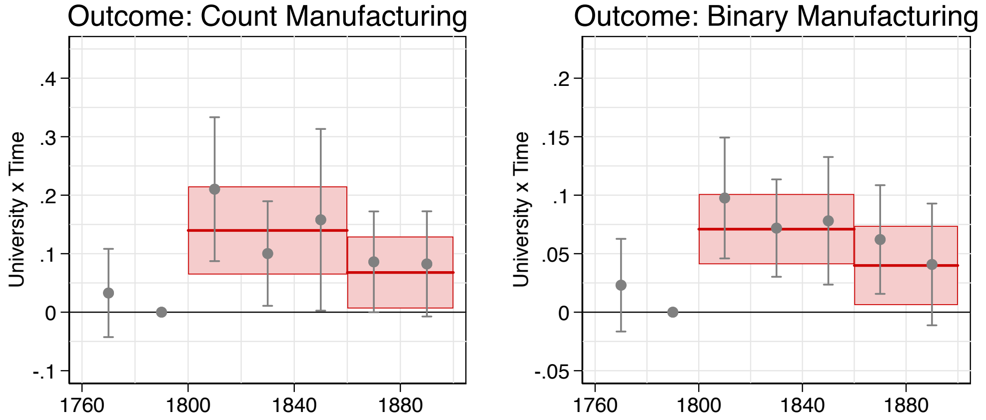
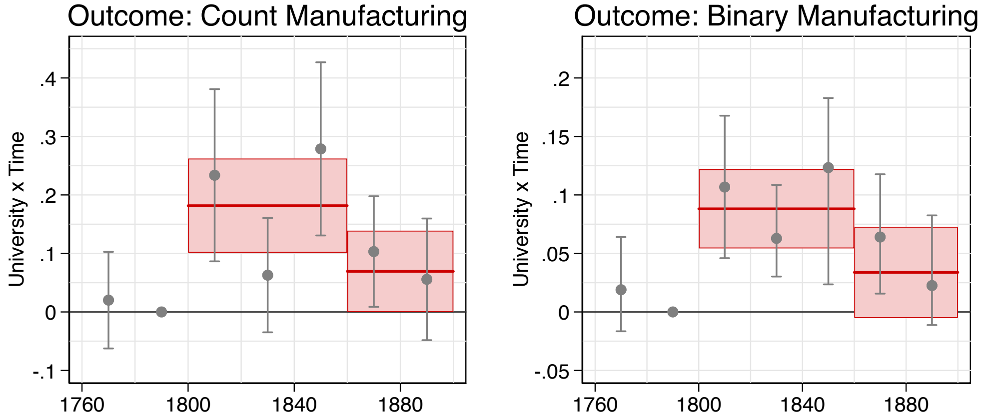
[24] See Voth (2021) for a discussion of spatial autocorrelation in economic history research, including the role of spatially-varying controls (see also Kelly 2019). We also find our estimates hold accounting for potential serial correlation following Bertrand, Duflo, and Mullainathan (2004), as shown in Appendix C.

Figure 4: Universities and Manufacturing

A. All Cities



B. Cities with No Change in University Exposure



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).

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.

C. Regional Differences. An important question is whether the relationship between universities and manufacturing reflects regional differences in development.

Several regional factors have been emphasized as determinants of economic activity. In Eastern Prussia, starting in 1807 the Stein-Hardenberg Reforms modernized agricultural tenancy arrangements, abolished guilds, and granted cities self-government rights. In Western regions, the Napoleonic occupation led to a "big bang" shifting economic institutions, which was followed by differentially greater urbanization after 1850 (Acemoglu et al. 2011). More generally, historians suggest that German industrialization was shaped by "regionally varying, gradual institutional evolution" (Tilly and Kopsidis 2020; p. 11).[25] It is thus natural to wonder whether regionally varying factors could explain the stylized facts (Table 2) and the pattern in our baseline estimates (Figure 4).

To answer questions about the role of regional factors, we investigate the relationship between universities and manufacturing *within* regions. Table 3 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 subject to Napoleonic institutional reforms. Column 3 restricts to the territories of 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.

We extend our analysis to study the relationship between universities and manufacturing *within* political territories in column 5. We locate cities in 44 territories comprising the German Confederation as of 1815, which we then consider as time invariant regional identifiers. We find that universities are strongly predictive of manufacturing after 1800, controlling for variation shared at the territory-by-time level and thus when we compare cities exposed to common patterns of time-varying, regional institutional change (Table 3, column 5). To clarify, for the Principality of Brunswick, our analysis compares manufacturing

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[25] The Napoleonic blockade also had the potential to deliver regionally varying changes in protection from British imports (Crouzet 1964; Juhász 2018). Our analysis of within-region differences in university exposure and manufacturing shows the university effect operated locally and was not driven by regional changes.

Table 3: 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	All Germany	Eastern Prussia	Western Prussia	Outside Prussia	Within Territory
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 No Change in University Exposure										
	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) and Colella et al. (2019). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

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-territory variation are provided in Appendix A.

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.

D. Time-Varying Factors. Given that regional factors do not account for the relationship between universities and manufacturing, it is natural to wonder about confounders that vary over time *within* regions. Prior research emphasizes several factors as potential confounders in our setting: (1) cross-sectional differences in prior industrial development that influenced manufacturing dynamics in the 1800s; (2) local changes in schooling besides universities; (3) the development of railroads; and (4) the time-varying implications of the location of coal deposits. We consider these factors as follows.

First, the *prior development* of proto-industrial manufacturing was a potentially important influence on the development of manufacturing in the 1800s (Kopsidis and Bromley 2017; Kreidte, Medick, and Schlumbohm 1977).[26] We therefore examine how differences in manufacturing before 1760, which we observe in 1 in 6 cities, relate to the development of manufacturing in our study period. We test whether the estimated university effect holds controlling for the post-1800 advantages enjoyed by cities with earlier manufacturing. We also examine whether the relationships between universities and manufacturing, and between prior manufacturing and post-1800 dynamics, are different when we focus our analysis on the development of industries that are new to a city. We thus focus some analyses on the development of industries in which a given city had no prior (pre-1760) industrial history.

Second, the expansion of *schooling* is also a potential factor in local development

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[26] The rich literature on the development of proto-industrial manufacturing contains limited quantitative and econometric analysis (e.g. Kreidte, Medick, and Schlumbohm 1977; Kaufhold 1986; Ogilvie 1996b).

(Lundgreen 1975). To examine the role of schooling, we code information on all schools in the cities we study. To preview the analysis, *higher schools*, which provided advanced training outside the university system, were unique in having a strong relationship with manufacturing over the first half of the 1800s. However, higher schools do not explain the university effect and are not confounders. In fact, higher schools themselves appear *after* local increases in manufacturing. Higher schools include *Gymnasia*, *Gewerbeschulen* (technical schools), *Lyzeen* (Lyceum), and *Realschulen*.[27] Elementary, middle, and continuing education schools have little explanatory power for the development of manufacturing until the late 1800s and are also not confounders in our analysis.[28] We provide details below and in Appendix F.

Third, *railroads* promoted manufacturing in ways that varied locally (Fremdling 1977). We measure and control for railroad connections period-by-period with a binary variable for cities on railway lines. We also present analyses restricted to the period before the development of the railroad network, which help us interpret the university effects.

Fourth, proximity to *coal* deposits became a key factor for industrial activity in Germany, particularly after 1840 as coal-using technology diffused (Wrigley 1961). We classify cities close to or far from coal deposits, measured as above or below median distance, and examine whether cities close to coal enjoyed developmental advantages after 1800 or after 1840.

We also consider the implications of changes in legal institutions, focusing on the adoption of "free enterprise" (*Gewerbefreiheit*) laws. These institutional changes spread in a staggered manner across the territories of the German Confederation, and have been found to shape urbanization after 1850 (Acemoglu et al. 2011). The effects of these institutions are already absorbed in our analyses with territory-×-time fixed effects. However, the relationship between these laws and manufacturing provides us with a benchmark for the magnitude of the university effects and can be estimated in models studying the variation *across* territories.

Table 4 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

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[27] Our results are also robust to controlling for the presence *Technische Hochschulen*, which were established starting in the 1820s and evolved in the late 1800s to became Germany's "technical universities." We find a weak and statistically insignificant relationship between *Technische Hochschulen* and local manufacturing.

[28] Prior research documents a positive relationship between elementary education, literacy, and manufacturing in the late 1800s (Becker, Hornung, and Woessmann 2011; Becker and Woessmann 2009). Our analysis shows elementary and middle schools do not explain manufacturing before the mid-1800s.

(Table 4 column 1 compares to Table 3 column 1). These other factors are, however, important explanatory factors in their own right. The estimates on early manufacturing, higher schools, and coal post-1840 are 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.[29] A history of early manufactures was even more strongly associated with manufacturing over this pre-railroad period, consistent with historical evidence pointing to continuities in development operating alongside the university effect.

We next extend our analysis to consider the timing of the relationship between higher schools and manufacturing (column 3). To do so, we introduce leads and lags for higher schools. We find that while the university effect is stable, only *future* higher schools have a strong, statistically significant relationship with current manufacturing. This indicates that higher schools were established after manufacturing increased at the city-level and points to the endogeneity of schooling in our setting.

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).

We next focus on the role of universities in promoting *new* manufacturing activities (columns 5 and 6). We study a proxy for industrial change: whether a city near a university typically developed more manufacturing in industries that were new to that city after 1800, when compared to a city far from a university. We define "new manufacturing" for a given city to be activities in two-digit SIC industries in which that city had no manufacturing before 1760.[30] Thus for a city with no historical textile industry, activities in textiles are "new manufacturing," whereas such activities are not new in cities with textiles before 1760.

When we study the development of new manufacturing industries, the post-1800 university effect remains almost unchanged, while the effect of early manufacturing declines

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[29] 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.

[30] A considerable amount of proto-industrial activity was located outside cities, including in some rural locations. Our data cover settlements that received city rights, including hundreds of quite small settlements – often with populations of a few hundred people – but do not provide global coverage of proto-industrial development in rural locations.

Table 4: Time-Varying Determinants of Manufacturing

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Outcome: Count of Manufacturing Events						Outcome: Binary	
	In All Industries				In New Industries		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**	0.12***	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*		0.07*		0.01	
	(0.03)	(0.04)	(0.04)		(0.04)		(0.01)	
Early Manufactures × Post-1800	0.15***	0.20***	0.20***	0.18**	0.11**	0.09	0.04	0.03
	(0.05)	(0.07)	(0.07)	(0.07)	(0.06)	(0.06)	(0.02)	(0.02)
Coal × Post-1800	-0.03	-0.02	-0.02	-0.08*	-0.01	-0.08*	0.03**	-0.00
	(0.04)	(0.04)	(0.04)	(0.05)	(0.03)	(0.04)	(0.01)	(0.02)
Coal × Post-1840	0.13***							
	(0.05)							
Railroad Connection	0.24***							
	(0.06)							
Higher School	0.18***	0.20***	0.11	0.11	0.08	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**	0.13**	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)	(0.09)	(0.09)	(0.04)	(0.04)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	No	Yes	No	Yes	No
Territory-×-Time FE	No	No	No	Yes	No	Yes	No	Yes
Observations	15778	9016	9016	9016	9016	9016	9016	9016
Mean Outcome	0.27	0.19	0.19	0.19	0.17	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 5-6 study counts of manufacturing in 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 3. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Conley (1999) and Colella et al. (2019). Statistical significance at the 90, 95, and 99 percent confidence level denoted “*”, “**”, and “***”, respectively.

in magnitude compared to the baseline for all sectors (column 5). When we study within-territory variation, universities remain highly significant predictors of new manufacturing (column 6). While universities and historical manufacturing explain patterns of change after 1800, in relative terms universities thus explain new activities more than old. Historical manufacturing, in contrast, has a relatively muted, diffuse relation with new manufacturing.

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.

5 High and Low Knowledge Manufacturing

Both history and theory invite the question: were economic shifts towards universities more pronounced in industries using knowledge that flowed from or was tied to universities?

To study the heterogeneity of the university effect across industries, and the relationship between manufacturing and university knowledge, we measure industries as more or less "university 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. We define "high knowledge" industries as those in which university educated inventors account for 50% of inventions 1760-1860.[31]

We extend our baseline analysis to study how universities were associated with shifts in manufacturing in higher and lower knowledge industries. We examine three outcomes: high knowledge manufacturing; low knowledge manufacturing; and net high knowledge manufacturing, defined as the difference between high and low knowledge manufacturing.

Figure 5 presents our findings and underlying evidence on the pattern of invention. 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

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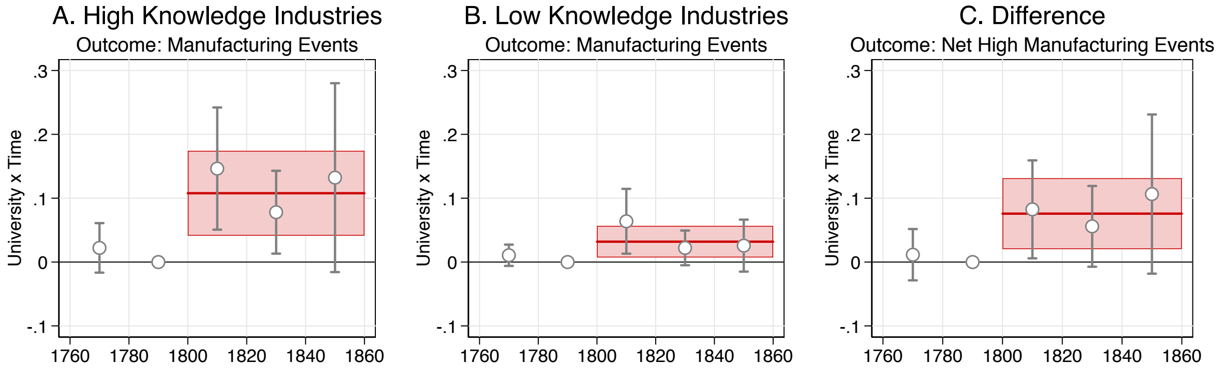
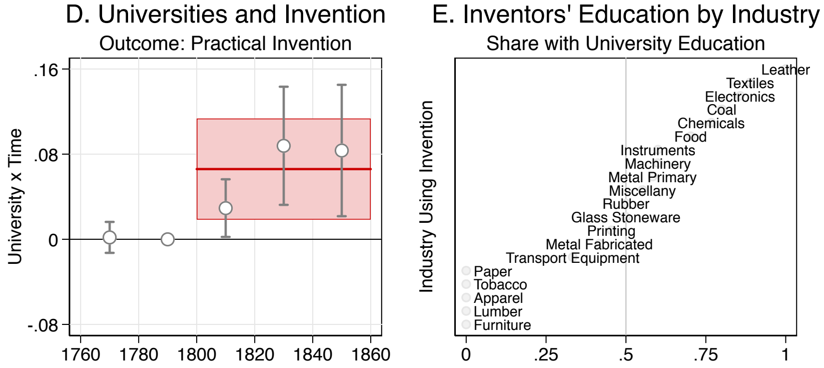
[31] Our data on discoveries comprise practical inventions and scientific break-throughs. Practical inventions and manufacturing activities are classified at the two-digit SIC level. Inventions are classified by the industry using them. Thus chemical dyes are classified as inventions used in the textile industry. See Section 3.

Figure 5: 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.

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 provides evidence on the underlying patterns of invention. Graph D presents regression estimates documenting that practical invention shifted strongly towards universities after 1800. This finding connects back to the motivation for our study, in which we show that a broad measure of science and discovery expanded near universities after 1800 (Figure 1 above). We now confirm that universities were associated with a differential expansion of economically useful knowledge in the era after the French Revolution, and not before this temporal pivot. Graph E shows the underlying variation across industries in the share of inventions made by university educated inventors, which we use to classify industries as "high" or "low" knowledge.[32]

To interpret the estimates in Figure 5 several observations are important. First, the differential shift towards universities in high knowledge manufacturing may embody both exogenous (supply-side) and endogenous (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 and early 1800s. Indeed, the inventions we study and use to classify industries are themselves, in part, endogenous outcomes in this larger post-shock context. In this respect, the causal process that we study has parallels with the economic role of universities in the United States after World War II. As in the US, we observe a political shock that promoted science and technology in universities and made it possible for universities to respond to demand in new ways, including as conduits for induced technological change.[33]

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.

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[32] Our estimates in Panel I are robust to alternate categorizations of "high" and "low" knowledge industries, including when we classify all industries with university-educated inventors as high knowledge.

[33] On how, in the changed political environment after the second world war, universities in the United States became distinguished by their responsiveness to economic signals, see Rosenberg (2000). There are of course 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 contributions on modest budgets, however the funding required for research in the 19th century was also comparatively modest (McClelland 2008).

6 Technological Change and the Quality of Innovation

Our evidence documenting shifts in the location of manufacturing raises questions about the relationship between universities and (1) technological change in manufacturing and (2) the quality of industrial innovation. To address these questions, we expand our analysis beyond the evidence contained in the *Deutsches Städtebuch* both out of necessity and to document how the larger 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 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

Given the central role of technological change in the industrialization process (Landes 1969), it is natural to wonder whether universities were associated with the adoption of *advanced* technology. 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.[34]

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).[35] 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

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[34] There is significant ambiguity in the historical designations used to describe manufacturing enterprises themselves. For example, the words *Fabrik* and *Manufaktur* do not uniformly map onto "factory" and (pre- or proto-industrial) "manufactory," respectively. See, for example, Freudenberger and Redlich (1964).

[35] 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: Illustration of Mechanization by Type of Establishment

Type of Establishment	Mechanized
cotton machine spinning (*Baumwollmaschinespinnerei*)	Yes
cotton spinning (*Baumwollspinnerei*)	No
wool carded yarn machine spinning (*Schafwollstreichgarnmaschinenspinnerei*)	Yes
wool spinning (*Schafwollspinnerei*)	No
flax spinning (*Flachsspinnerei*)	No
spinning (*Spinnerei*)	No
cloth manufacture with machine spinning (*Tuchmanufaktur mit Maschinenspinnerei*)	Yes
mechanical machine building workshop (*mechanische Machinebauwerkstatt*)	Yes

This table illustrates the types of manufacturing establishments in Saxony in the early 1800s as recorded in Forberger (1982). "Type of Establishment" records our translations and the German designations for *Art der Fabrik* from Forberger (1982). We classify mechanization as shown. For details see Appendix A.

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 individual factories as mechanized or not. Table 5 illustrates the classification we apply to 233 workshops and factories established in the early 1800s in cities in Saxony, based on the descriptions provided by Forberger (1982). We emphasize that our classification provides a *proxy* measure of technology choice, and acknowledge that firms sometimes combined mechanized and non-mechanized production processes. Appendix A presents further details on the data.

We find that mechanized manufacturing concentrated in cities closer to universities in the early 1800s. Table 6 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 for pre-1800 manufacturing (column 2). In contrast, we find a weaker and insignificant relationship between universities and other, 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, which was a particular center of manufacturing. Our results also hold when we allow for arbitrary spatial correlation and when we study rural manufacturing. We document these points in Appendix D.

For our interpretation of the evidence several observations are important. First, when we

Table 6: Universities and Mechanization

	(1)	(2)	(3)	(4)	(5)	(6)
	Number of Firms Mechanized		Number of Firms Other		Share of Firms Mechanized	
University	1.90***	1.50***	0.55	0.43	0.37**	0.35*
	(0.64)	(0.56)	(0.66)	(0.64)	(0.17)	(0.18)
Manufacturing 1750-1799		0.26***		0.47**		0.01
		(0.08)		(0.23)		(0.01)
Manufacturing 1700-1749		-0.45		-2.28*		-0.01
		(0.60)		(1.30)		(0.10)
Manufacturing pre-1700		-0.03		1.20		-0.07
		(0.60)		(0.85)		(0.14)
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 number of firms and mechanization of establishments set up in cities in Saxony between 1800 and 1830. "University" is an indicator for cities below median distance to a university. "Manufacturing 1750-99" and "Manufacturing 1700-49" measure the number of manufacturing establishments in a city in these periods. "Manufacturing pre-1700" measures manufacturing before 1700. The outcome in columns 1 and 2 is the number of firms in a city using mechanized technology. The outcome in columns 3 and 4 is the number of firms using non-mechanized technology. These regressions are estimated across 164 cities in Saxony with negative binomial regressions. The outcome in columns 5 and 6 is the share of firms in a given city using mechanized technology, estimated with OLS, for the 38 cities with manufacturing establishments. 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 coded from Forberger (1982; 1958).

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. Further, the larger impact of mechanization in the early 1800s unfolded gradually and via indirect channels, including the development of mechanics' workshops and the demonstration effects of the adoption of technologies developed abroad (Wolff 1979). Indeed, 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

A second natural question for our analysis concerns the *quality* of industrial innovation. Did universities foster high quality innovations and, specifically, 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).[36] 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.[37]

To formalize these comparisons, we estimate cross-sectional regressions of the form: $exhibits_i = \alpha + \beta X_i + u_i$. The outcome is the number of exhibits from city i of a given type (all, low quality, or high quality) and X is an indicator for cities closer to universities.

We present our estimates in Table 7. Proximity to a university is associated with 40 percent more total exhibits (0.34 in log counts), however this estimate is only weakly significant (Panel A, column 1). When we disaggregate the data, we find that proximity to universities strongly predicts high quality innovations but does not predict the number of lower quality innovations (columns 3 and 2, respectively). When we disaggregate high quality exhibits by type using the exhibition's classification, we find that proximity to universities was most strongly associated with award-winning exhibits of machinery and somewhat less strongly associated with high quality exhibits of materials and manufactures (columns 4-6).[38]

The fact that firms in cities close to universities produced innovations that won internationally competitive prizes is, we argue, important. It suggests that universities

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[36] On the Crystal Palace exhibition as a rich source of evidence on innovation see Moser (2005; 2013), who studies how differences in countries' patent systems explain cross-country differences in exhibits and prizes.

[37] While our baseline analysis considers all award-winning exhibits "high quality," we find an even stronger relationship between universities and awards of Council Medals which were the most competitive prizes.

[38] In the catalogue, we observe 12 Council Medal awards, 201 Honourable Mentions, and 239 Prize Medals. We find that the relationship between proximity to universities and awards is strongest for Council Medals and positive but weaker for Prize Medals and Honourable mentions.

Table 7: Industrial Innovations at the First World's Fair

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome: Number of Exhibits from a City					
	Total	Low	High	High Quality By Type		
	Exhibits	Quality	Quality	Materials	Machines	Manufactures
Panel A						
University	0.34*	0.14	0.82**	1.03***	1.54***	0.65*
	(0.19)	(0.14)	(0.37)	(0.31)	(0.31)	(0.35)
Panel B						
Discoveries 1830-1849	0.92***	0.96***	0.78***	0.61***	0.97***	0.74***
	(0.10)	(0.14)	(0.13)	(0.15)	(0.25)	(0.12)
Observations	2254	2254	2254	2254	2254	2254

This table reports negative binomial regression estimates in which the outcome 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 outcome in column 2 is the number of "Low Quality" exhibits, defined as those that did not receive awards. The outcomes in columns 3-6 are the number of "High Quality" exhibits, defined as exhibits awarded a Council Medal, Prize Medal, Honourable Mention, or money prize. Robust standard errors clustered by region in the *Städtebuch*.

shaped not only the spatial pattern of industrialization within Germany, but also the process that took German industry toward the world technology frontier. We find German cities near universities producing internationally recognized innovations in machines and materials by the mid-1800s. These estimates 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 E).

The Crystal Palace data also confirm and point to the value of our separately collected evidence on science and invention. Table 7, Panel B shows that the number of Crystal Palace exhibits from a city varies proportionately in the cross-section, with almost unit elasticity, with the measure of scientific and technological discovery we construct from the history of science literature. Our measure is a particularly strong predictor of high quality machine innovations at Crystal Palace. However, our measure varies across both 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 5 above).

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 also 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. 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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Appendices – For Online Publication

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), focusing on the number of workers and the number of factories at the two-digit SIC level, described in Section A.2 below.

Universities. We construct data on the location and dates of operation of universities from Rüegg (2004a;b).

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. We present this analysis and discuss vocational, middle, and elementary schools in Appendix F.

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 break-throughs 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 histories of inventors drawn 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 provides an illustrative examples of our data building on Darmstaedter, du Bois-Reymond, and Schaefer (1908) that we examine in Section 5.

Table A4 presents summary statistics on the city-level cross-sectional dataset we use to examine technological change in Saxony (Section 6.1).

Table A5 presents summary statistics on the cross-sectional city-level dataset on industrial innovations exhibited at the 1851 Crystal Palace exhibition (Section 6.2).

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: 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.

Table A4: 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, coded as indicated in Table 5. "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 A5: Summary Statistics on Innovations Exhibited 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).

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 administrative data, when and where administrative data are available. We specifically examine how our measure of manufacturing constructed from the *Städtebuch* is correlated with manufacturing activity recorded in the Prussian census of 1849, which provides detailed county-level data on the number of factories and the number of workers in different types of manufacturing activity and the first large scale administrative data on manufacturing in Germany.

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.[39] To estimate these relationships, we aggregate our city-level data to the level of their respective Prussian counties.[40] We similarly 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. Given that examine a cross-section of count data, we estimate negative binomial regressions.

Table A6 shows that there is a strong positive 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 (misleadingly)

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[39] 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. We exclude events from the 1840s as these may have included events recorded as a result of the Prussian census itself.

[40] The mean Prussian county comprises 3.5 *Städtebuch* cities.

regress information from the Census on itself, but this also implies that our measure does not capture any 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 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)

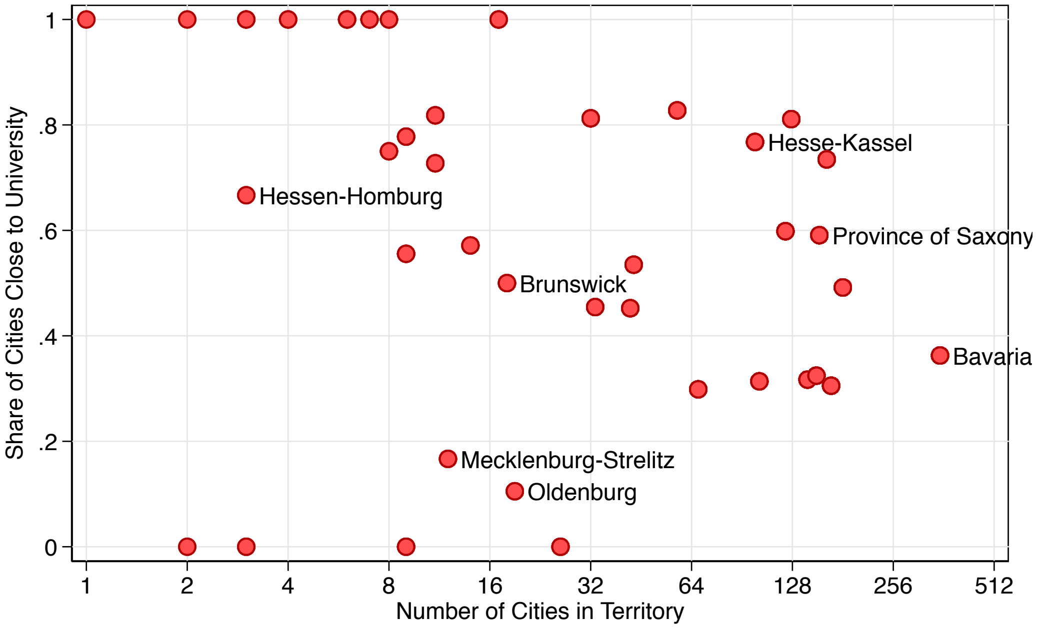
This table reports regression estimates in which the outcome is either the number of factories (columns 1-2) or the number of workers (columns 3-4) in a given industry and county in the 1849 Prussian census. Each row presents estimates from industry-specific binomial regressions: $man_i^c = \alpha + \beta man_i^s + \epsilon_i$. 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 3 and Table 4). 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.

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.

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 small difference between number of cities in Saxony listed in Table A7 and examined in our analysis of mechanization in Saxony in Table 6.

Table A7: Cities and Proximity to Universities by Territory

Territory	Cities by Proximity to University in 1800s 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

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 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.

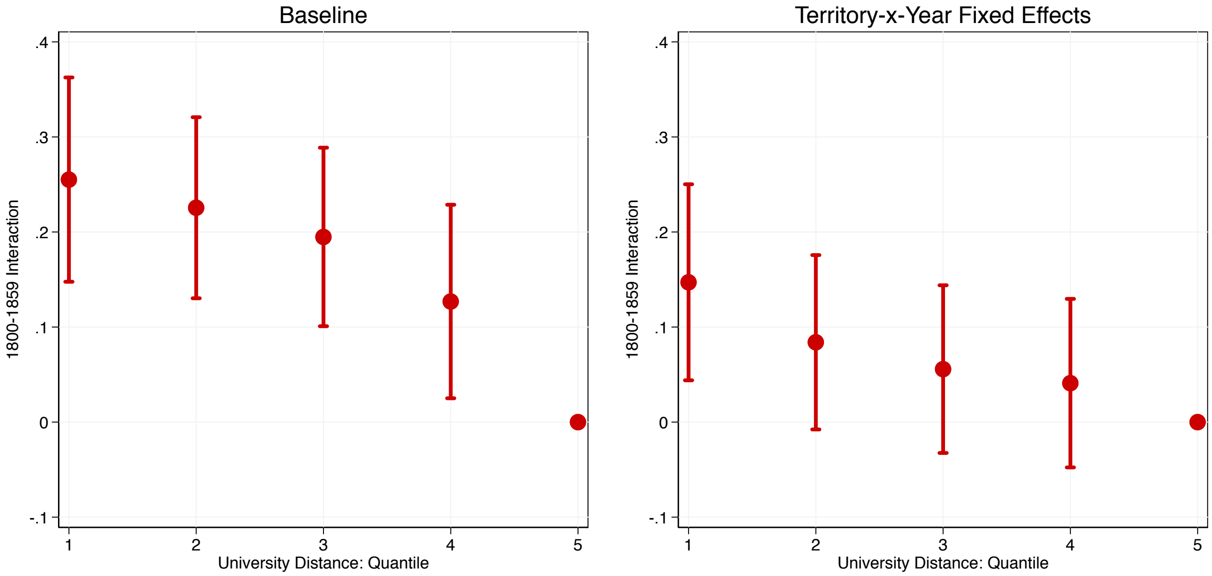
B.1 Distance to Universities and Shifts in Manufacturing

Our baseline analysis draws a binary distinction between cities close to and far from a university. To clarify the underlying pattern of spillovers, it is helpful to consider the role of distance both more flexibly and in a linear framework.

First, to clarify the pattern of spillovers from universities into manufacturing, we examine the role of distance more flexibly. We return to the framework of our baseline analysis, but examine how manufacturing shifts differentially after 1800 for cities closer to and farther from universities. We operationalize this by testing how manufacturing shifts for cities in different quantiles of the distance distribution.

Figure B1 presents estimates on the interactions between an indicator for the 1800-1859 period and indicators for distance quintiles. The lefthand panel corresponds to our baseline specification (Table 3, column 1) and shows that the post-1800 shift in manufacturing declined in distance from a university.[41] We observe a similar, but muted pattern when we study comparisons within territories (the righthand panel corresponds to Table 3, column 5). This evidence suggests that while the comparison between "close" and "far" is a useful heuristic, the process we document reflects an underlying spatial gradient.

Figure B1: Distance Quantiles and Manufacturing Shifts



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 an indicator for the period 1800-1859 and indicators for a given city's distance quintile, with 1 the closest cities and 5 the farthest. The left panel presents estimates that correspond to Table 3, Panel A column 1 (baseline estimate: 0.14). The right panel corresponds to Table 3, Panel A column 5 (fixed effects estimate: 0.07). Estimated specifications include interactions between indicators for distance quantiles and an indicator for the 1860-1899 period and city fixed effects. The left panel includes year fixed effects. Standard errors allow for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999) and Colella et al. (2019).

Second, to further clarify the economic process, we examine the relationship between manufacturing and distance to universities 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 B2 presents our estimates examining distance linearly and compares Figure 4

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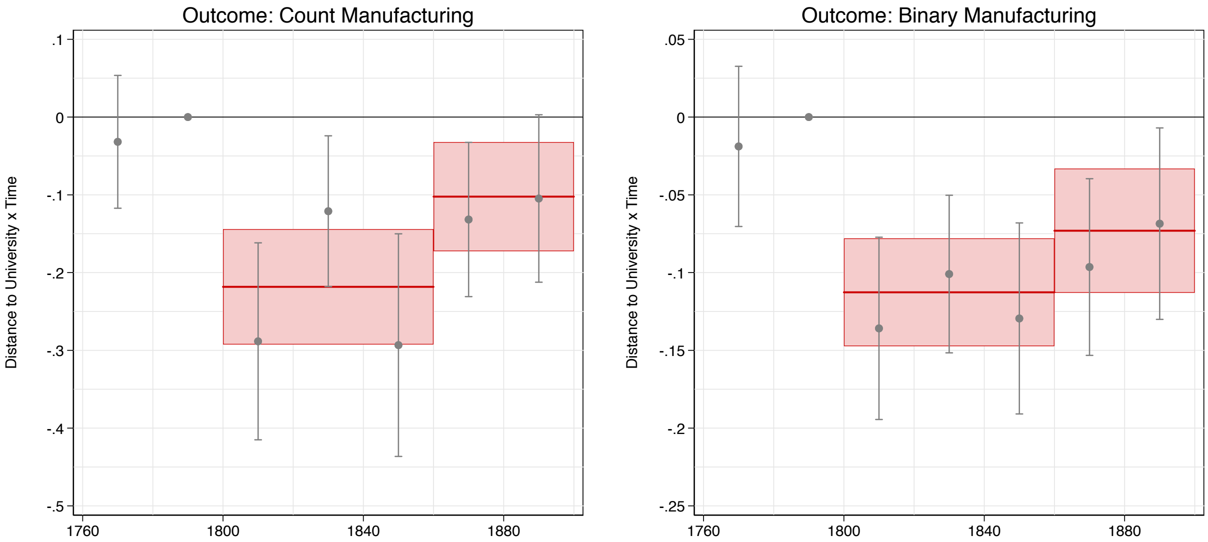
[41] The mean distances to a university for quantiles 1, 2, 3, 4, and 5 are as follows: 23 km, 45 km, 62 km, 82 km and 132 km, respectively. Thus a differentially large decline is observed moving from quantile 4 to 5.

(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 B2, 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 3 in the main text). These shifts also compare to the mean count outcome of 0.27.

Figure B2: 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.

B.2 New Universities and Manufacturing

The fact that new universities were established in the period we study naturally raises a question: did the new universities have a more or less pronounced relationship with manufacturing than the historic universities?

To address this question, we examine the heterogeneity in the university effect across old 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 B1 shows that cities near new universities enjoyed no clear advantages. 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).

While these findings should be interpreted carefully, the evidence indicates that the development of manufacturing around new universities proceeded in manner similar to that observed around pre-existing universities. This, in turn, suggests a broadly shared dynamic in which the university system as a whole had important implications for industrial development after 1800 and casts some doubt on the idea that the new universities at Berlin and Munich were unique and potentially endogenous drivers of development.

Table B1: 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 3, columns 1 and 6). Standard errors are estimated allowing for arbitrary spatial correlation within 25 kilometers following the methodology of Conley (1999).

B.3 Pre-existing Universities and Manufacturing

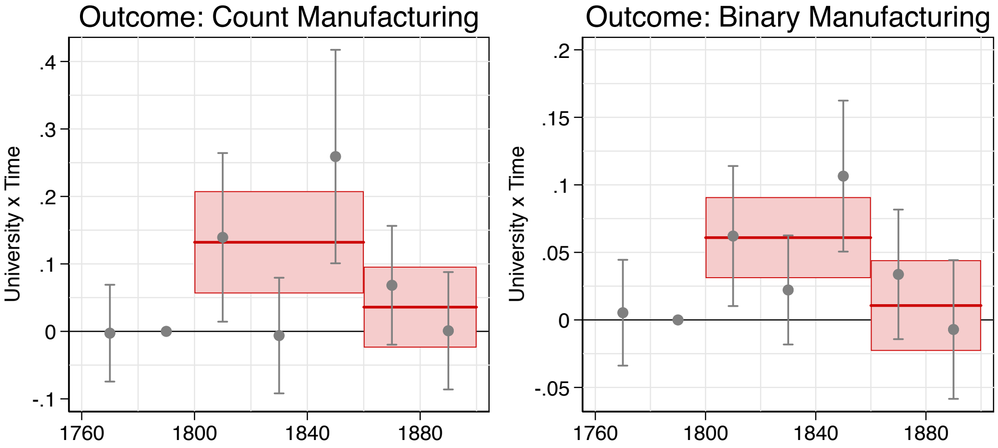
The baseline analysis in the main text examines shifts in manufacturing for cities closer to and farther from universities. We focus our main analysis on differences in cities' exposure to universities that were open in the 1800s and show that the effects we estimate are not driven by changes in university locations. In particular, we show that when we restrict the analysis to cities for which university exposure did not change over the period we study that we obtain similar estimates of the "university effect."

Differences in historic exposure to universities as they existed before the French Revolution provide another lens through which we can examine shifts in manufacturing. Given that universities were not associated with differences in the level or trend of manufacturing before the political shocks of the late 1700s, and that these shocks were transmitted through universities, differences in exposure to pre-1789 universities offer comparisons somewhat akin to intention-to-treat analysis.

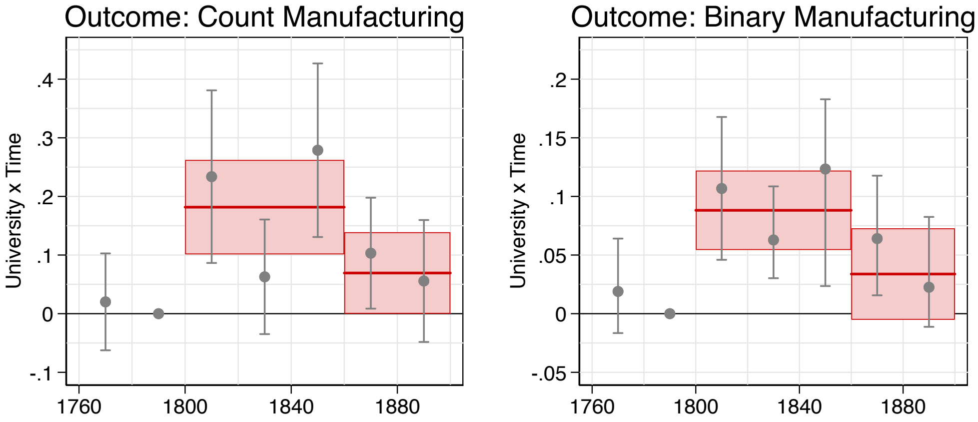
Figure B3 presents estimates that extend the analysis to study how exposure to pre-1789 universities explains manufacturing. We find that cities closer to pre-1789 universities

Figure B3: 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.

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 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.

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?

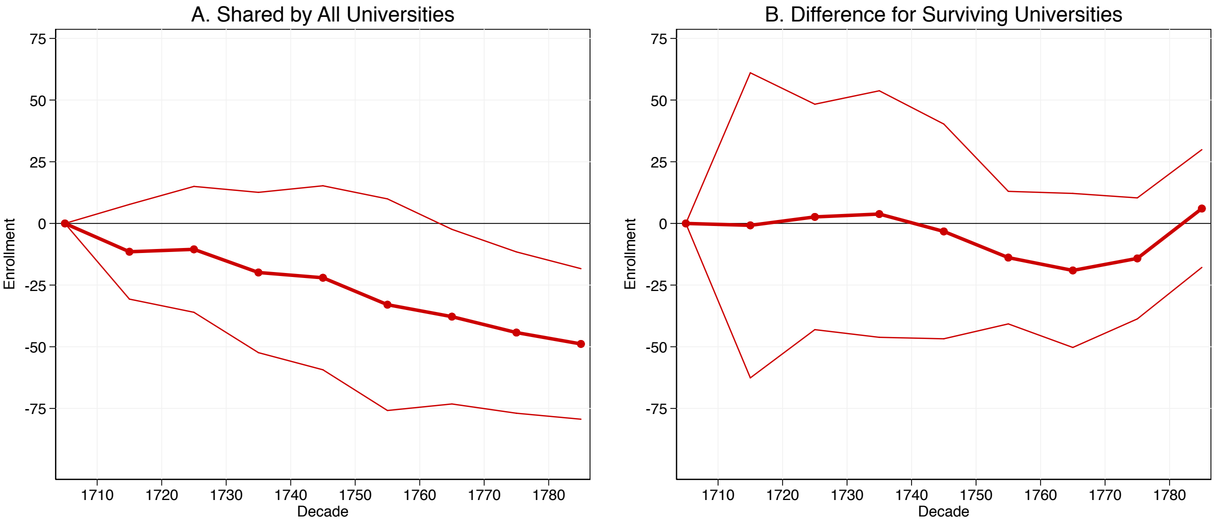
Enrollment patterns provide important indications of university quality, as they reflect the historic competitiveness of the German university system and the geographic mobility of students and faculty (Eulenburg 1904; Rüegg 2004a; Turner 1975). We therefore assemble university-year level data on enrollments 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 B4 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).

Figure B4: 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.

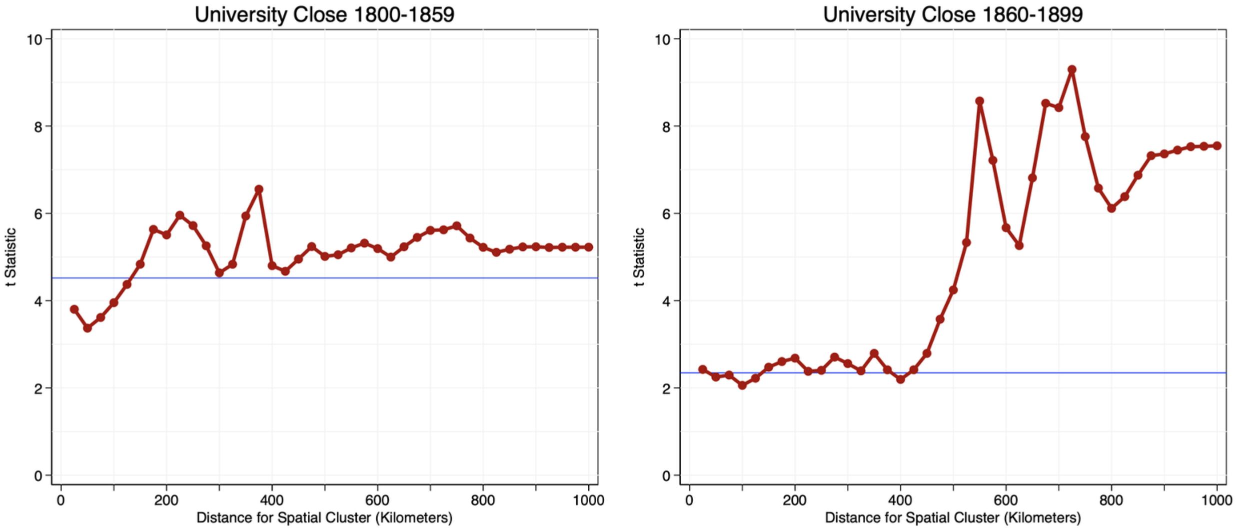
C Inference and Spatial Autocorrelation

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 3 (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 3, 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 (see Colella et al. 2019; Kelly 2019). 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).[42]

We illustrate our findings by re-estimating the baseline regression specification in Table 3 (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.

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, 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.

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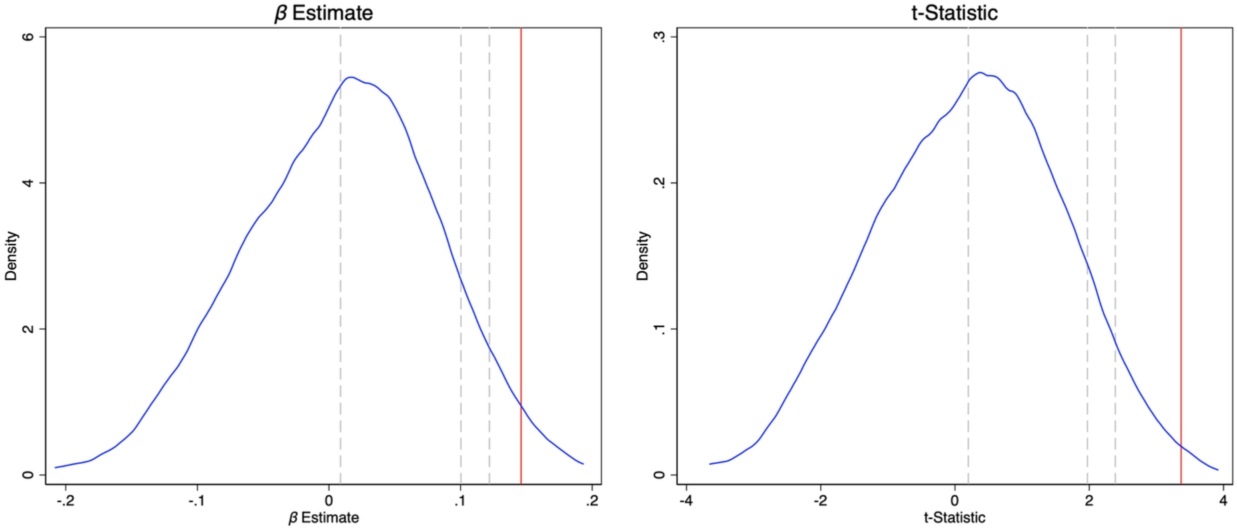
[42] Note that in our data many such grid cells contain multiple cities. Randomization at the level of the city generates "artificial university" locations that are relatively more concentrated in the most densely urbanized areas of historic Germany than actual universities were. However, even in this case our estimates are not consistent with a spatial noise falsification.

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 3, 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 3, column 1).

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

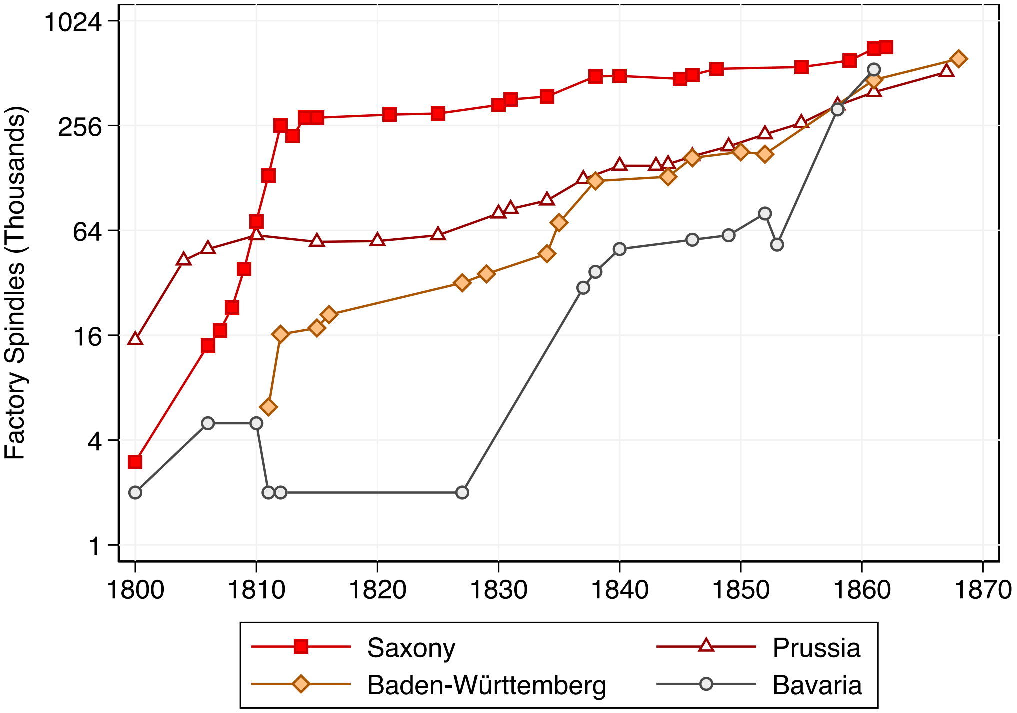
This table reports regression estimates examining the count and presence of manufacturing events over the period 1760-1839. The outcome is manufacturing at the city-time-period level. The "Pre" period is 1760-1799. The "Post" period is 1800-1839. "University × Post 1800" interacts an indicator for cities 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 a leading region in this process (Tilly and Kopsidis 2020; Forberger 1982; Pollard 1981). Disaggregated evidence on mechanization at the establishment and city levels is limited outside Saxony. However, Kirchhain (1973) provides evidence on the number of spindles in textile factories, a key measure of mechanization, across regions within Germany. Figure D1 summarizes Kirchhain's (1973) evidence and shows that mechanization increased in the first decades of the 1800s and these increases were largest in Saxony.

Figure D1: The Mechanization of German Textiles



This graph plots data on the number of spindles in textile plants across regions from Kirchhain (1973).

This evidence naturally invites a question about the university effect we estimate in 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 4 (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 virtually no wedge or difference between the university effect in Germany and the university effect in Saxony. Thus, when we examine our main data on manufacturing, the patterns we observe within Saxony are very similar to the patterns we observe more broadly and in other regions.

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 4 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. We consider the sensitivity of our baseline estimates and potential spatial correlation.

Sensitivity of baseline results. The historical literature indicates that within Saxony manufacturing was concentrated in specific cities, with a particularly large concentration of firms 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: 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 D2, our findings when we restrict the sample in these ways are very similar to our baseline estimates (in Table 6).

Spatial correlation. Second, we present estimates of standard errors that account for arbitrary spatial correlation across different distance horizons. Table D3 presents OLS estimates corresponding to our baseline estimates in Table 6 in the main text. We estimate standard errors that allow for arbitary spatial correlation over 10, 25, 50, and 100 kilometers.

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, the Botanical Garden, the Observatory, the Chemical Laboratory, the 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." (Müller, Ziche, and Ries 2001; p. 227 – our translation)

Significantly, Johann Heinrich Voigt observed that he was unable to satisfy young mechanics, who were not enrolled as fully matriculated university 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 Müller, Ziche, and Ries 2001; p. 228 – our translation)

The Physikalisch-Mechanische Anstalt that Voigt established had three objectives (cited in Müller, Ziche, and Ries 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 were established with an eye on developing the local economy and investigating local resources.

Mathematics. The historical evidence suggests that mathematical research promoted technological innovation both directly and through spillovers. A notable example of a mathematics professor having a more or less direct positive impact on technical knowledge is Abraham Gotthelp Kästner at Göttingen. Kästner 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 concrete 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. One dimension of innovation in the structure of scientific research at universities involved 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 (Müller, Ziche, and Ries 2001; p. 140).[43] Müller, Ziche, and Ries (2001) conclude that the such new institutions around the pre-existing faculties at the university of Jena played a critical role in the development of research in the early decades of the 1800s.

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).

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

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, however, natural to wonder whether the findings shift when we account for the expansion of different levels and types of schooling. It is also natural to wonder whether the *number* of schools operating in a city – rather than simply the *presence* of a given type of school – explains variation in manufacturing activity and could be a confounder. 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. This appendix provides more comprehensive examination of the relationship between different types and levels of educational provision and industrial development. To measure the provision of education along 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. Our data collection reflects the fact that multiple dimensions of educational provision changed in historic Germany over the period we study. These changes included not only the shifts in universities that we focus on, but also educational reforms which led to a large scale expansion of schooling at lower levels and more comprehensive attempts to provide school infrastructure supporting effective compulsory education (Kindleberger 1975), as well as the establishment of higher-level technical institutions during the mid-1800s.

Classification of Schools. 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 to incorporate measures of different types of schools.

We first examine how the presence of different types of schools was related to manufacturing in Table F1. We begin with evidence across the 1760-1899 period. Column 1 of Table F1 replicates the estimates in the main text (see Table 4, 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 in a given city and proximity to *Technische Hochschulen* (Table F1, Column 2). In particular, 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 and exposure 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*. Further, over the period through 1839 we find no large or statistically significant relationship between middle schools and vocational schools and manufacturing outcomes. 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*, conditional on binary measures of other forms of schooling.

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 indeed other time-varying factors associated with development. We therefore expand our analysis to examine the relationship between universities and manufacturing accounting for differences across cities in the numbers of different types of schools. As shown in Table F2, our key findings are unchanged when we account for the number of different schools in a city (Columns 1 and 2). 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 4). 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, the Establishment of Schools, and Manufacturing

	(1)	(2)	(3)	(4)
	Outcome: Count of Manufacturing Events			
	1760-1899		1760-1839	
	Baseline	All Schools	Baseline	All Schools
University × 1800-1859	0.14***	0.13***	0.13***	0.13***
	(0.04)	(0.04)	(0.03)	(0.03)
University × 1860-1899	0.06*	0.06*		
	(0.03)	(0.03)		
Railroad Connection	0.24***	0.23***		
	(0.05)	(0.05)		
Coal × Post-1840	0.13**	0.12**		
	(0.06)	(0.06)		
Coal × Post-1800	-0.03	-0.03	-0.02	-0.02
	(0.05)	(0.05)	(0.04)	(0.04)
Free Enterprise Law	0.10**	0.10**	0.07	0.07
	(0.04)	(0.04)	(0.04)	(0.04)
Early Manufactures × Post-1800	0.15***	0.15***	0.20***	0.20***
	(0.05)	(0.05)	(0.08)	(0.08)
Higher School: Indicator	0.18***	0.15***	0.20***	0.18**
	(0.04)	(0.04)	(0.07)	(0.07)
Lower School: Indicator		0.03		0.06
		(0.03)		(0.04)
Middle School: Indicator		0.07**		0.06
		(0.03)		(0.06)
Vocational School: Indicator		0.08**		0.03
		(0.03)		(0.07)
Technische Hochschule		-0.03		0.06*
		(0.06)		(0.04)
City and Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	15778	15778	9016	9016

This table reports regression estimates with variables defined as above. "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. The schooling indicators measure whether schools of a given type are present in a city, as described in the text. "Technische Hochschule" is an indicator for cities within 50 kilometers of such an institution in a given period. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Colella et al. (2019). Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

Table F2: Universities, School Density, and Manufacturing

	(1)	(2)	(3)	(4)
	Outcome: Count of Manufacturing Events			
	1760-1899		1760-1839	
	Baseline	All Schools	Baseline	All Schools
University × 1800-1859	0.14***	0.14***	0.13***	0.13***
	(0.04)	(0.04)	(0.03)	(0.03)
University × 1860-1899	0.06*	0.06*		
	(0.03)	(0.03)		
Railroad Connection	0.22***	0.21***		
	(0.05)	(0.05)		
Coal × Post-1840	0.14**	0.13**		
	(0.06)	(0.06)		
Coal × Post-1800	-0.02	-0.02	-0.02	-0.02
	(0.05)	(0.05)	(0.04)	(0.04)
Free Enterprise Law	0.10**	0.10**	0.07*	0.07
	(0.04)	(0.04)	(0.04)	(0.04)
Early Manufactures × Post-1800	0.14***	0.13**	0.20***	0.20***
	(0.05)	(0.05)	(0.08)	(0.08)
Higher School: Count	0.09***	0.05***	0.08**	0.06*
	(0.02)	(0.02)	(0.04)	(0.04)
Lower School: Count		0.03**		0.01
		(0.02)		(0.02)
Middle School: Count		0.00		0.07
		(0.02)		(0.06)
Vocational School: Count		0.04**		0.01
		(0.02)		(0.03)
Technische Hochschule		-0.04		0.04
		(0.06)		(0.04)
City and Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	15778	15778	9016	9016

This table reports regression estimates with variables defined as above. “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. The schooling count variables measure the number of schools of a given type present in a city, as described in the text. “Technische Hochschule” is an indicator for cities within 50 kilometers of such an institution in a given period. Standard errors allow for arbitrary spatial correlation within 25 kilometers following methodology of Colella et al. (2019). Statistical significance at the 90, 95, and 99 percent confidence level denoted “*”, “**”, and “***”, respectively.