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

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Abstract

We study the role of higher education in promoting the transition to industrial capitalism where modern research universities first developed: nineteenth century Germany. We construct novel microdata on invention, scientific activity, and manufacturing across virtually all towns in Germany between 1760 and 1900. Invention, scientific activity, and manufacturing developed similarly in towns nearer to and farther from universities in the 1700s, and then shifted towards universities and accelerated in the early 1800s. After 1800, we find a significant positive shift in the probability that inventors were educated or employed at universities. Manufacturing in which invention was university-intensive located nearer to universities. These shifts in invention and manufacturing reflected changes in German universities, politics, and culture that were precipitated by the French Revolution and Napoleonic invasion of the early 1800s.

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

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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

Were research universities instrumental for the transition to modern economic growth? A large literature argues that universities and advanced science played a limited role in the Industrial Revolution in England (Mitch 1999). At the same time science and higher education are viewed as a potential "cure for technological backwardness" (Landes 1969; p. 151-2). In this paper, we study the role of universities in promoting technical knowledge and the transition to industrial capitalism where modern research universities first developed: nineteenth century Germany.[1]

Germany industrialized between the late 1700s and late 1800s. Germany went from a position of relative economic backwardness to the world frontier of science and science-based industry (Scribner and Ogilvie 1996; Turner 1987). The model of the modern research university, defined by the combination of teaching and research and the aim of *increasing* scientific knowledge, was developed in Germany in this period (McClelland 2008; Rüegg 2004a). Historical research suggests that the German university system shaped the pattern of economic development (Landes 1969; Paulsen 1902). Significantly, changes in the universities preceded other structural shifts. In German history we observe, "the growth of teaching and research excellence in a preindustrial society lacking a strong middle class" (Cassidy 1981; p. 657). However, almost no quantitative research in economics has studied this process.

Prior research on the transition to modern growth in Germany, and on the role of universities, has been limited by the nature of the data examined. Existing data on invention and industrial activity in Germany are almost entirely restricted to the period from 1840 forwards and in many cases the later 1800s. Reflecting the data, there is limited prior quantitative research on the transition to modern growth in Germany, including the economic role of universities in this process.[2] Tilly's (1991; p. 177) observation that the period before

[1] We use "Germany" and "German" as short-hands. We analyse universities, invention, science, and industry across 2,254 historically German-speaking towns 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.

[2] We survey the existing evidence below, including research on "proto-industrial" manufacturing that

1840 is, "largely *terra incognita* from an econometric point of view" still holds.

We construct novel microdata on invention, scientific discovery, and manufacturing at the town-by-sector level from the mid-1700s through the late 1800s, and document a significant increase in economic development associated with universities starting in the early 1800s. We find that invention, science, and manufacturing developed similarly in towns nearer to and farther from universities in the 1700s, and then shifted geographically towards universities and began to accelerate in the early 1800s. This effect was particularly pronounced from 1800 until 1860, when transportation costs started to decline significantly.

The shift in the relationship between universities and economic activity reflected political shocks that transformed knowledge production. The French Revolution and Napoleonic invasion of Germany shifted the demand for and supply of research. These political events led to sudden and sharp changes in German culture, society, and institutions, including German universities (Hagemann 2006; Whaley 2012; Blackbourn 2003). Over the 1700s, German universities focused on theology and law and experienced steadily declining enrollments (Turner 1975). The French Revolution and Napoleonic invasion shifted the values of intellectual and administrative elites, and led to the development of a new model of university education in Germany, characterized by an explicitly pro-science orientation (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). By the mid-1800s, the excellence of German universities and their superiority in the sciences was recognized by educators and policy makers in the US and the UK (e.g. Arnold 1868), and ultimately led to the diffusion of the research university model in other countries starting in the later 1800s (Urquiola 2020).

We trace the influence of universities on invention, scientific discovery, and manufacturing as Germany industrialized between the mid-1700s and the late 1800s.

To study invention and science, we construct microdata on invention and scientific discovery. We gather evidence on technical inventions and basic scientific discoveries over periods economists have not previously investigated, including before German patent systems

predated the shifts in economic activity we document (e.g. Ogilvie 2008; 1996; Kaufhold 1986; Kisch 1972).

developed in the mid-1800s.[3] We gather and build on data from the history of science and technology literature.[4] We build on the *Handbuch zur Geschichte der Naturwissenschaften und der Technik*, a historic catalogue of thousands of major technical and scientific discoveries that was assembled by a team of 64 scholars, including multiple Nobel Laureates. We construct new evidence on the town location of each technical or scientific discovery and classify inventions and discoveries in narrow knowledge and technology categories. We use historical sources to identify the educational backgrounds and employment histories of inventors and scientists.

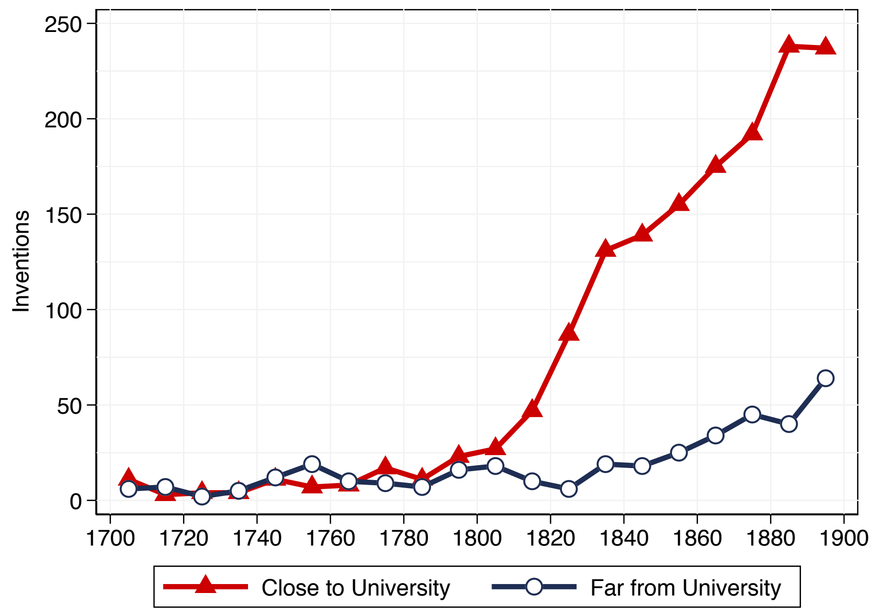
We use the data to study the pattern of invention and science. Figure 1 summarizes the data and shows that invention and scientific discovery increased and shifted geographically towards universities in the early 1800s. In our quantitative analysis, we also study the development of ideas *within* narrow technological and knowledge categories, such as "steam engines" or "chemical synthesis." We find that the likelihood that the first invention in a technological or knowledge category was made by an inventor or scientist with a university education or position, or in a university town, rose significantly after the 1790s. Subsequent inventions in the same knowledge or technology category are less likely to be made by university-connected inventors and scientists.

To study manufacturing, we construct novel microdata on individual manufacturing establishments at the town-by-sector level across virtually every town in historical Germany from 1760 through 1899. We construct information on the presence and number of different manufacturing establishments from the *Deutsches Städtebuch* (Keyser 1939-1974), a multi-volume encyclopedia of historic cities and towns, to measure the extensive and intensive margins of industrialization. We show that our measures of local industrial activity strongly predict the number of factories and the number of workers at the two-digit industrial sector level in periods where industrial censuses exist. We then use our richer and more disaggregated data to document several key findings. First, towns near to universities had no advantages in manufacturing until the early 1800s. Second, manufacturing expanded significantly in towns near universities in the first decades of the 1800s. The shift in

[3] Patents were not widely issued in central Europe until the mid-1800s and a unified patent system for the German Empire was only established in 1877. For a review, see Donges and Selgert (2019a). We discuss the advantages and limitations of our data below.

[4] Our data collection is in the spirit of Schmookler's (1966) examination of important inventions and, more recently, MacLeod and Nuvolari's (2016) survey of evidence on historical innovation.

Figure 1: Invention and Scientific Discovery Across German Towns



This graph plots data on major inventions and scientific discoveries from Darmstaedter, du Bois-Reymond, and Schaefer (1908), located across 2,254 German towns recorded in Keyser (1939-1974). Towns "Close to University" are those below median distance to a university, and towns "Far from University" are those above median distance, in a given decade.

manufacturing activity we document thus followed the political shocks that began with the French Revolution, and occurred decades before the development of the German customs union in the 1830s and before the development of the railroad network, which began in the 1840s. Third, we find that proximity to universities promoted manufacturing when we study all the variation in the data and when we study variation *within* the constituent territories of historic Germany.

Several pieces of evidence strongly indicate that the shifts in economic activity we document were in fact caused by changes running through the universities. First, our central findings do not reflect the selective or endogenous location of universities. While new universities were founded at Berlin (1810) and Munich (1825), and a number of historical universities were closed during the Napoleonic wars, these potentially endogenous changes in university locations do not drive our findings. Our results hold when we study variation in exposure to universities accounted for by institutions that were established for historical reasons long before the changes we study transpired, and when we study proximity to all pre-existing universities in the spirit of an intent-to-treat analysis. Second, our findings do not reflect institutional differences or other regional factors shared by towns in a given polity or region. We find that proximity to universities promoted economic activity in the same way when we study the variation in manufacturing *within* the constituent political units of historical Germany and in the same time periods.[5] Third, the shifts we document both preceded and are robust to accounting for other locally varying changes. This includes changes in education, such as development of technical colleges (*Technische Hochschulen*), which were established in some German cities starting in the mid-1820s, and the period-by-period development of the railroad.

We also provide evidence on the channels through which universities influenced economic activity. We find that the share of inventors with university degrees, with university positions, and living in university towns rose starting in the early 1800s. This finding qualifies classic arguments suggesting that a key transition in knowledge production occurred in the late-1820s, when the foundation of university research institutes led to increased professionalization in science (e.g. Ben-David 1971). We provide corroborating historical analysis documenting changes in the interactions between university professors and students and entrepreneurs and mechanics starting in the early 1800s.[6] We also provide historical evidence on the role of competition among universities for faculty and students, which shaped how German universities changed in the 1800s. Evidence on the universities as producers of graduates directly employed in industry is more mixed, as we discuss below.

Our research contributes to the literature on innovation and growth. German history provides a canonical example of how changes in knowledge production may influence the path of innovation and industrial development. Hardach (1972; pp. 64-5 – emphasis in original) observed that, "the question of *the start of German industrialization* is exceedingly important" and subject to debate. An influential literature argues that the industrial revolution in Germany took off with a "big spurt" in the 1840s, driven by the development of railroads and heavy industry (e.g. Gerschenkron 1943; 1962; Fremdling 1977; Tipton 1976), but the existing evidence on the industrialization process before 1840 is largely non-quantitative (Tilly 1991; p. 177).[7] Similarly, the quantitative analysis of invention has largely

[5] We discuss regional heterogeneity in the development of manufacturing, in universities, and in other factors such as railroads, the customs union (*Zollverein*), coal deposits, and economic institutions, below.

[6] Consistent with our quantitative evidence, these changes precede the *formal* establishment of research institutes and seminars at universities, which increased dramatically starting in the 1830s (Titze 1995).

[7] An exception is Hornung's (2014) study of town-level manufacturing circa 1802. Other scholars have

been restricted to patent data and, for Germany, evidence from the 1850s onwards (Moser 2013; MacLeod and Nuvolari 2016; Donges and Selgert 2019a). We construct geographically disaggregated data on science, technology, and industrial activity that span the 1700s and 1800s. In the data, we find significant shifts in knowledge production and economic activity associated with changes in universities and in the philosophy of education that date from the late 1700s and the early 1800s. These changes preceded the development of railroads and heavy industry, the customs union which reduced internal barriers to trade starting in 1834, and technical colleges which were established starting in the later 1820s. More broadly, the evidence points to the central role universities played in the transformation of the German economy as it went from a position of relative backwardness towards the world frontier in science, technology, and manufacturing.

Our historical analysis examines political and cultural changes behind this transformation. The French Revolution and Napoleonic invasion drove an interlocking set of changes in German culture, politics, and education. Narrative evidence indicates that these political events drove sharp changes in the realm of ideas that preceded reforms in universities. This is confirmed when we examine the spread of pro-science ideas in the media. The historical evidence is thus consistent with Kuznets's (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 [and shaped development] at critical junctures." More generally, we study changes in the cultural and knowledge processes economic historians place at the heart of growth (e.g. Mokyr 2016).

We also contribute to the literature on the economics of education. Prior research has found that foundation of new universities is associated with increased regional GDP in the 20th century (Valero and Reenen 2019) and that land grant universities in the USA were associated with increases in agricultural productivity (Kantor and Whalley 2019).[8] Historical studies indicate that universities shaped institutional change in medieval Europe (Cantoni and Yuchtman 2014) and the development of science in the Renaissance (Dittmar 2019), but played a limited role in the English industrial revolution (Mitch 1999). Prior research has

provided quantitative but non-econometric evidence on industrialization: Kirchhain (1973) and Forberger (1958; 1982) show that there was significant development in German textiles in the early 1800s. Hornung (2015) finds that railroads were associated with population growth in 1840s Prussia.

[8]Kantor and Whalley (2019) find significant but temporary increases in agricultural productivity. See also Kantor and Whalley (2014) and Foray and Lissoni's (2010) review of universities and innovation.

found a positive relationship between *primary* education and industrial activity in German history: Becker, Hornung, and Woessmann (2011) find that cross-county variation in school enrollment rates in 1816 Prussia predicts industrial activity in 1849 and 1882; Becker and Woessmann (2009) find that pre-industrial changes in religion shaped primary education and thus industrial activity in late 1800s Germany. In related work, Squicciarini and Voigtländer (2015) show that pre-industrial differences in local *upper tail* human capital across French cities, measured by encyclopedia subscriptions, explain the subsequent local diffusion of the industrial revolution. In contrast, our research documents how a changes in German universities led to shifts in the production of knowledge and economic activity starting in the first decades of the 1800s. Our findings describe a channel through which universities and upper tail human capital (Mokyr 2018) influenced the path of innovation and development.

Finally, our paper also relates to research on the consequences of institutional change. Acemoglu et al. (2011) find that the Napoleonic occupation led to institutional changes in Western German territories in the early 1800s, and that these changes led to increases in territory-level urbanization after 1850. In contrast, we study how the French Revolution and Napoleonic invasion generated shocks to the German university system, leading to increased invention, science, and manufacturing starting in the early 1800s. Our findings are not principally driven by the territory-level institutional processes examined by Acemoglu et al. (2011). We observe the effects of changes in the universities across Germany – not just in Western territories impacted by Napoleonic institutional change – and when we study *within* territory variation in exposure to universities, as we show below.

2 The Historical Process

2.1 Industrialization in Germany

Between the late 1700s and the late 1800s, the German economy industrialized. Germany transitioned from a position of relative backwardness to being an advanced industrial economy at the world frontier in invention and in several leading industrial sectors (Landes 1969; Borchardt 1973; Ogilvie and Overy 2003; Pierenkemper and Tilly 2004).

Timing. The timing and nature of the industrialization process in Germany are subject to debate. A leading 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, with the development of the railroad network, heavy industry, and large scale banking (c.f. Hoffmann 1963; Tipton 1976; Fremdling 1977). Recent research in economics draws on this literature, and argues that Germany was "pre-industrial" in the first decades of the 1800s (Becker, Hornung, and Woessmann 2011; Hornung 2014).[9]

A second strand of the literature argues that a significant shift towards industrialization took place in the late 1700s and early 1800s. König (1899), Meerwein (1914), and Forberger (1958; 1982) document rapid increases in the mechanization of textiles in Saxony in the 1790s and early 1800s. Kirchhain (1973) documents that there were also sharp increases in the mechanization of the textile industry in Prussia and in Baden-Württemberg between 1800 and 1815 (see Appendix C). Engelsing (1968; p. 73) argues that the late 1700s marked the shift between a "traditional" and "modern" economy because the initial adoption of technologies such as steam engines dates from this time.[10] Kuczynski (1961; pp. 24, 87) suggests that the introduction of German-built steam engines in the late 1700s marked a decisive shift in the development of the productive forces, but describes the period between 1815 and 1839 as the "industrial revolution" in Germany.[11]

A third strand of literature argues that structural changes in the German economy were relatively gradual and continuous. Kaufhold (1986) documents the development of rural "industrial regions" between 1650 and 1800. Ogilvie (1996) argues that the evidence indicates that industrialization was part of a longer-run transformation of economic activity. Kopsidis and Bromley (2016; 2017) similarly argue that on-going processes of economic development explain the shift to heavy industry and urbanization after the mid-1800s.[12]

The debate over the timing of industrialization reflects several key features of the larger social processes. In particular, there was substantial variation in industrialization across

[9] Becker, Hornung, and Woessmann (2011) argue that in 1816 the German economy was pre-industrial. Hornung (2014; p. 96-7) studies variation in productivity in textile manufacturing across Prussian towns in the first decade of the 1800s, a period he describes as "preindustrial' and before the Industrial Revolution.

[10] Henderson (1956; p. 202) similarly argues that the origins of German industrialization date from the late 1700s, highlighting blast furnaces, foundaries, and engineering works established in the later 1700s.

[11] Mottek (1960), in contrast, argued that a preparatory period starting in the 1780s with the initial adoption of steam engines and spinning machines set the stage for industrial transition after 1834, i.e. following the introduction of the German customs union (*Zollverein*).

[12] Consistent with these observations, Fremdling (1995) shows that national accounts from pre-1980 scholarship are likely underestimate development pre-1850. Tilly (2001; p. 157) notes: "The historiographical implications could be far-reaching: Germany's relative backwardness in the so-called 'take-off' period of industrialisation was quite likely significantly less."

regions and sectors (Tipton 1976). Further, a large share of the German population remained employed in agriculture into the late 1800s (Kopsidis and Bromley 2017).[13]

Causal factors. The causal factors shaping German industrialization are also subject to debate, with prior research pointing to technological, educational, and institutional factors.

First, a leading view is that the introduction of railroad technology after 1840 drove a shift towards heavy industry and fostered the development of banking (Fremdling 1977; Gerschenkron 1962).[14] However, historical evidence suggests railroads were themselves responses to demand-side factors and prior development (Kreidte, Medick, and Schlumbohm 1977). Significantly for our analysis, historical evidence indicates that the major declines in transport costs due to the railroads were only realized after 1860 (Fremdling and Hohorst 1979; Wrigley 1961).[15]

Second, a large literature points to the importance of education. Becker and Woessmann (2009) find that differences in primary and secondary education explain variation in industrial development in the 1840s and 1870s, while Becker, Hornung, and Woessmann (2011) find that differences in primary education observed in 1816 explain variation in industrial development across counties in the later 1800s. Classic research in economic history points to the importance of more advanced scientific and technical training, but typically suggest such "upper tail human capital" mattered in the later 1800s. Thus Landes (1969; p. 187) suggests that, "*Wissenschaftliche Bildung* was to pay handsomely in the second half of the century."

Third, several dimensions of politics and institutional change have been tied to industrialization. A large literature points to role of the Prussian state in fostering development, by relaxing restrictions on economic activity and promoting industry for geostrategic reasons (Vogel 1980; 1983), but considerable research questions whether Prussian policy in fact and on net promoted industry (Sperber 1985). In more recent work, Acemoglu et al. (2011) find that the Napoleonic occupation of Western regions led to institutional changes promoting economic freedom that ultimately led to greater urbanization after 1850.[16]

[13]The available evidence suggests minimal increases in real wages 1760-1850 (Pfister 2017). Productivity comparisons by sector begin in the 1870s (e.g. Broadberry and Burhop 2010).

[14]Related evidence points to the importance of geography, and in particular the location of coal deposits, for the development of industrial activity after the introduction of railroad technology (Fernihough and O'Rourke 2014; Kopsidis and Bromley 2016). We discuss the role of coal further below.

[15]Hornung (2015) finds a positive relationship between railroads and population across Prussian cities starting about 1850.

[16]For consistent narrative evidence on textile manufacturing in the Rhineland, see Kisch (1989).

Finally, Crouzet (1964; p. 579) argues that the Napoleonic wars may have promoted textile manufacturing by raising effective protection against British imports, but argues that absent the war industrial progress on the continent might have been even higher.[17]

Limitations of existing evidence. Where the prior literature uses econometric methods to investigate the development of manufacturing or inventive activity, almost all previous work considers data from periods after 1840.[18] 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."[19] Hardach (1972; pp. 64-5) similarly notes that while questions concerning the start of German industrialization are "exceedingly important," they have been difficult for scholars to answer given the absence of standard, agreed measures of industrial activity in the early 1800s.

2.2 Knowledge Production and Universities in Germany

There were profound changes in knowledge production in Germany between the late 1700s and early 1800s. Indeed, "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' " (Turner 1987; p. 56). Into the late 1700s, scientific and technical activity in Germany was limited, universities focused on theology and law, and university enrollments were declining (Bahti 1987; Turner 1975; Eulenburg 1904). Over the 1800s, Germany emerged as a world leader in science, with research universities and dynamic, associated industries.

Narrative evidence suggests that several aspects of this transition were particularly important. These include: (i) a pro-scientific shift in ideas, that was influenced by the

[17]Crouzet (1964; p. 579) observes that the conflict had negative effects on many industries and argues, "It is most likely that if there had been no war, if relations with England had been maintained, if a moderate protection had been established, economic and technical progress on the Continent would have been faster."

[18]Quantitative research on inventive activity is largely restricted to the patent record. See *inter alia* Streb, Baten, and Yin (2006), Donges and Selgert (2019a;b), Donges, Meier, and Silva (2019). Moser's (2005) study of patented and non-patented innovation examines evidence from the 1851 World's Fair and 1876 Centennial Exhibition, and is thus similarly situated in the middle 1800s.

[19]To be clear, Acemoglu et al. (2011) study regional urbanization before and after the mid-1800s. Our research, in contrast, studies the implications of changes in higher education that varied both across and *within* regions. Fernihough and O'Rourke (2014) and Kopsidis and Bromley (2016) similarly study city populations as a proxy for development.

French Revolution starting in 1789, (ii) the closure of universities as a result of the French Revolution, (iii) the reform of university education and the development of the research-oriented "Humboldtian university model" in the early 1800s, and (iv) the establishment of research institutes and seminars starting around 1830.

Cultural changes contributed to the shift towards science. Narrative evidence suggests that, "the ideal of a rigorous science experienced a spectacular upsurge" following the publication of Immanuel Kant's *Critique of Judgment* in 1790 (Van Bommel 2015; pp. 12-14). Kant advocated scientific (*wissenschaftlich*) argument and evidence. Narrative evidence suggests that Kant's intervention led to sudden and profound changes in values and concepts within the German scholarly community, including a take-off in the use and value attached to the term "scientific."[20] While enlightenment ideas were diffusing in Germany before 1789, both quantitative and narrative evidence suggests that the shift towards *science* coincided with and was promoted by the French Revolution, as we discuss below (Section 2.3).

A set of interlocking changed occurred in the university system. First, the French invasion of Germany redrew the political map, leading to consolidation of polities and universities. A large number of universities were closed. State support and the aims of university education shifted away from producing and supplying bureaucrats for state lets and towards scientific activity. Second, the Prussian reforms of 1809-10 included the foundation of the university Berlin and institutionalization of the research-oriented university ideal or "Humboldt model," advocated by Interior Minister Wilhelm von Humboldt, arguably the most influential education policy maker in German history. The consequences of these reforms viewed included: a shift of prestige and resources from the law, medicine, and theology faculties towards the philosophy faculty which became the preeminent location of scientific activity; the introduction of research seminars and institutes starting in the late 1820s; and the development of model that combined education and research in order to increase knowledge. These developments reflected the fact that the German university *system* was characterized by "competition and widespread initiative at the intellectual level" (Kindleberger 1975; p. 260), due to the number of universities and the ability of students

[20] Narrative evidence indicates that the take-off in the use and value of "scientific" led to the eclipse of previously important concepts: "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" (Van Bommel 2015; p. 14).

and faculty to move between institutions (Ben-David 1971). Significantly, while influential research has stressed the importance of the foundation of the university of Berlin in 1810 and the institutionalization of scientific research in seminars and research institutes in the late 1820s (e.g. Ben-David 1968; Ben-David and Zloczower 1962), we observe preliminary shifts in science, invention, and manufacturing associated with universities in the earler 1800s.

Changes in universities also fosted new interactions between universities and broader society. For example, at the university of Jena a "physical-mechanical" society was established in 1802 explicitly 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; p. 229). Consistent with such narrative evidence, in our data on inventions and discovery we find that a substantial number of inventors worked in or around university facilities without being employed as university professors.

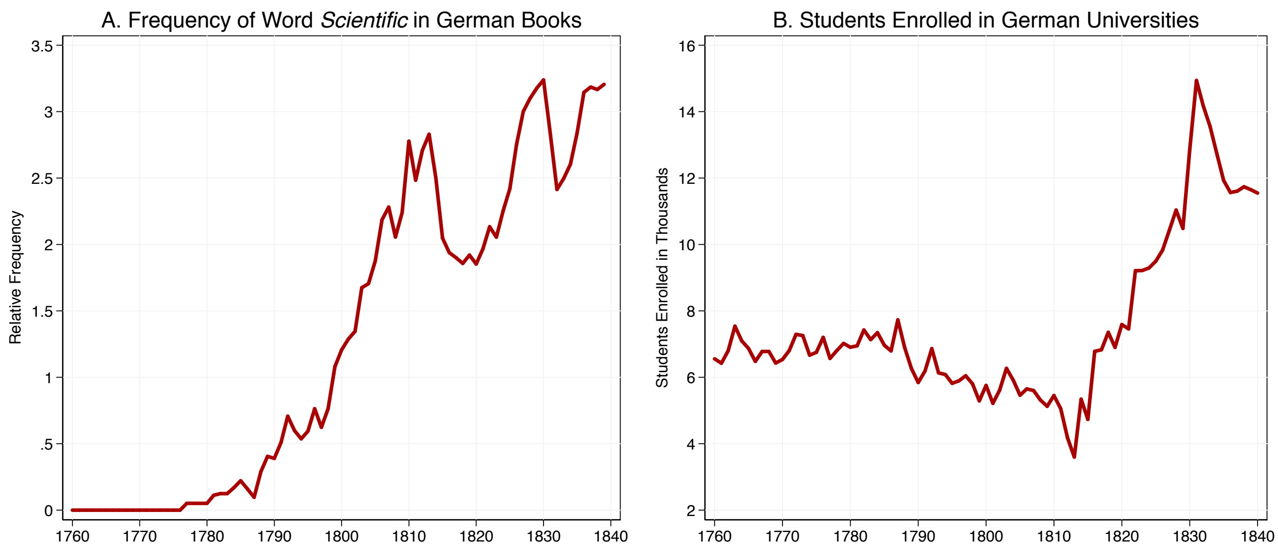
Several other institutions and mechanisms for the development of knowledge developed besides universities. German states reformed primary and secondary education at the territorial level. Policy makers also moved to establish "vocational schools" (*Gewerbeschulen*) to support the formation of a skilled work force and "technical higher schools" (*Technische Hochschulen*), starting in the mid-1820s. It is natural to wonder whether and how the influence of these institutions related to the effects of universities. Significantly, these other educational institutions were established several decades into the process we consider and, as a rule, were located in capital cities and not in university cities. Thus *Technische Hochschulen* were established at Karlsruhe in 1825, Darmstadt 1826, Munich 1827, Dresden 1828, Stuttgart 1829, and Hannover 1831. In our quantitative analysis, we find the effects of universities are evident before other innovations in schooling were introduced.

Figure 2 provides quantitative evidence on the diffusion of scientific ideas and changes in university enrollments. Panel A shows that the German-language word for scientific inquiry and systematic study (*wissenschaftliche*) came into use and rapidly diffused in German books in the late 1700s and early 1800s.[21] Panel B shows that the number of students at German universities was in slow and steady decline across the 1700s, and began to increase sharply in the early 1800s. Figure 2 indicates large scale changes in knowledge and education before

[21] Typically, *wissenschaftliche* is translated as "scientific," but is the German language term for *systematic study* and applies to inquiry in and outside the "natural sciences."

the mid-1800s, and that changes in language preceded changes in the number of students in university education.

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).

2.3 The French Revolution and Napoleonic Wars as Shocks

The French Revolution, beginning in 1789, and the Napoleonic wars of the early 1800s had profound implications for universities and economic development in Germany.

The French Revolution elicited considerable enthusiasm among sections of the liberal bourgeoisie and in German university towns in the 1790s. The revolution in France was understood by contemporaries as offering a model and source of ideas relating to the processes through which societies might undertake large scale social change (Hobsbawm 1990). Whaley (2012; p. 600*) notes: "the sense of time suddenly moving with extraordinary speed, the sense that nothing would ever be the same again, is the leitmotif of many letters and memoirs of this period…In making sense of the French Revolution and placing it in world-historical context, German intellectuals discovered themselves as the true progenitors of modernity."

The cultural changes precipitated by the French Revolution promoted science in Germany. On the supply-side, the French Revolution profoundly influenced the production of new ideas. For example, Kant wrote his *Critique of Judgment*, which led to a pro-scientific shift in values, in 1789 and 1790 (Kant 1987 [1790]; p. xxix) over a period in which the French Revolution "occupied him entirely; he linked everything to it," according to the memoir of his friend Reinhold Jachmann.[22] More conceptually, Karl Marx (1975 [1842]; p. 213) observed that Kant's work should be considered as, "the German theory of the French Revolution." On the demand side, the French Revolution shifted the values and interests within the educated elite towards new forms of inquiry that were ultimately supportive of scientific and technical discovery. For example, in 1793 Johann Kiesewetter wrote to Kant, "Everyone is truly anxious to see your system of morality appear, and all the more so just now since the French Revolution has stimulated a mass of such questions anew" (Kant 1999; p. 463).

The Napoleonic wars delivered a further shock to German societies. Napoleon's invasion and defeat of the Prussian army at Jena in 1806 transformed the political landscape: the Holy Roman Empire collapsed, a new state system was formed in what is now Germany, and the beliefs and objectives of policy makers shifted. Hagemann (2006; p. 587) notes, "The Prussian army had been victorious since the Seven Years' War [of 1756 to 1763] and felt invincible, and broad segments of Prussian society shared this assessment. A devastating defeat only five days after the declaration of war in 1806 delivered an even greater shock." Kindleberger (1975; p. 260) observes, "the Germans responded to defeat with educational reform. An enormous drive was made after Jena [1806]..."

The Napoleonic invasion led to a range of institutional reforms. In territories subject to French rule, guilds were abolished and restrictions on economic activity were relaxed. Acemoglu et al. (2011) find that these institutional changes promoted urbanization after 1850 in Western regions. The Napoleonic invasion also changed politics and led to institutional reforms in territories not subject to French rule: Prussian policy makers responded by modernizing their school system. While the elimination of restrictions on economic activity is widely viewed as promoting to industrialization, Saxony was a leading industrial region and preserved guild restrictions until the mid-1800s (Borchardt 1973).

[22] A friend recalled, "Kant was so keen on having the newspapers in those critical moments that he would have queued for hours in front of the post-office; there was no greater pleasure we could give him except for bringing the latest and authentic news from France." (Jachmann 1804)

2.4 The Locations of Universities

Our analysis examines the role of universities in promoting local economic development, and thus naturally invites questions concerning the location of universities and their role in promoting economic development before the industrial revolution.

Historically, German universities were located in smaller towns, as a result of decisions taken between that 1300s and 1500s. Segal (2018; p. 57) observes that, "Before the dissolution of the Holy Roman Empire [in 1805]. . . universities were scattered across the many German principalities, and with the exceptions of those in Vienna, Leipzig and Königsberg, generally located in small towns," at locations that were, "already too fixed to be manipulated by the new states" in the 1800s. The prestige of historical universities in small provincial towns meant they could not be shifted (Rüegg 2004b).

The French Revolution and the Napoleonic invasion led to the closure and the foundation of universities. The closure of universities reflected political factors that were independent of the strength or quality or the institutions themselves (Rüegg 2004b; Turner 1987). New universities were opened at Berlin (1809-1810), Bonn (1818), and Munich (1825). While universities in Berlin and Munich were in political capitals, and used to promote political and economic objectives, the university at Berlin was itself founded by the Prussian authorities to offset their loss of the university at Halle due to military events (McClelland 2008; p. 50). Prior to the Napoleonic wars, Prussia's principle university was in Halle. In 1807, the Treaty of Tilsit stripped Prussia of half its territory, including region of Lower Saxony in which Halle is located, depriving Prussia of its main university (Dieterici 1836; p. 60).

Several pieces of evidence indicate that the potentially endogeneity of university locations is unlikely to explain our findings. First, historical evidence strongly indicates exogenous political factors account for the university closures of the early 1800s. Second, we find no differential trends in economic development nearer to universities prior to the political shocks of the French Revolution and the Napoleonic wars (Section 4). We also test for and find no significant differences in *ex ante* enrollment growth for the universities that were closed or remained open after the French Revolution (Appendix B). Third, our key findings hold when we study variation in proximity to universities open before the French Revolution, thereby focusing on the implications of historic universities whose locations or closures were not shaped by invention and industrial activity during the industrial era. Our findings thus hold when we exclude from consideration variation due to universities founded in the 1800s, whose locations were potentially more likely to reflect other factors shaping development (Section 4). Fourth, our findings similarly hold when we control for other factors that varied across space and time, such as the establishment of technical schools, territory-level changes in schooling and institutions, and the development of the railroad network (Section 4).

3 Data

3.1 Invention and Science

We construct data on technological and scientific 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 study period. Darmstaedter's project was produced by 60+ contributors including four Nobel Laureates. Contributors had expertise in architecture, astronomy, chemistry, civil engineering, electrochemistry, engineering, intellectual property, the history of science, library science and archives, mathematics, metallurgy, medicine, physics, signals and communications technology, transportation technology, and steam technology.

The handbook describes contributions and identifies the scientists and inventors responsible (we use "inventors" as shorthand for inventors and scientists). With a team of German graduate students, we match inventions and discoveries to towns based on the location of the inventor, using information on the lives and employment histories of individual inventors drawn from the *Deutsche Biographie*, the *World Biographical Information System* and historical sources. We further classify observations with industrial applications with SIC codes for down-stream industries for which inventions were inputs and for the industries producing inventions, where applicable. Table 1 provides an illustrative example of five observations in our database.

The data have advantages and limitations. They provide an unparalleled body of evidence on technical and scientific discovery, spanning both practical invention and basic science and covering key time periods for which no German patent data exist. The data were also explicitly conceived of as providing evidence that future scholars might use to examine factors that shape the development of science and technology, including "their condition in... changing political conditions" (Darmstaedter and du Bois-Reymond 1904; p. II). By construction, the data reflect major discoveries that can be attributed to individuals and not "tweaking" improvements, e.g. as emphasized by Meisenzahl and Mokyr (2012). In our baseline analysis, we restrict attention to inventions where our historical evidence unambiguously indicates the town location of the inventions. However, our findings are robust to flexibly incorporating the limited number of observations where there is some ambiguity over the precise location.[23] Finally, Darmstaedter and du Bois-Reymond (1904) record observations that include purely conceptual break-throughs, early technology prototypes, and the adoption or installation of effective and commercially viable technologies. In this respect, the data reflect the fact that the distinction between "invention" and "innovation" is often gradual and blurry, as more broadly argued by Rosenberg (1976).[24]

Table 1: Example of Individual Inventions and Discoveries

Subject Classification				Producing	Inventor
Original	English	Year	Town	Industry	University
Registrierapparate, selbsttätige	Automatic register apparatus	1805	Berlin	Equipment	1
Spannungsreihe der Metalle	Metal stress tests	1808	Halle	Metals	1
Glycirrhizin	Glycyrrhizic acid	1808	Kiel	Chemicals	1
Stahl- und Flusseisenbereitung	Steel and cast iron production	1811	Essen	Metals	0
Silbersalze	Silver salts	1811	Bayreuth	Chemicals	1

The "Subject Classification" is the hand-coded classification of the subject of the invention and scientific discovery. The "Year" is the year of the invention or discovery as per Darmstaedter, du Bois-Reymond, and Schaefer (1908). The "Town" is the location of the invention or discovery, which is coded in our research based on historical and biographical sources. The "Producing Industry" is our classification of the industry that produced the given invention or break-through. The classification follows the two-digit SIC coding but combines in "Metals" the separate SIC classifications for "Primary Metals" and "Fabricated Metals". The "Inventor University" column records whether the inventor had a university education.

[23]For example, in some cases we know inventors lived in two or more cities but cannot determine unambiguously which city they were living in the precise year they made a discovery. Our results are robust to assigning these observations to the candidate cities randomly, equally, or on a *pro rata* basis.

[24]In terms of the lexicon suggested by Joseph Schumpeter, the data we examine include invention and innovation observations, and observations where the invention-innovation distinction may be problematic.

3.2 Industry and Manufacturing

Our principal data record industrial and manufacturing activity at the town-level and are drawn from the *Deutsches Städtebuch* (Keyser 1939-1974), an encyclopedia of German towns. The *Deutsches Städtebuch* entries provide a description of the economic development of the town, including the history of manufacturing activities and establishments. We rely on the entry on "*Die Wirtschaft*" (The Economy), including the section on "*Handelshauser, Fabriken, Kaufmannsgesellschaften usw.*" (Commercial houses, factories, trading companies, etc.). We code the precise date and type of all manufacturing and industrial activities, and classify these activities in two-digit SIC codes. The underlying observation in our data is a manufacturing "event": the opening or presence of a factory or manufacturing establishment of a specific type in a given town-year. For example, in 1801 the *Deutsches Städtebuch* records among other observations: a printing establishment (*Buchdruckerei*) in Schwabach; a machine factory or plant (*Machinenfabrik*) in Mannheim; a wire factory (*Drahtfabrik*) in Allersberg; a grain mill (*Getreidemühle*) in Bad Neustadt an der Saale; 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 presence and/or opening of manufacturing establishments. For a limited subset of observations, Keyser (1939-1974) provides further information on the number of employees, as we discuss below. Second, the dating of some observations in the *Deutsches Städtebuch* is approximate. Some factories and establishments are recorded as opening "around" or "circa" a given year.[25] Our baseline analysis assigns approximate years to corresponding decades, however our findings are robust to restricting the analysis to observations without ambiguity. Moreover, in our analysis we study how differences in proximity to universities are associated with differences in manufacturing activity, controlling for factors shared across all towns in a given period and for factors shared by all towns in a given territory and time period. Third, our measure of manufacturing events should be interpreted as a *proxy* for manufacturing activity. Below we show that our proxy measure predicts the number of factories and the number of workers at the two-digit industrial classification level in periods when the Prussian

[25] A further limited number of observations appear with even more roughly defined dates, such as "in the 19th century" (*im 19. Jahrhundert*). We exclude these observations from our baseline analysis.

Census provides administrative data on manufacturing, e.g. 1849 (Becker et al. 2014). We present summary statistics on the manufacturing data in Section 4 and Appendix A.

4 Industry

4.1 Overview

We use the evidence on manufacturing in the *Deutsches Städtebuch* to study the development of industry by town and sector. Figure 3 provides summary snapshots of the data, illustrating the local density of towns and manufacturing over the period 1800 through 1859, before the railroad transportation costs fell significantly in German-speaking Europe (Fremdling and Hohorst 1979; Wrigley 1961).

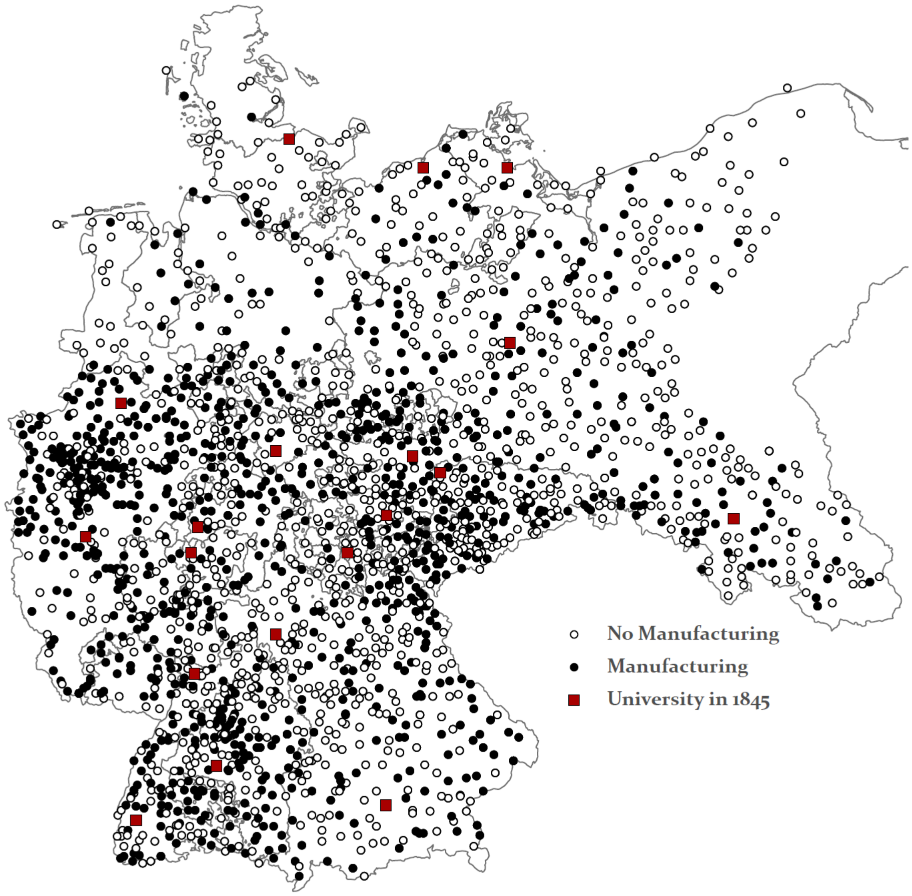
Table 2 summarizes the data on manufacturing before and after 1800 and highlights key facts. Before 1800, manufacturing was if anything slightly higher in towns farther from universities. After 1800, manufacturing increased overall and shifted towards towns with universities. The shift in manufacturing towards towns with universities is observed in the period 1800-1859, hence before the significant drop in price of railroad transport. We further consider the development of the railroad network starting in the 1840s below. In our analysis below, we first document that the evidence from the *Städtebuch* strongly predicts administrative data on factories and employment where these are available.

Table 2: Universities and 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	0.12	0.13	179	188
1800-1859	0.67	0.50	1445	970
1860-1899	0.63	0.61	1023	979

This table reports summary statistics on manufacturing for 2,254 towns 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. Median distance to a university was 58 km.

Figure 3: Manufacturing in German Towns 1800-1859



This map presents evidence on manufacturing across 2,254 towns recorded in the *Deutsches Städtebuch* (Keyser 1939-1974). Towns with any manufacturing events 1800-1859 are indicated with black circular markers. Towns with no manufacturing events 1800-1859 are indicated with white circular markers. The locations of universities as of 1845 are indicated with larger square markers (shaded red in online version).

4.2 Manufacturing in *Städtebuch* and in administrative data

We first document how our measure of manufacturing constructed from the *Städtebuch* compares to administrative data, where administrative data are available.

We 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 sector-by-sector basis, estimating cross-sectional regressions:

$$man_i^c = \alpha + \beta man_i^s + \epsilon_i$$

Here man_i^c is manufacturing activity in the 1849 Prussian Census, measured by the number of factories or by the number of workers in a given two-digit industrial sector in county i. Similarly, man_i^s is the number of manufacturing events in given sector in county i recorded in the *Städtebuch* between 1820 and 1839. To estimate these relationships, we aggregate our town-level data to the level of their respective Prussian counties.[26] We similarly aggregate manufacturing events to the sectoral level, following the two-digit SIC coding for manufacturing activity but amalgamating all metal-related manufacturing in a single sector. Given that examine a cross-section of count data, we estimate negative binomial regressions.

Table 3 shows that there is a strong positive correlation between our measure of manufacturing and the number of factories and workers in a given sector. 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.[27] We exclude the 1840s from the *Städtebuch* measure because for some towns 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) 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 sectors 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 sector.

4.3 Universities and Manufacturing in the Panel

Baseline. We estimate the relationship between manufacturing and the proximity to universities

[26] The mean Prussian county comprises 3.5 *Städtebuch* towns.

[27] To be clear, we do not directly observe the closure of factories in the *Städtebuch*.

Table 3: Evidence on Manufacturing by Sector

	(1)	(2)	(3)	(4)
	Outcome: Manufacturing in 1849 Census			
	Number of Factories in Given Sector		Number of Workers in Given Sector	
Manufacturing in Städtebuch 1820-1839	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 sector and county in the 1849 Prussian census. Each row presents estimates from sector-specific binomial regressions: $man_i^c = \alpha + \beta, am_i^s + \epsilon_i$. 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 sector recorded in the *Deutsches Städtebuch* (Keyser 1939-1974) from 1820 through 1839. Town-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.

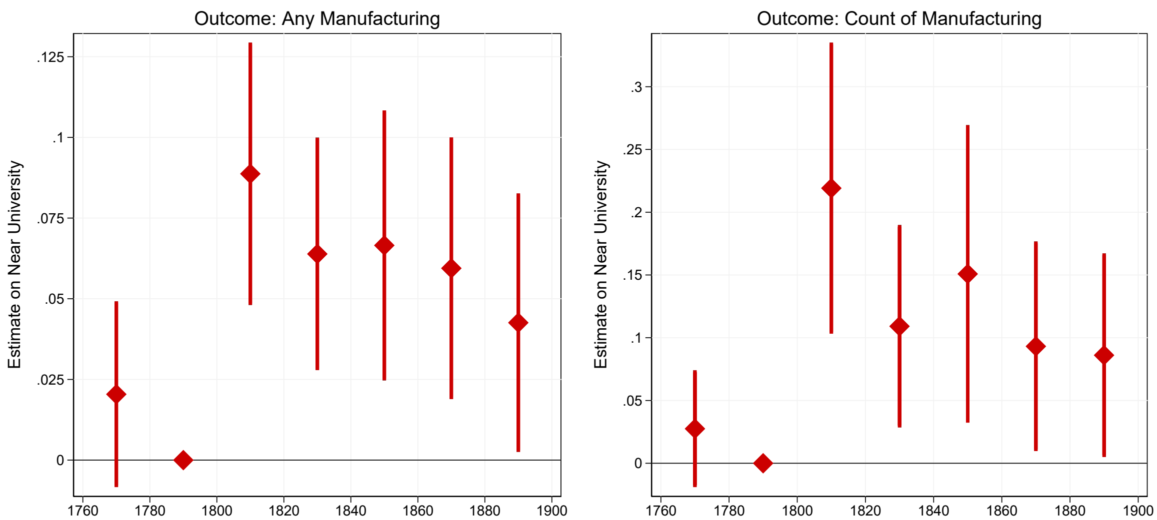
$$manufacturing_{it} = \theta_i + \delta_t + \sum_s \beta_s[uni_i \times time_s] + \epsilon_{it}, \quad (1)$$

where uni_i is either an indicator for below-median distance to a university or log(distance) as of 1840.

Potential selection in location of universities. Over the period we study, several universities were opened and closed, raising possible questions about whether towns' proximity to university may have reflected underlying economic differences across regions. The universities of Berlin and Munich opened in 1810 and 1826, respectively, while a number of universities were closed during and a result of the Napoleonic wars. For example, Erfurt closed in 1804 and Fulda closed in 1803.

To address questions around the possible endogeneity of university locations, we present further estimates in which we examine how proximity to historic universities established and open before the French revolution was related to subsequent economic development. In

Figure 4: Manufacturing and Proximity to Universities



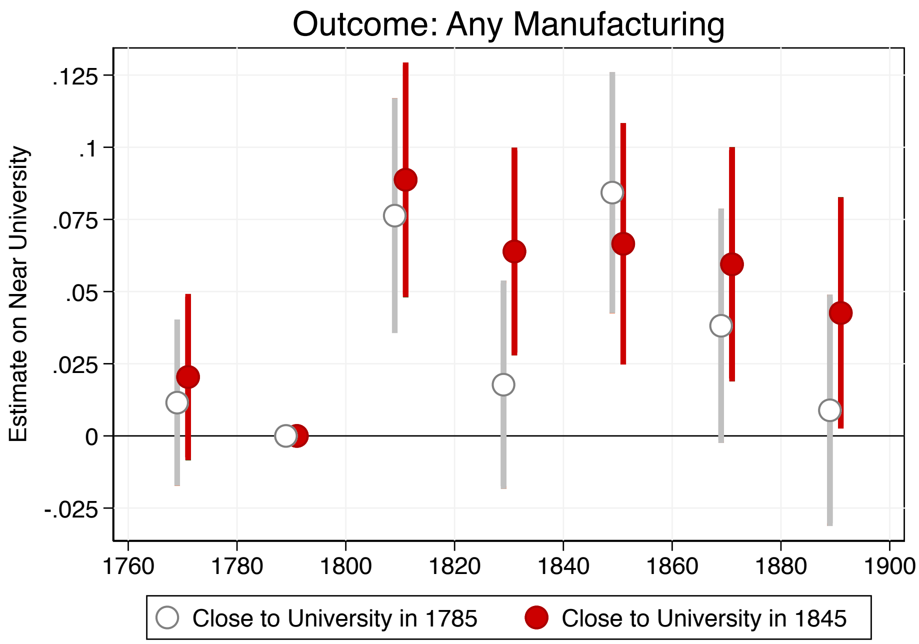
This graph plots estimates from regressions in which the outcome measures manufacturing events in a town-time-period. In Panel A, the outcome is an indicator for any manufacturing in a town-period. In Panel B, the outcome is the number of manufacturing events in the town-period. Data on manufacturing are constructed from Keyser (1939-1974). Figures present parameter estimates on variables that interact proximity to universities, measured by an indicator variable for towns below median distance to a university, and time fixed effects. Standard errors are clustered by town.

these estimates, potential selection in the opening and closure of universities during and in response to the possibilities of the industrial revolution is not at play.

Figure 5 presents our estimates using measures of proximity to university towns before and after the changes we investigate. These estimates indicate that proximity to towns with universities in 1785 and proximity to towns with universities in 1845 were associated with similar, positive shifts in manufacturing between 1800 and the 1850s. After the 1850s, a differential advantage is observed for towns with universities in 1845, reflecting the increasing development of manufacturing around the new universities at Berlin and Munich.

Regional and Time-Varying Factors. It is natural to wonder whether and how exposure to universities may have been correlated or interacted with other regional and time-varying factors that influenced the development of manufacturing. Proximity and exposure to universities may have been correlated with institutional reforms that previous literature indicates played an important role in shaping economic development. Leading candidates include the "modernizing" Stein-Hardenberg Reforms of 1808 to 1820 in Prussia and the legal introduction of "free enterprise" (*Gewerbefreiheit*), which was rolled out in a staggered

Figure 5: Manufacturing and Universities Before and After French Revolution



This graph plots estimates from regressions in which the outcome is an indicator for manufacturing events in a town-time-period. The figure presents estimates using two measures of proximity to universities: (i) an indicator for towns that were below median distance to universities in 1785 and (ii) an indicator for towns that were below median distance from universities in a given period, i.e. given the universities open in a given time period. Standard errors are clustered by town.

manner across the 44 constituent polities of the German Bund after 1810. Acemoglu et al. (2011) present evidence indicating that these institutional changes were concentrated in regions of Western Germany where the Napoleonic occupation had an important impact on rules: this naturally leads one to wonder whether the university effect we estimate is concentrated or larger in Western German regions where these reforms occurred. Motivated by the observation that railroads led to significant declines in transport costs starting after 1860 (Fremdling and Hohorst 1979), we consider whether the relationship between universities and manufacturing shifted after both 1800 and 1860.

Table 4 reports regression estimates that examine several dimensions of the variation in the manufacturing data. Column 1 reports baseline estimates showing that proximity to a university was associated with an additional 0.12 manufacturing events after 1800 relative to a mean of 0.27. Column 2 constructs a counterfactual in which towns close to a university are compared to towns in the same territory-period far from a university.[28] We find that

[28]There is variation in the number of towns in a territory and in the proximity of towns to universities

proximity to universities was associated with a 0.06 manufacturing events within territory-period. This indicates that the advantages of proximity to universities were not driven by institutional and related factors that were shared by towns in a given territory and time period. Column 3 focuses the analysis on towns in historic Prussia, where we find a much larger estimate. Column 4 further focuses on towns in Eastern Prussia, where we find a similarly large effect across towns which were not subject to Napoleonic institutional reforms. Column 5 restricts to the territories of Western Prussia, where the Napoleonic institutional changes studied by Acemoglu et al. (2011) were concentrated. Here we find a weaker and statistically insignificant university effect. Our findings are thus strongest in Eastern regions were institutional changes were *not* introduced by the Napoleonic armies. Outside Prussia we find a significant but quantitatively somewhat smaller estimate, as shown in column 6.

The relationship between universities and manufacturing holds when we consider factors tied to the industrial revolution in Germany that varied across space and time. Prior research on industrialization in Germany emphasizes: the role of railroads (Fremdling 1977); the introduction of free enterprise laws (Acemoglu et al. 2011); proximity to coal deposits, particularly after 1840 (Wrigley 1961); and patterns of prior development which may have had evolving consequences for the development of manufacturing over the course of the 1800s (Kopsidis and Bromley 2017; Kreidte, Medick, and Schlumbohm 1977). We measure railroad connections with an indicator for cities within 1-2 kilometers of railway lines. We classify cities as above or below median distance to coal deposits and examine whether cities close to coal enjoyed advantages after 1800 or after 1840. We consider the potential implications of prior economic development, by interacting an indicator for the post-1800 period with an indicator the presence of manufacturing before 1760, which we observe in approximately 1 in 6 cities. We find that the estimated post-1800 effect of universities holds almost unchanged when we account for: the development of the railroad network, which began in the late 1830s; the introduction of free enterprise laws, which date from the early 1800s; the shifting implications of initial, pre-1760 manufacturing for future manufacturing; and the time-varying advantages of proximity to coal deposits. These other time- and spatially-varying factors do explain variation in manufacturing, however the stability of the estimated

within territories. For example, in 1805 the Principality of Brunswick had 9 towns close to and 9 far from a university; the Province of Saxony has 91 towns close to and 63 far from a university.

university effect strongly indicates that universities conferred economic advantages that were not driven by other regional factors that were changing over time.[29]

The development of manufacturing in new sectors also helps us understand the role of universities in economic change. To study the development of new types of economic activity, we further focus our analysis on manufacturing in sectors that were new to a given city. We define the potential "new sectors" for a given city as the two-digit SIC sectors which that city had no manufacturing before 1760.[30] When we study the development of manufacturing in new sectors, we find that the post-1800 university effect remains almost unchanged, but that effect of early, pre-1760 manufacturing declines in magnitude (column 8).[31]

To consider the sequence of development more tightly, we further restrict our analysis of new manufacturing to the period before the development of the railroad network and before the emergence of coal as a significant factor for manufacturing. In this period, running through from 1760 through the 1830s, we find the post-1800 university effect remains strongly positive and statistically significant, while the effect of free enterprise laws and of prior early manufacturing are positive but statistically insignificant (see column 9).[32]

To consider the implications of potentially endogenous university locations, it is also helpful to examine the implications of proximity to historic university locations that were not shifted over the period we study. Table 5 therefore examines shifts in manufacturing associated with the historic – pre-French Revolution – geography of universities in Germany. We find that over the period from 1800 through 1859, manufacturing increased in towns closer to the locations of these historic universities, broadly consistent with our baseline above.In the post-1860 period we find the relationship between these historic locations and manufacturing is weaker and less precise overall (column 1) and vanishes when we examine within-territory-time variation (column 2).

[29]We have also examined the relationship between higher technical schools and manufacturing, focusing on the *Technische Hochschulen* which developed in our time frame and evolved in the late 1800s to became Germany's "technical universities." We find a weak, statistically insignificant and *negative* relationship between *Technische Hochschulen* and local manufacturing.

[30]To clarify, for a city with no historical textile industry, the textile sector is a "new sector." For a city with a textile industry dating to before the mid-1700s, the textile sector is not a "new sector" in our analysis.

[31]We note that there is no statistically significant difference between the post-1800 estimates for the university effect and effect of early manufacturing.

[32]We consider the period through 1839 to be the pre-railroad era. The very first railway construction in Germany was undertaken in the late 1830s. Our results are robust to restricting to years well before any railroads were built.

Table 4: Manufacturing and Proximity to Universities Active in the 1800s

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Outcome: Number of Manufacturing Events in a Town-Period								
	All Manufacturing Events							In New Sectors	
	Baseline Model	Within Territory-Time	Only Prussia	East Prussia	West Prussia	Outside Prussia	All Towns	All Periods	Restricted 1760-1839
Period 1800-1859 × University Close	0.15***	0.08**	0.22***	0.20***	0.16	0.11***	0.15***	0.13***	0.13***
	(0.03)	(0.03)	(0.06)	(0.07)	(0.10)	(0.04)	(0.03)	(0.03)	(0.03)
Period 1860-1899 × University Close	0.08**	0.05	0.16***	0.22***	0.02	0.02	0.08**	0.07**	
	(0.03)	(0.04)	(0.06)	(0.07)	(0.09)	(0.04)	(0.03)	(0.03)	
Free Enterprise Law							0.10***	0.09***	0.06
							(0.03)	(0.03)	(0.04)
Railroad Connection							0.25***	0.25***	
							(0.06)	(0.06)	
Post-1800 × Early Manufacturing							0.15***	0.09**	0.12
							(0.06)	(0.05)	(0.07)
Post-1840 × Coal							0.12***	0.11***	
							(0.04)	(0.04)	
Post-1800 × Coal							-0.03	-0.03	-0.02
							(0.04)	(0.03)	(0.04)
Time FE	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Territory × Time FE	No	Yes	No	No	No	No	No	No	No
Observations	15778	15778	6125	3717	2408	9653	15778	15778	9016

This table reports regression estimates in which the outcome is the number of manufacturing events 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. Columns 1 through 7 examine all manufacturing events. Columns 8 and 9 restrict analysis to manufacturing events in "new sectors," defined as two-digit SIC sectors in which a given town had no manufacturing before 1760. Column 9 further restricts analysis to the period 1760 through 1839. "Post 1800 × University Close interacts a post-1800 indicator with an indicator for towns currently close to a university. The "Territory × Time" fixed effects in column 2 interact indicators for 44 territories, defined as of 1815, with time period indicators. Columns 3-6 examine subsets of the data relative to the set of towns in Prussia as of 1849. "Railroad Connection" uses data from Kunz and Zipf (2008) to measure the presence of a railroad: calculated as an indicator for a railroad line within 2 kilometers in a given decade. "Free Enterprise Law" is an indicator for the presence of a regional (territorial) free enterprise law from Acemoglu et al. (2011). "Post-1800 × Early Manufacturing" interacts an indicator for post-1800 periods and an indicator for pre-1760 manufacturing activity. Standard errors are clustered by town. Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

Table 5: Manufacturing and Proximity to Universities Active in the 1780s

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Outcome: Number of Manufacturing Events in a Town-Period								
	All Manufacturing Events							In New Sectors	
	Baseline Model	Within Territory-Time	Only Prussia	East Prussia	West Prussia	Outside Prussia	All Towns	All Periods	Restricted 1760-1839
Period 1800-1859 × University Close	0.14***	0.07**	0.27***	0.32***	0.00	0.08**	0.14***	0.13***	0.07**
	(0.03)	(0.04)	(0.06)	(0.08)	(0.11)	(0.04)	(0.03)	(0.03)	(0.04)
Period 1860-1899 × University Close	0.04	-0.00	0.16***	0.29***	-0.13	-0.03	0.05	0.04	
	(0.03)	(0.04)	(0.06)	(0.08)	(0.10)	(0.04)	(0.03)	(0.03)	
Free Enterprise Law							0.09***	0.08***	0.06
							(0.03)	(0.03)	(0.05)
Railroad Connection							0.25***	0.25***	
							(0.06)	(0.06)	
Post-1800 × Early Manufacturing							0.16***	0.10**	0.12*
							(0.06)	(0.05)	(0.07)
Post-1840 × Coal							0.12***	0.11***	
							(0.04)	(0.04)	
Post-1800 × Coal							-0.03	-0.03	-0.03
							(0.04)	(0.03)	(0.04)
Time FE	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Territory × Time FE	No	Yes	No	No	No	No	No	No	No
Observations	15778	15778	6125	3717	2408	9653	15778	15778	9016

This table reports regression estimates in which the outcome is the number of manufacturing events 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. Columns 1 through 7 examine all manufacturing events. Columns 8 and 9 restrict analysis to manufacturing events in "new sectors," defined as two-digit SIC sectors in which a given town had no manufacturing before 1760. Column 9 further restricts analysis to the period 1760 through 1839. "Post 1800 × University Close interacts a post-1800 indicator with an indicator for towns currently close to a university. The "Territory × Time" fixed effects in column 2 interact indicators for 44 territories, defined as of 1815, with time period indicators. Columns 3-6 examine subsets of the data relative to the set of towns in Prussia as of 1849. "Railroad Connection" uses data from Kunz and Zipf (2008) to measure the presence of a railroad: calculated as an indicator for a railroad line within 2 kilometers in a given decade. "Free Enterprise Law" is an indicator for the presence of a regional (territorial) free enterprise law from Acemoglu et al. (2011). "Post-1800 × Early Manufacturing" interacts an indicator for post-1800 periods and an indicator for pre-1760 manufacturing activity. Standard errors are clustered by town. Statistical significance at the 90, 95, and 99 percent confidence level denoted "*", "**", and "***", respectively.

5 Invention, Universities, and Manufacturing

In this section, we present *preliminary analysis* examining the pattern of invention and science. We focus on changes in the geography of invention and science; the employment of inventors and scientists at universities; and the sectoral relationship between invention at universities and the location of manufacturing. The analyses we present here are early stage indications of our on-going research.

First, we use study how invention and scientific discovery varied for cities "close" and "far" from university, revisiting the baseline set-up used to examine the development of manufacturing. We estimate the relationship:

$$inventions_{it} = \theta_i + \delta_t + \sum_s \beta_s [uni_i \times time_s] + \epsilon_{it} \tag{2}$$

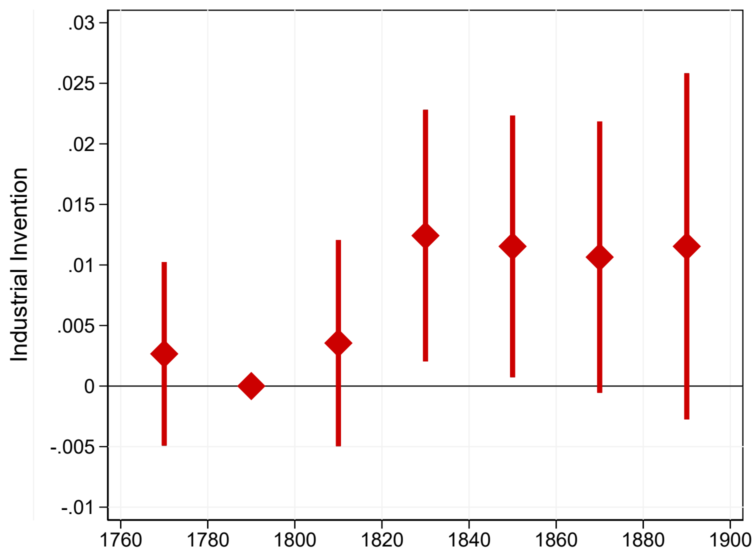
where uni_i is either an indicator for below-median distance to a university. We obtain similar results when we examine the logarithm of distance.

Figure 6 presents our estimates. We find that proximity to universities was associated with increases in discovery and invention after 1800. Proximity is associated with increasing invention starting after the 1780s, with one notable period of relative decline in the 1810s, when narrative evidence suggests military conflict may have disturbed university life.

Second, to more directly consider the role of universities in supporting invention and discovery, we examine the university employment of inventors and scientists. We find that the share of inventions and scientific breakthroughs made by inventors (scientists) with university employment increased sharply in the early 1800s. Figure 7 summarizes the data by plotting local polynomial regression estimates. The share of inventions made by inventors with university employment was roughly stable at around 45 percent over the late 1700s. This rose sharply to over 60 percent between 1800 and the mid-1800s, stabilized, and then declined slightly after 1860.

Third, while narrative evidence suggests that the period after 1800 was characterized by a pro-science shift in ideas and ideology, it is natural to wonder what more finely grained evidence suggests about the timing of changes in the relationship between university education and invention. To investigate this question, we test how this relationship shifts

Figure 6: Proximity to Universities and Invention



The graph plots estimates from regression analysis in which the outcome is the presence of a scientific discovery or invention in a town-time-period. Figure plots parameter estimates on the interaction between proximity to a university, measured with an indicator for towns below median distance to a university in the 1800s, and time fixed effects, measured in twenty year periods. Standard errors are clustered by town.

over time. We estimate:

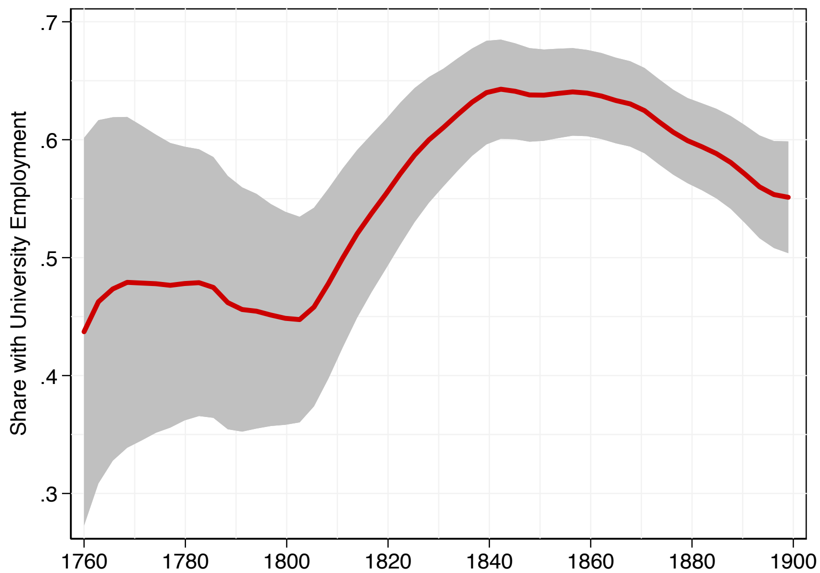
$$y_{it} = \alpha + \beta \text{Year of Innovation} + \gamma post_t + \epsilon_{it} \tag{3}$$

Here y_{it} is an indicator for an inventor or scientist with a university degree, worked at a university, or lived in a university town and $post_t$ is an indicator for a post period.

Table 6 shows the results. We find that inventions were more likely made by university-educated inventors after 1800 (column 1) and by inventors employed a university (column 2). Living in a university town has not effect on inventive activity (column 3). We then ask whether universities were important for trailblazers, defined at the first invention in a sector. We therefore augment our regression an indicator for first invention recorded in its category and the interaction with post-1800. University-education *per se* or living in a university town does not change the probability of a making a first discovery (columns 4 and 6). Trailblazers differentially worked at universities after 1800 (column 5), indicating the importance of universities for economies expanding into new sectors.

Fourth, the pattern of invention and economic geography across sectors provides

Figure 7: University Employment Among Inventors and Scientists



This graph plots evidence on the share of inventions and scientific discoveries made by inventors and scientists with university positions. Data on inventions and scientific break-throughs are from Darmstaedter, du Bois-Reymond, and Schaefer (1908). Information on university employment is constructed using biographical information from *Deutsche Biographie*, *World Biographical Information System*, and historical sources. The figure plots local polynomial regression estimates. The unit of observation is an invention or scientific discovery. The outcome measures whether a given invention (discovery) was made by someone with university employment.

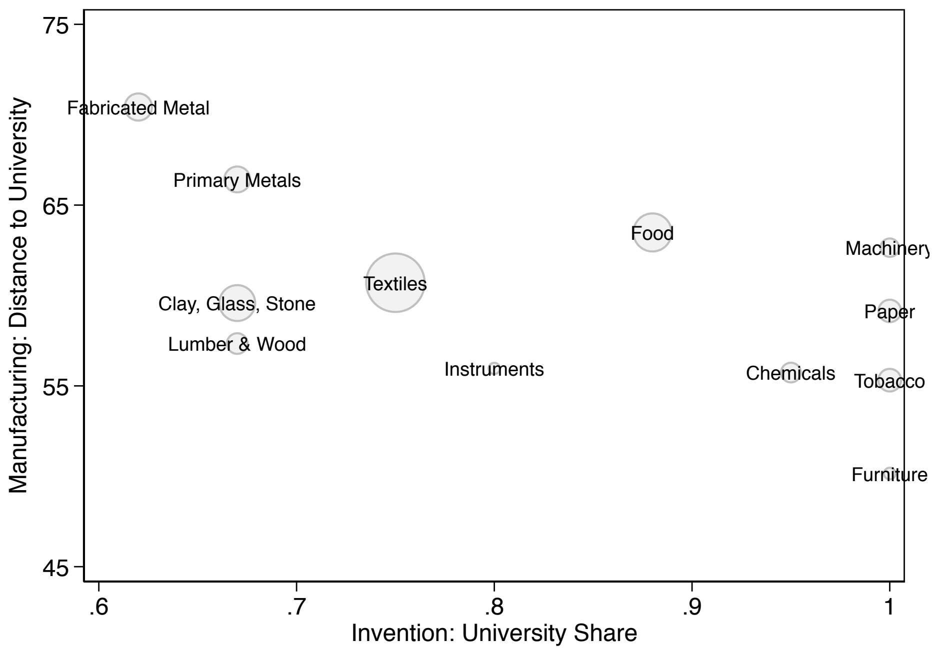
supporting evidence on the role of universities. Our baseline findings indicate that both (i) manufacturing and (ii) invention and science developed around universities, particularly after 1800. When we disaggregate our data we see that these patterns are particularly pronounced in those manufacturing sectors for which the relevant innovations were themselves more closely tied to universities. The share of inventions made by an inventor employed at a university provides one measure of the university intensity of invention. To study variation in the university intensity of invention by manufacturing sector, we assign inventions to the two-digit SIC sectors in which they were used or served as inputs (in the spirit of Schmookler 1966). Figure 8 shows that after 1800 manufacturing in sectors with a higher university intensity in the pattern of invention tended to locate more closely to universities.

Table 6: University Education, Employment, and Invention

	(1) Study	(2) Work	(3) Town	(4) Study	(5) Work	(6) Town
Year of Invention	-0.001**	-0.000	-0.000	-0.001*	-0.000	-0.000
	(0.001)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)
Post 1800	0.271**	0.187***	0.122	0.218*	0.026	0.082
	(0.116)	(0.047)	(0.118)	(0.128)	(0.066)	(0.102)
First Invention in Category				-0.047	-0.178**	-0.009
				(0.075)	(0.082)	(0.075)
First Invention × Post 1800				0.092	0.271***	0.073
				(0.075)	(0.088)	(0.088)
Observations	2345	2345	2345	2345	2345	2345
Total: First Post 1800				0.045	0.093	0.064
P-Value on Total				0.015	0.000	0.017

This table reports regression estimates examining the probability that a given invention or scientific discovery was made by an inventor or scientist with a connection to a university. The outcomes are indicator variables for inventors educated at German universities (columns 1 and 3), with university positions (columns 2 and 4), or located in university towns (columns 3 and 6). Inventors educated at German universities are those who studied at universities located in towns covered by the *Deutsches Städtebuch*. The unit of analysis is the individual invention or scientific discovery from Darmstaedter, du Bois-Reymond, and Schaefer (1908). "Post 1800" is an indicator for observations after 1800. "First Invention in Category" is an indicator for inventions that are the first in a finely-grained subject category (see Data section for details). "First Invention × Post 1800" is the interaction between these two indicators. The line "Total: First Post 1800" reports the sum of the "First Invention in Category" and "First Invention × Post 1800" estimates and the line "P-Value on Total" reports the corresponding p-value. Standard errors are clustered by town.

Figure 8: University Invention and the Location of Manufacturing



This graph plots sectoral data on the location of manufacturing establishments observed 1800 to 1839 and the university-intensity of invention. The vertical axis records the mean distance to a university across manufacturing events in a given two-digit SIC sector between 1800 to 1839, using data on manufacturing from the *Deutsches Städtebuch*. The horizonal axis records the share of inventions in the corresponding sector that were made by inventors employed by universities or other inventors living in university towns, using data on inventions from Darmstaedter, du Bois-Reymond, and Schaefer (1908). Individual inventions are assigned to the sectors that either produced or used them. Biographical information on inventors is used to assign inventions to locations and thus to calculate the "university share" of inventions in a sector. Markers are scaled to reflect the number of inventions in a given sector.

6 Conclusion

The German path to industrial capitalism provides a canonical example of catch-up growth and has been the subject of long-running interpretive debate. The debate reflects the fact that the quantitative evidence previously examined is almost entirely drawn from the period after 1840.

We gather new data on invention, science, and manufacturing spanning the 1700s and 1800s. We find that significant transformations in the German economy occurred around universities starting in the early 1800s. The shifts in invention and industry associated with universities came decades before before the development of railroads and coal-based industry. The spatial and temporal pattern of change indicates that universities played a central role in the process through which Germany industrialized and shifted from relative technological backwardness towards the world frontier in science-based industry.

The economic changes we document reflected political shocks that transformed culture, education, knowledge production, and industrial activity. An interlocking set of cultural and institutional changes reshaped German universities, promoting science and ultimately a model of the university as a center of research that has since diffused internationally. German history thus provides a model of how political and cultural change that shifts the orientation of higher education towards science and technology can have profound consequences for the path of technological and industrial development. While we trace these processes over the 1700s and 1800s, the subsequent convulsions in German society in the 20th century – resulting from war, economic dislocation, and the rise of Fascism – point to the importance of the political economy environment in shaping these processes and to the potential fragility of science-based growth.

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Appendices – For Online Publication

A Data

Data appendix under construction.

B The Locations of Universities

To test whether enrollments evolved similarly at universities that were and were not closed during the era of the French Revolution and Napoloenic invasion, we examine annual data on enrollments across universities from Eulenburg (1904). We estimate:

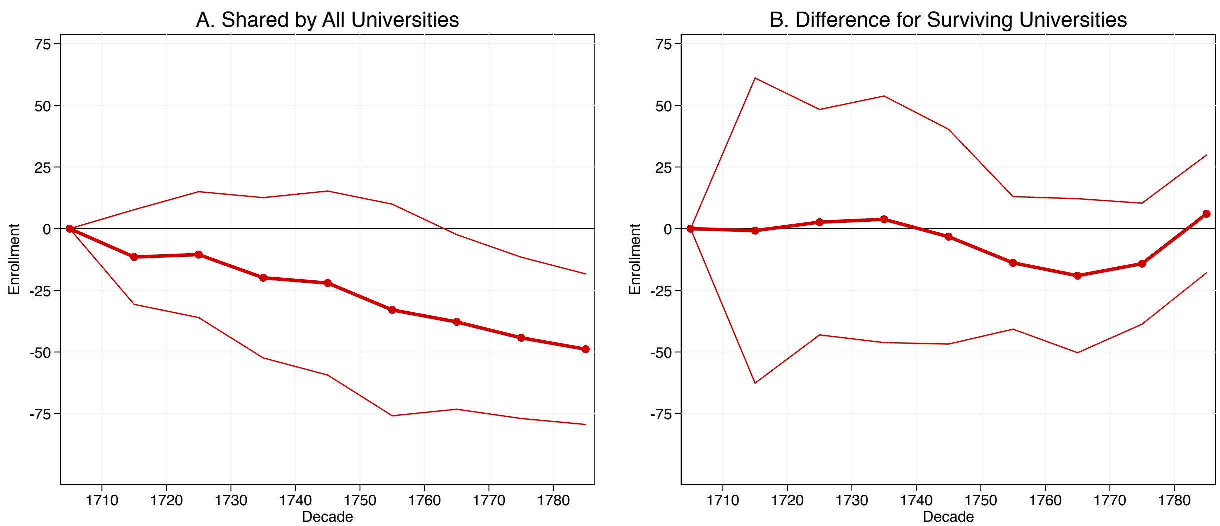
$$enroll_{it} = \alpha_i + \delta_{decade} + \sum_{s=1700}^{1780} \beta_s(\delta_{decade} \times survive_i) + \epsilon_{it} \tag{4}$$

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, and the β estimate variation in enrollment specific to surviving universities in each decade.

Figure B1 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).

While considerable evidence indicates university closures were due to exogenous events, the new universities established in the 1800s were designed to advance larger efforts to transform states, economies, and knowledge production. The new universities at Berlin (1807) and Munich (1820) were – unlike the pre-existing universities – set up in political capitals. Proximity to these universities may have been correlated with other factors and externalities. However, our results are not driven by the universities of Berlin or Munich, as we show below.

Figure B1: University Enrollment Estimates Before the French Revolution



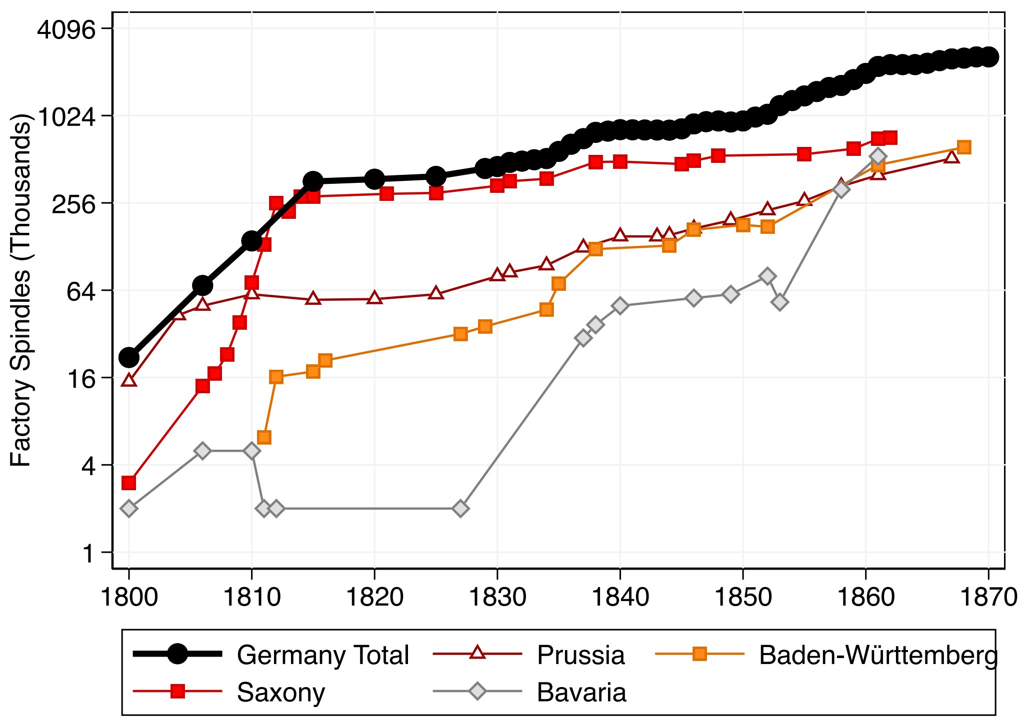
This graph plots regression estimates examining enrollments at German universities. Graphs report estimates from equation (4), in which the outcome is the number of students enrolled in a university-year. Panel A plots decade fixed effects. Panel B plots parameter estimates on the interaction between (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 Historical Evidence on Industrialization

This appendix reviews evidence on industrialization from the historical literature.

Prior research indicates significant growth in the mechanization of the textile industry around 1800. For example, Kirchhain (1973) provides evidence on the mechanization of the textile industry across regions in German-speaking Europe across the 1800s. Kirchhain's (1973) evidence shows that there were significant increases in the number of spindles, a key measure of mechanization, in the first decades of the 1800s, including over the period 1800 to 1805, i.e. before Napoleon defeated the Prussian army at Jena.

Figure C1: The Mechanization of German Textiles



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