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The Mechanics of the Industrial Revolution

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Abstract

For contemporaries, Britain's success in developing the technologies of the early Industrial Revolution rested in large part on its abundant supply of artisan skills, notably in metalworking. In this paper we outline a simple process where successful industrialization occurs in regions that start with low wages and high mechanical skills, and show that these two factors strongly explain the growth of the textile industry across the 41 counties of England between the 1760s and 1830s. By contrast, literacy and access to capital have no power in predicting industrialization, nor does proximity to coal. Although unimportant as a source of power for early textile machinery, Britain's coal was vital as a source of cheap heat that allowed it over centuries to develop a unique range of sophisticated metalworking industries. From these activities came artisans, from watchmakers to iron founders, whose industrial skills were in demand not just in Britain but across all of Europe. Against the view that living standards were stagnant during the Industrial Revolution, we find that real wages rose sharply in the industrializing north and collapsed in the previously prosperous south.

*Preliminary version, please do not cite without permission. The helpful suggestions of Peter Solar are acknowledged.

However, the errors are not in the art but in the artificers. He that works with less accuracy is an imperfect mechanic; and if he could work with perfect accuracy he would be the most perfect mechanic of all.

Isaac Newton. Introduction to *Principia Mathematica*. 1687.

1 Introduction.

The Industrial Revolution of the late eighteenth century saw the high wage textile manufacturing areas of southern England deindustrialize as they failed to adopt the new mechanical technology being developed in the low wage north. To understand how this process occurred, this paper explores the reasons that informed contemporaries gave to explain Britain's spectacular industrial success: its unique abundance of skilled artisans, and especially metalworkers.

Early on, James Watt recognized the importance of metalworkers. In a letter to Roebuck he wrote that "you ask what is the principal hindrance to erecting engines? It is always smith-work" (Smiles, 1863, p. 179). In the words of the statesman Richard Cobden "Our strength, wealth, and commerce grow out of the skilled labour of the men working in metals. They are at the foundation of our manufacturing greatness."¹ For Cobden, Britain's leadership in the industrial transformation of Europe was rooted in its uniquely deep and diverse pool of artisans with the mechanical skills to design, build, operate, maintain and continually improve the increasingly sophisticated machinery that began to appear in the mid-eighteenth century. Without this pre-existing pool of mechanical expertise—ranging from watch- and clock-makers to millwrights, tool-makers, and foundry men—inventors like Arkwright and Watt would no more have been able to turn their ideas into usable technologies than were their talented French contemporaries such as Vaucanson and Senot, or than Leonardo da Vinci had been in the fifteenth century.²

¹This appears at the conclusion of Samuel Smiles's (1863, 331) paean to British mechanical skill, *Industrial Biography: Iron-workers and Tool-makers*.

²Besides his mechanical duck and punch card loom, Jacques de Vaucanson invented a lathe with a slide rest around 1750, forty years before American David Wilkinson and Eng-

That an abundance of mechanical skill was vital to Britain's industrial success runs against a widespread preconception that the technological innovations of the early Industrial Revolution were, for the most part, fairly rudimentary. Certainly, what is perhaps the best known invention of the eighteenth century, the spinning jenny, was indeed a simple wooden machine that could be put together by any moderately competent local carpenter.³ However, practically every other subsequent advance in technology required novel machinery or production processes that were unusually complicated by the standards of the time. Crompton's mule (1779), perhaps the paradigmatic textile invention of the Industrial Revolution, was an involved and complex piece of machinery that required at least six years of experimentation and the close integration spindles, rollers, and carriage. And no piece of industrial machinery remotely compared with the sophistication and complexity of Watt's later steam engine with its governor, double-acting expansion mechanism, and "sun and planet" gears.

Despite its historical importance, the supply of artisanal and mechanical competence rarely appears in modern analyses of the Industrial Revolution.⁴ Our approach, by contrast, is to focus on a simple process where the accumulation of artisanal skill drives technological progress, in a way that mirrors the historical pattern of early industrialization. Specifically, as transport networks improved and English markets integrated from the late seventeenth century onwards, regions specialized according to their comparative advantage; with areas of poor agricultural potential (reflected in their low wages) increasingly specializing in manufacturing activities. Naturally, many of these proto-industrial activities, such as making nails

lishman Henry Maudslay; while Senot (of whom, revealingly, nothing else is known, not even his first name) devised a screw cutting lathe a few years before Maudslay (1797). Both were vital machine tool technologies but neither was subsequently developed in France (Daumas, 1972, 112).

³Thus Cardwell (1994, 186) wrote that the new textile machinery involved no new principles or materials "that would have puzzled Archimedes," while Allen (2009*b*, p. 190) views the jenny, which he deems "not rocket science," as encapsulating the "Industrial Revolution in Miniature." McCloskey (2010, pp. 355-365), too, subscribes to the "practical tinkers" view. Yet these tinkers, such as John Smeaton, William Murdoch and so many others, were informed and connected to practical science and advanced engineering, and spoke their language.

⁴Meisenzahl and Mokyr (2012) distinguish between major inventors, tweekers, and implementers. Most of the best artisans in the Industrial Revolution probably were both tweekers and implementers, making minor improvements and adaptations when installing the equipment and machinery that embodied the new technology. Yet they have remained anonymous for the most part. See also Kelly, Mokyr and Ó Gráda (2020). For an early pioneering study, see Harris (1992), especially Ch. 1.

or low quality textiles, required only rudimentary skills and offered little potential for technological advance. However, a few forms of manufacturing—especially in exacting forms of metal work such as watch making, iron founding, instrument and tool making—created concentrations of skilled and versatile workers, artisans whose mechanical skills could be readily be adapted and transferred to making the increasingly sophisticated machinery of the early Industrial Revolution.

This simple framework leads to two specific empirical predictions. First, the areas that industrialized first were those in which potentially useful mechanical skill had already concentrated before the Industrial Revolution. Second, these concentrations of skill were to be found primarily in low-wage areas already specializing in technologically demanding production, particularly in metalwork.

To test these predictions, we analyze the pattern of male employment across the 41 counties of England (although the Industrial Revolution was very much a British phenomenon, data for Scotland and Wales are sparse). England is a large and diverse country, and from the late eighteenth century low wage northern areas industrialized rapidly, while hitherto prosperous southern areas deindustrialized and experienced severe falls in real wages. The widespread notion that living standards were static during the Industrial Revolution (Feinstein, 1998) is simply a statistical artefact of aggregating together two regions that were moving in sharply opposite directions.

We start with textiles, where our dependent variable is the share of male employment in textile production in 1831. To measure the supply of pre-existing skill we use data from the 1851 Census on the occupations of workers aged 60 and above born in each county: men who would mostly have been apprenticed in the late 1790s to masters who had trained a generation earlier. We find that the percentage of men working as mechanics and toolmakers, alongside low wages in the 1760s and market access, explain 70 per cent of the variation in textile employment in the middle of the nineteenth century. The estimated elasticities are substantial: the supply of skilled workers has an elasticity of two, and wages have an elasticity of -6. In other words, high wages acted as a powerful disincentive to successful mechanization. Given the limited use of steam, proximity to coal has no explanatory power as we would expect. Other potential explanatory variables that we consider similarly do not add much: literacy in particular. To the extent that energy using capital was being used to substitute for labour, one might expect the availability of finance to have facilitated industrialization, but the density of local banks, which were concentrated in the high wage manufacturing areas of the south, had no predictive power.

The natural reservation about these regressions is that the supply of mechanical skill in the 1790s was endogenous: new textile industries, even at that early stage, might have attracted skilled workers rather than vice versa. To control for this we use as an instrument the cost of becoming an apprentice watchmaker in the mid-eighteenth century. Our presumption is that in areas with large skilled metalworking sectors this would have been relatively low. This instrument strongly explains 1790s skills and when the regressions are re-estimated the coefficients remain unchanged, as they do if we add a variety of other potential instruments.

Turning to metals, although a nearby supply of coal for smelting and forging was necessary for an industry to emerge it was not sufficient. Instead, heavy metallurgy concentrated in areas of the West Midlands which had been accumulating expertise in particular processes since at least the sixteenth century.

As a placebo complementing our tests for textiles and metals, we analyse the location of traditional manufactures where technology was static at this time: food processing, shoes, garments, and woodworking. In these cases the low wages and accumulated skill that we emphasize have little explanatory power.

Although our focus here is on the regions of England, we can see the same process of abundant skill driving industrialization when we compare Britain with France. At the level of unskilled labourers it is well known that, after adjusting for the superior productivity of English workers, real wages in France in the late eighteenth century were no lower than in England: (Kelly, Mokyr and Ó Gráda, 2014). However, when it came to highly skilled labour, the vital ingredient for successful industrialization, English wages were considerably lower leading to a modest but persistent flow of top-level artisans from England into France from the mid eighteenth century to the mid nineteenth century, a flow that increased significantly after 1815. Their importance in developing the cotton industry and railways is described by Bensimon (2011), and a detailed account of their role in importing new iron-working technology is given by Belhoste and Woronoff (2004).

Mechanical skill not only drove the mechanization of textiles, the expansion of the textile industry in turn drove further skill accumulation. Manchester in the 1820s became the world centre of machine tool devel-

opment to shape the large number of cast iron parts for textile machinery, before moving on to become a centre of locomotive production.⁵

Our paper sheds direct light on one of the most misunderstood topics of the Industrial Revolution, namely the role of human capital in driving the process. Because human capital is now associated with years of schooling and rates of literacy, the role of human capital in the Industrial Revolution has been dismissed. Scholars such as Mitch (1999) have shown the Britain was a leader neither in sending children to be educated nor in teaching them basic literacy skills, and De Pleijt, Nuvolari and Weisdorf (2019) have confirmed that the years of the Industrial Revolution witnessed little or no increase in mean years of schooling. Yet the human capital that mattered at the time was primarily artisanal, and while at times it did require literacy and numeracy, the way it was acquired was through personal transmission based on apprentice-master relations.

Our finding that industry located in areas with pre-existing concentrations of mechanical skill, which were in turn associated with low wages, should not be seen as an effort to impose some simplistic interpretation onto the deep transformations of the eighteenth century along the lines of “Low wages and high mechanical skills caused the Industrial Revolution.” Instead we see British industrialization as a lengthy and historically contingent process of slowly accelerating technological change, in which practical procedural knowledge grew alongside formal propositional knowledge in a process that stretched back centuries.

The transport networks that permitted regional specialization began to improve in the late seventeenth century, and the use of coal for metal working and other industries expanded from the middle ages. Guilds for the most part were weak or absent in England by the late seventeenth century and increasingly seen as inimical to the rights of private property, thereby allowing a flexible apprenticeship system that was highly responsive to the demand for new skills (De la Croix, Doepke and Mokyr 2018; Mokyr 2018). Although military spending was high everywhere, Britain’s well funded navy supported a market for specialized metal goods from navigational instruments to massive wrought iron anchors, and cast iron cannon that dwarfed the brass field artillery of European armies. Extensive commercialized agriculture drove demand for heavy iron implements, while overseas colonies absorbed iron nails and other hardware, and stimulated the de-

⁵Habakkuk’s (1962) claim that machine tools were developed in the United States to substitute for expensive skilled labour is exaggerated (see Musson, 1975; Kelly and Ó Gráda, 2020).

velopment of the copper industry (Zahadieh, 2013). Moreover, Britain was notable for a relatively large and prosperous “middling class” that gave rise to substantial markets for consumer goods that required precision manufacturing and high quality materials in the form of watches, fancy toys, costume jewellery, musical instruments, high-end cutlery and porcelain.

European culture, and especially English and Scottish culture, was changing at the same time, with a growing idea that continuous improvement in material existence was possible, driven by the purposeful accumulation of technical knowledge (Spadafora, 1990; Friedel, 2007, pp. 171-89; Slack, 2015). The accelerating progress of science contributed increasingly to advances in technology, both directly through advances in chemistry and through the classic industrial enlightenment inventions such as the steam engine and the pocket watch; and indirectly through a spreading culture of systematic precision measurement and carefully controlled experimentation (Heilbron, 1990).

The literature on the economic origins of the British Industrial Revolution is large and includes surveys by Berg (1994), Clark (2014), Crafts (1986), McCloskey (2016), and Mokyr (2009). Our focus here on mechanical skill is perhaps closest to Berg’s, which rests Britain’s distinctiveness on “the extraordinary industry and inventiveness of her manufacturing people” (1994, 7). A recent paper that looks at the reverse causal connection, associating the growth of skilled labor with the diffusion of steam engines, is De Pleijt, Nuvolari, and Weisdorf (2018).

The rest of the paper is as follows. In Section 2 we show the historical importance of artisan skill in developing some of the best known technologies of the Industrial Revolution, Section 3 argues that the real importance of coal to early industrialization was as a source of artisan skill and heat in metalworking rather than as a means of generating power, and Section 4 looks at the historical supply of skilled workers. A simple specific factors framework for understanding British industrialization is given in Section 5 and developed further in the Appendix. The historical pattern of growth in England is described in Section 6, and our measure of mechanical skill is outlined in Section 7. The predictions of the model are tested empirically in Section 7. Sections 8 to 10 describe our regression results for textiles, metals, and traditional industries and Section 11 concludes.

2 Mechanical Skill in the British Industrial Revolution.

How early industrialists saw their “combined operation of many orders of work people ... tending with assiduous skill a series of productive machines continuously impelled by a central power” (Ure, 1835, p. 13) is captured in late eighteenth century insurance contracts which divide the asset value of a factory’s contents into two parts: its “millwright’s work” or power; and its “clockmaker’s work” or machinery.⁶ Materials, workmanship, and tools were strongly complementary. Better steelmaking (following the crucible process invented in 1740) yielded better hand tools, and improved tools—files, lathes, edge tools—made the new machines (Harris, 1998, 220–221). For contemporary observers, the successful development of Britain’s factory system stemmed from an abundance of long existing artisanal skills combined to new purposes. Here we will show the contribution of Lancashire watchmakers to the development of early textile machinery, and the role of the Birmingham metal trades in developing Watt’s steam engine. One important group that we do not discuss here are the millwrights, highly skilled carpenters and mechanics, who built power sources like waterwheels, windmills, and even horse-driven wheels and the shafts and gears used to transmit their energy to machinery: these are examined in detail by Mokyr, Sarid and van der Beek (2020).

2.1 Textile Machinery.

Despite the widespread view that the advances in the textile industry during the Industrial Revolution required few advanced skill or formal knowledge, much of the technology was anything but simple, even if perhaps it did not depend on detailed understanding of the *Principia*. Hargreaves’ spinning jenny, the first major advance in cotton spinning, was a rudimentary, hand-powered machine that could be built by any competent local carpenter. However as the leading Manchester cotton spinner John Kennedy recalled in 1815, with the appearance of Arkwright’s water frame in 1789 and its intricately meshing metal rollers, spindles, and gearing, “a higher class of mechanics such as watch and clock-makers, white-smiths, and mathematical instrument makers began to be wanted; and in a short time a wide field was opened for the application of their more accurate and scientific

⁶For instance, in 1799 the textile mill of Bissett and Co. was insured for £2,950, made up of £350 for millwright’s work, £950 for clockmaker’s work, with the remainder for buildings and stock (Tann, 1970, 33).

mechanism" (Kennedy, 1819, 124). This view is supported by the large number of newspaper advertisements from the 1770s onward, looking for smiths, watchmakers, and toolmakers (Musson and Robinson, 1969, 427–458).⁷ The components of the spinning frame—rollers, spindles, flyers—were challenging to build and required a high level of precision. Before the British machine-tool industry invented the means to make those components with interchangeable parts, they relied on "highly proficient skills" (Cookson, 2018, 64).

In 1791, the engineer John Rennie in London was complaining that because of its high wages "in respect to workmen, the Cotton Trade has deprived this place of many of the best Clock Makers and Instrument Makers so much so that they can scarcely be had to do the ordinary business" (Musson and Robinson, 1969, p. 438). Precision skills were in demand not only in cotton but in other advancing sectors like pottery and steam: for instance both Wedgewood and Watt were supplied with tools and lathes by the Liverpool clock-maker John Wyke (Musson and Robinson, 1969, p. 437). Similarly, at first Crompton's Mule—which allowed spinning of fine and high-quality yarns—began as a small wooden machine produced by an inventor who "knew nothing of mechanics beyond what he had taught himself." However, it was soon improved and scaled up to an iron mechanism by "an ingenious mechanic, Henry Stones, of Horwich" and subsequently driven by water power so that within a few years it could drive 400 spindles, compared to the 20–30 on the original Crompton machine (Baines, 1835, 200–201).

Moreover, many industries that depended on high-precision manufacturing were the beneficiaries of one of the most important technological spin-offs of the Scientific Revolution: watchmaking. It was in an effort to make a usable "sea watch" or marine chronometer that Hooke (and/or Huygens) came up with the idea of the balance spring that allowed the first practical watches to be made, and this led directly to England's large watchmaking industry (Kelly and Ó Gráda, 2016). The positive spillovers from the precision crafts of the clock and watch industry to textile machinery have often been stressed (for instance by Allen 2009*a*, 205–206). When Arkwright, assisted by a local watchmaker John Kay, began to build the first spinning frame, they approached the Warrington instrument maker and engineer Peter Atherton who "agreed to lend Kay a smith and watch-tool maker, to make the heavier parts of the engine, and Kay undertook to

⁷This shows, moreover, how employers took it for granted that many of these artisans regularly read newspapers or knew somebody who did.

make the clock-maker's part of it..." (Baines 1835, 151; see also Musson and Robinson, 1969, p. 439). The best-known inventor to be trained as a clock-maker was Benjamin Huntsman, the inventor of the crucible steelmaking process (1740). Also notable was John Whitehurst, a Derby clockmaker, who advised many early industrialists, including his fellow members of the Lunar Society Boulton and Watt. Like many other leading figures of the British Industrial Enlightenment, he had little formal education beyond his apprenticeship, yet clearly was a learned and literate man. He wrote a book on geology and one on the construction of chimneys and stoves.

The fast-wearing brass gears of early textile machines were soon replaced by cast iron ones. This meant that their construction was first taken over by iron founders and makers of large clocks whose facility with heavy lathes and gear cutters readily transferred from brass to iron, and the gearing of a textile machine was invariably referred to as its clockwork.⁸ Rapidly, however, the large scale of the cotton industry led to the emergence of firms of specialized machine builders, some of whom went on to manufacture machine tools and locomotives.

2.2 Steam Engines.

Just as Lancashire's agglomeration of watch makers was vital to the successful development of powered textile machinery, so was the concentration of metal trades in Birmingham for that of the steam engine. This connection went back to the dawn of the age of steam. Although Newcomen had come up with the idea of an atmospheric engine before 1710 in Cornwall, he could not get it to work for its intended purpose of pumping mines until "being near Birmingham, and having the assistance of so many admirable and ingenious workmen, they came, about 1712, to the method of making the pump valves, clacks, and buckets, whereas they had but an imperfect notion of them before" (Desaguliers, 1744, 533).

Birmingham metalworking was equally instrumental to the success of Watt's engine. As is well known, although Watt had built his first experimental engine in Scotland in 1768, his progress was frustrated by its flimsy, poorly fitting cylinder until, in 1774, he moved to Boulton's large metal works in Birmingham (with the optimistic promise from Boulton of craftsmen who could work "with as great a difference of accuracy as there is

⁸Cookson (2018, 80–81), who focusses on the later adoption of machinery in the Yorkshire woollen industry, is quite cautious in her assessment of the role of clockmaking to machine building, stresses the central importance of gears in Arkwright-type machines as the cardings were moved through rollers by a clock-work like mechanism.

between the blacksmith and the mathematical instrument maker" (Smiles, 1865, 203). Even in Birmingham, Watt often complained about "villainous bad workmanship" and everything had to be done by hand (Smiles, 1863, p. 180).

The cylinder is the most familiar component of a steam engine that required exacting skills in metalworking, but it is not the only one. Other large parts like frames and gears needed competent founders and forge-men to cast and shape them, and low quality castings were the most common reason for the poor performance of many early Watt engines (Tann, 1970, 83). The most intricate component of a steam engine was its valve gear (Hills, 1970, 201), but, to a trained instrument maker like Watt, able to draw on a pool of watchmakers, this presented few challenges. By contrast, boilers riveted together from small iron plates—and often needing to be sealed against leaks by continually adding oatmeal or dung—remained a universal (and sometimes lethal) weakness of steam engines until the mid-nineteenth century (Hills, 1989, 120–128).

The Boulton and Watt works in Soho illustrate how useful knowledge and high-level craftsmanship met to produce a revolutionary device. It is an often-repeated tale that the steam-engine's success was in large part attributable to the skills of ironmaster John Wilkinson who could provide him with precision-made cylinders with close tolerances. Moreover, the firm's success depended on the supply of useful knowledge from two further sources. First, the two partners benefited from interaction with educated and sophisticated men both at the Scottish universities (e.g. John Roebuck, John Robison, and Joseph Black) where Watt still had contacts, and their fellow members of the Lunar Society.

Second, the enterprise depended on highly skilled mechanics, who were able to carry out the instructions and improve upon them. Among them the best-known was William Murdoch, a successful inventor himself and widely credited with the first practical method of using gaslight (Griffiths, 1992). Another was John Southern, a highly competent engineer known for the invention of the graphical indicator diagram in which a curve provides a measure of the work done by the engine in one cycle, an instrument that was essential in computing the amount of work done in an expansive steam engine (Cardwell 1994, 215; Wise 1997, 231). A third, James Lawson, was not only an outstanding engineer and manager but also an astute observer of economic conditions in the kingdom (Roll, 1930, 261–262).

Beyond these employees, who held management positions, there were fitters who were "highly skilled craftsmen, with a long experience and many years of apprenticeship." Similarly high-quality artisans employed by Boul-

ton and Watt were turners, skilled workers in metal whose job was to draw-file and finish the pistons and air-pump rods (Roll, 1930, 183). James Watt's own writing, dating from 1794, noted that "most of our engineers who have not been regularly bred to the theoretical or practical part of the business have been bred to analogous ones such as millwrights, architects, surveyors etc" (cited by Jones 2008, 216–217). Britain was capable of producing a substantial number of engineers and other highly skilled artisans, and the firms that were at the cutting edge of the Industrial Revolution depended on them.

It should be stressed that Britain's early advantage in water and steam power, as in most other areas of technology, lay in its practitioners and mechanics—not in the physicists and applied mathematicians who subsequently explained why these devices worked. The British leading lights in the improvement of water mills were empirically-minded experimentalists and practical engineers such as John Smeaton, William Strutt, and John Rennie. The foremost theoreticians of the machine in the late eighteenth century lived in France, the best-known of them perhaps the mathematician Jean-Charles Borda, whose 1767 work on water mills was foundational (Reynolds, 2002). Less well-known to historians is Gaspard Riche de Prony (1755-1839) who wrote the best engineering textbook on machinery in 1790, including a chapter on steam engines that was better than anything available in English at the time. No less distinguished was the polymath engineer Augustin de Bétancourt, author of *Essai sur la composition des machines* (1808), which was translated into English twice, reprinted as late as 1840 and taught in engineering schools all over Europe. British engineers learned their trade from other engineers as apprentices; in France engineering schools taught from mathematically sophisticated textbooks (Cardwell, 1994, p. 205). Yet the practical implications of formal engineering science could not be fully realized until after the middle of the nineteenth century, and until then Britain's mechanics were the asset driving its indisputable leadership.

2.3 Wrought Iron

The familiar story that Henry Cort "invented" wrought iron with his patents of 1783 and 1784 again conceals both how the innovation grew out of centuries of accumulated metalworking skill, and needed several years of development by skilled ironmasters to become commercially viable. The process of puddling iron involves smelting pig iron in a reverberatory (heat reflecting) furnace. In these furnaces, which date back at least to the sixteenth

century, coal was kept separate from the contents which were heated by hot gases flowing over them. These was used first for brass making, later for glass and pottery, and finally in the 1740s to melt iron with charcoal in clay crucibles to make high quality steel (invented by Huntsman). Cort stood on the shoulders of generations of skilled ironmasters who had sought the solution for the problem of a cheap and easy way of making wrought iron and while he himself qualifies as an uneducated tinkerer, he took the trouble to consult Joseph Black while working on his invention.

However, even after Cort had the idea of smelting iron in a reverberatory furnace, it was only in the early 1790s after years of experimentation by the Welsh ironmaster Richard Crawshay at his large Cyfartha iron works that he could produce iron of a quality and price that his customers were willing to buy instead of the traditional stamped and hammered product (Hyde, 1977, 95–102).

3 Coal as a Source of Heat, Power and Skill

There is a widespread misapprehension that Britain's abundant coal resources gave it a cheap source of power for early textile machinery. In reality, spinning yarn and weaving it into cloth required little power, and before Roberts' 1817 planing machine made iron plates affordable, machinery parts were made of wood wherever possible (Kelly and Ó Gráda, 2020). Cotton was woven almost entirely by hand until the 1820s and, von Tunzelmann (1978, 179) estimates that as late as 1800 only a quarter of Lancashire cotton at most was spun using steam powered machinery.⁹ As Jones (2010, 86) observes, the industrial decline of the west of England owed little to expensive coal.

Across most of the British economy hydraulic energy remained "the primary source of industrial power in the preindustrial age" (Kander, Malanima and Warde, 2013, 154). Kanefsky (cited by Crafts 2004, Table 3) estimated that water power accounted for 70 per cent of industrial power in 1800 compared with 20 per cent for coal, and was only overtaken by coal around 1830.¹⁰ The reasons are clear: besides not needing to pay for fuel (on top of heavy annual royalties to Boulton and Watt), water cost only

⁹The same is true for the use of steam power applied to the bellows of the coke-smelting furnaces. Steam engines were used here, but remained subsidiary to water power for many years. Hyde (1977, p. 71) concludes that "had there been no steam engines of any kind, a substantial coke smelting sector would nevertheless have developed by 1790."

¹⁰It is notable that in Wrigley (1988)—which popularized the idea of the British Industrial Revolution as a transition from an inherently limited "advanced organic economy" of wood

about one quarter as much per horsepower as steam to install (Chapman, 1970, 241); the efficiency of water wheels improved dramatically through the experimental work of Smeaton, Rennie, and others; and the lifetime of new iron water wheels was measured in decades compared with years for steam.¹¹ The technological cogs and gears were old and familiar. In textiles, moreover, the uneven power output of steam engines (until Watt invented the spinning ball governor in 1788) made them unsuitable for powering spinning machines, and steam was only adopted in the early nineteenth century when the reliability and efficiency of the engines was improved and suitable sites for water power, most of which were already occupied for milling and other activities, became scarcer.

3.1 Heat

The fact that the textile industry had become mechanized before it had recourse to steam power does not imply that coal did not matter for British industrialization. On the contrary, Britain's abundant coal was vital as a source of heat for a growing variety of increasingly sophisticated industrial process, in metalworking especially (Harris, 1992, pp. 18-32). The extensive use of industrial coal goes back to the Middle Ages when it came to be used to work iron in forges. The next decisive step came in the sixteenth century, as we noted above, with the reverberatory furnace that Cort and finally Crawshaw were able to apply to produce wrought iron in the early 1790s. Coal had been replacing wood as the main source of heat for centuries. Indeed, the use of coal in smelting ore instead of charcoal in the second half of the eighteenth century, often seen as a pathbreaking innovation, was perhaps "virtually the last" major conversion of fuel from wood to coal (Harris, 1988, 26).

Maintaining high, even heat in a large furnace over several days is not a straightforward task, made more difficult by the fact that coal varies hugely in its chemical composition and ash content. As a result, generations of furnace men acquired unique if almost exclusively tacit know-how in effectively using their local coal for particular processes, a knowledge whose absence in continental Europe further hindered early efforts to adopt British technology there. J.R. Harris described these skills as "unanalysable pieces of expertise, the 'knacks' of the trade" (1992, p. 33). Given the importance

and animal power to one powered by inorganic energy in the form of coal—water power is mentioned only twice in passing (pages 27, 75) and is absent from the index.

¹¹Britain's most famous cotton mill, Robert Owen's New Lanark, was entirely water powered until its closure in 1968 (Hills 105)

of skilled metalworkers for developing early textile and steam machinery that we saw above, it is hardly surprising that the Industrial Revolution took place mostly inside a triangle of towns that had been centres of metal working since at least the sixteenth century: Liverpool, Birmingham, and Sheffield.¹²

Liverpool was the hub of a watchmaking industry already noted in the mid-eighteenth century (not least by Adam Smith) for its large size and intensive division of labour (Kelly and Ó Gráda, 2016). Birmingham was known for its extensive variety of metal trades ranging from forging and casting in the neighbouring Black Country, to more intricate work like guns, clocks, locks, and the mass-produced “toys” (decorative metal goods like buttons and costume jewellery) that were the core of Boulton’s enterprise when Watt arrived.¹³

The third centre, Sheffield, originated crucible steel—the first method to make high-quality steel on a large scale, invented by the clockmaker Benjamin Huntsman in 1740—which gave Britain a unique advantage in metal-working tools, especially the high quality files and similar implements that were increasingly in demand for shaping machine parts. By contrast, the inferiority of France’s steel products, especially files, and its consequent reliance on British imports proved a source of strategic concern for French governments throughout the eighteenth century, and led to repeated and expensive failures to replicate British technology (Harris, 1992, 78–112).

The importance of this triangle not only for production but for innovation can be seen from the location of major inventions (as opposed to patents) during the eighteenth and early nineteenth centuries recorded by Dudley (2017). Of 11 inventions from 1700 to 1750, seven occurred in Birmingham, Manchester or Yorkshire, and two in London; whereas of 35 for 1751–1800 these areas accounted for 19 and 8 respectively. For 1801–1850, Manchester is credited with 13, Birmingham with only one, and London with 10.

¹²The importance of these areas was highlighted by Berg (1994, 223–245).

¹³Samuel Smiles, in his *Life of Matthew Boulton* cites the eighteenth century historian William Hutton who moved to Birmingham in 1740 and recounted that the people of the city were “a species I had never seen; their very step along the street shewed alacrity” (Hutton (1781, p. 63). Smiles added that they “were indeed as alert as they looked—steady workers and clever mechanics—men who struck hard on the anvil. The artisans of the place had the advantage of a long training in mechanical skill. It had been bred in their bone and descended to them from their fathers as an inheritance. In no town in England were there then to be found so many mechanics capable of executing entirely new work” (Smiles, 1865, 163).

These three existing centres of metallurgy were vital, then, to Britain's early technological dynamism, but what accounted for their location in the first place? In each case its original location was in part determined by the availability of fuel. The connection between the iron-processing and iron-using industries and the price of coal seems obvious. To be sure, before the mid eighteenth century iron could only be smelted with charcoal. However, once smelted, the pig iron still needed to be refined and worked into shape in forges that burned coal. It was the presence of suitable coal, alongside iron ore and fire clay, that stimulated the early growth of iron working in Birmingham and Sheffield. Huntsman's crucible steel depended on coke to attain the high temperatures he needed for his product. Similarly, the Lancashire watch industry grew around an 17 outcrop of low sulphur coal that was suited for smelting brass (Bailey and Barker, 1969).¹⁴ Yet the location of coal mines was not the only determinant of where other industries developed, and its importance declined as transport costs fell over the eighteenth century. The significance of skills is illustrated by the steel industry: Huntsman's crucible technique was soon enough copied by clever Sheffield competitors, whereas the French, despite strong government encouragement, were unable to make consistent high quality steel (Harris, 1992, p. 82).

Coal was shipped around England from its sources in the Midlands, the Northeast and South Wales using coastal shipping and, increasingly, canals, and the price of coal was no obstacle to the development of iron-using industries in London.¹⁵ The main effect of the co-location of iron industries and the energy they needed was the creation of a highly skilled labor force, people with the practical knowledge and training to deal with energy and materials, whose transformation defined the Industrial Revolution. The skills of ironmasters and those of colliers were strongly complementary just as the handling of materials and the harnessing of energy always are.

¹⁴There was one centre of precision metalworking with no coalfield nearby, London, where watch and instrument-making industries developed to supply a large consumer and maritime market. Although not a leading centre of industrial innovation during the early Industrial Revolution (with important exceptions like Maudslay's lathe, Donkin's paper-making machine, and Ramsden's dividing engine which allowed large scale production of navigation instruments) it became the hub of machine tool building in the 1820s.

¹⁵In the first half of the eighteenth century the average annual shipment of coal through coastal shipping from the north-eastern ports to London has been estimated at half a million tons a year. By 1780 coastal shipments of coal had risen to 1.5 million tons, and reached 5.7 million by 1829. But it was not just London that could access coal mined elsewhere. On the eve of the Industrial Revolution, there were no fewer than 580 locations in England and Wales that were accessible by navigable water routes. Jones 2010, p. 86 observes that price of coal in the West Counties was competitive with that in the West Riding of Yorkshire.

Physical geography, then, mattered, yet what really counted was the clustering of technical competence. Inevitably, regional specialization took place. As some parts of Britain industrialized, others deindustrialized (Berg 1994, 84-99; Jones, 2010). The largest and most instructive casualty was the West Country which had been the centre of the English textile production since the middle ages. Although the West Country was actually a large producer of charcoal iron, in the absence of coal this iron had to be sent to be worked in Birmingham, a fact that its leading historian sees as a major reason why its textile industry failed to mechanize successfully. “With no large coalfield nearby, no heavy iron or engineering industries, and no other local industry requiring precision engineering, the area lacked a pool of skilled labour to draw upon...” (Tann, 1974).

3.2 Coal Extraction

Besides the skills generated through its use, coal generated skill through the technical challenges in its extraction. (Mokyr, 2009, p. 115). These included not only pumping mines, but also how to locate seams, avoid explosions, and raise and transport the bulky coal over large distances: iron rails were first used to transport coal, and all the engineers who developed the steam engine after Watt—George Stephenson, John Blenkinsop, Timothy Hackworth, William Hedley, and Richard Trevithick—began in mining. Rising to the challenges set by mining (not only in coal) required a confluence of hydraulics, geology, metallurgy, mechanics, and chemistry, among others; and its innovative fervour spilled over to many other sectors.

In other words, the mining industry served as a focusing device for technology. While the emergence of steam power is the best-known example of spillovers of mining technology into other techniques, it was by no means the only one. Coal viewers were among the most skilled and sought-after professionals of the time (Pollard, 1968, 152–153). An example was John Curr (1756-1823), who was the first to introduce flanged rails in underground transportation of coal, and took out no fewer than nine patents for the use of rope and pulleys to hoist up the coal to the surface. He also wrote a coal viewer handbook (1794) which also contained much valuable information on Newcomen-style steam engines. John Buddle (1773-1843) was the best-known coal viewer of his time, and introduced a compound ventilation system into the mines that produced fresher and cleaner air underground. He also collaborated with Humphry Davy in developing the famous safety lamp of 1816.

The geologist William Smith (1769-1839), the father of stratigraphy, represented “the union of practical and theoretical knowledge” in both coal prospecting and agriculture (Phillips, 1844, 113). While it took decades before it fully transformed coal-prospecting, his work led to the discovery of significant coal deposits in east county Durham and to the opening of new collieries underneath the magnesian limestone in the area (Rennison, 2002, 639).

Progress in geology and prospecting for coal followed a pattern familiar from steam. Progress was achieved by “practical provincial men” such as Smith and Robert Bakewell. These people were at the technical foundation of the enormous expansion of the coalmining industry during the Industrial Revolution. They had little contact with the gentlemen-amateurs of British geological science organized in the Geological Society who, while were interested in the nature and composition of coal, could not be bothered with the mundane tasks of finding and extracting it (Porter, 1973). The net result was that just as French scientific mechanical engineers were far ahead of the British, the same was true in mining for Germans. It was in practical and empirical competence that the British coal mining industry excelled. Porter surely exaggerates when he sees coal mining as suffering from “the symptoms of a traditional industry” and wonders why the sector “was conspicuously backward in a country dedicated to the diffusion and application of useful knowledge” (Porter, 1973, 337). That view is not consistent with an industry in which output increased by 1300 percent in a century.

4 The Market for Artisan Skill

Naturally, England owed its large supply of proficient craftsmen to many more things than a fortuitous abundance of coal. On the supply side, the relative limited power of guilds meant that rapidly growing sectors could swiftly attract extra apprentices as Ben Zeev, Mokyr and van der Beek (2017) have shown.¹⁶ On the demand side, from the mid-seventeenth century the English were becoming an increasingly “polite and commercial people” (to use William Blackstone’s phrase) with rising prosperity caused by and causing urban expansion, growing overseas trade, intensified agriculture, and the improved transportation networks that made regional specialization possible.

¹⁶The impact of apprenticeship institutions on the transmission of knowledge is demonstrated by De la Croix, Doepke and Mokyr (2018).

British artisanal skills were the result of a flexible, market-based guild-free apprenticeship system (Ben Zeev, Mokyr and van der Beek 2017; Leunig, Minns and Wallis, 2012; Minns and Wallis 2012, Ogilvie, 2019, chapter 9), but also reflected, on the demand side, the relatively high standard of living in Britain (where Malthusian forces had long since disappeared) and its more equal income distribution (Mokyr, 2009, 17).¹⁷ The relatively large “middling class” in Britain meant that the demand for up-market middle class goods was on average higher than elsewhere. Many of these goods involved a high level of precision manufacturing and quality of materials that embodied sophisticated technological competence. The relative affluence of the working class, shown in such things as the high quality of their everyday clothes, was often noted (Styles, 2007, 13). Working class diets in Britain were renowned for their quality and high protein content, resulting in considerably taller, stronger workers than elsewhere (Kelly, Mokyr and Ó Gráda, 2014). English wages were high but English labour was not more expensive than elsewhere in Europe because its workers were more productive, as Thomas Malthus already realized.

Although Britain started with a uniquely large and flexible supply of artisans, the rapid rise in demand for their services in the late eighteenth century created notable skill shortages. Employers, including Boulton and Watt, continually suffered from having their millwrights poached by other firms and foreigners offering higher wages.¹⁸ Yet Eric Roll’s judgment still seems apposite: steam engines for many decades were out of reach of non-British entrepreneurs, because of Boulton and Watt’s advantages: superior knowledge, superior workmen, and above all, superior suppliers of the main component parts (Roll, 1930, 66).¹⁹

Predictably, as the producer of the most complicated large machine of its time, some of the severest shortages of skills were suffered by Boulton and Watt, resulting in unreliable engines, long delivery lags, and a complete ab-

¹⁷The Malthusian positive check disappeared in most areas around the time that poor relief appeared in the early seventeenth century; and the preventive check was insignificant in most places by the early eighteenth century (Kelly and Ó Gráda, 2014).

¹⁸In 1791 Boulton begged Rennie to lend him a man for nine days but Rennie could not oblige because “some Danish and American pimps that have been for sometime strolling around London have deprived me of some of my best workmen—and I am reduced to the necessity of making foremen of men scarcely fit to be hindmen” (Tann, 1970).

¹⁹Cookson (2018, 154–155) points out that the real need in the British Industrial Revolution was not for more “James Watts” but for “skilled workers with shopfloor duties.” The British apprenticeship system turned out to be able to adapt to the needs of a new set of skills, despite the difficulty that such training involved general and portable human capital and thus exposed the mills to the risk of having their workers bid away by competing firms.

sence of after-sales service. Hills (1970, p. 205) concludes that using steam as a source of power before 1790 “remained very much a hit and miss affair, relying more on the experience of millwrights than upon any properly determined principles.” To compensate for their often inadequate craftsmen, Boulton and Watt pioneered a form of industrial organization of unusual sophistication and complexity, where a standardized range of engines sizes (allowing a stock of spare parts to be kept on hand for customers experiencing breakdowns) were made on a systematic production line with a detailed and explicit division of labour (Roll, 1930, 179–184). All the same, despite Watt’s loud complaints, the technical competence of his employees was among the highest in Britain, let alone in Europe as a whole.

The need for a region to be close to large concentrations of diverse mechanical skill in order to industrialize successfully suggests a possible answer to a central question in the economic history of the Industrial Revolution: Why did some areas of large scale cottage industry (“proto-industry”) like northern and midland England go on to industrialize successfully, whereas others, such as the west of England, southern Ireland, and northern France, did not (Coleman, 1983)? The decisive characteristic that distinguished winners from losers, we argue, was a supply of mechanical expertise; a claim that we will test directly in Section 6 below.

5 Market Integration, the Accumulation of Skill, and the Industrial Revolution.

A decisive factor triggering the Industrial Revolution was national market integration in the eighteenth century driven by improved infrastructure and falling transport costs (which we detail in the next section), and allowing regions to specialize according to their comparative advantage (Szostak, 1991). Specifically, areas with poor soil began to specialize in manufacturing activities and to import food. This is most easily understood in a simple specific factors model where falling food prices reallocate unskilled labour to industry, and increase the incomes of skilled factors specific to that sector: see Figure 1.

In many areas in England, and in Europe more generally, this “proto-industry” took the form of low-tech manufacturing of products like down-market textiles, hardware, and nails, all with fairly limited potential for technological advance. However, in quite a few areas specialization took the form of skilled activities, largely, as Cobden recognized, in metalworking ranging from clock making to iron founding. The equipment used by hand-

loom weavers and frame-knitters had to be made by artisans much more skilled than those who used it (Cookson, 2018). In these sectors, technology and skills rose through learning by doing and by specialized factors using their higher income to invest in better training through apprenticeships for their sons.

Specialization driven by growing interregional trade was one driver of the changing economic environment in eighteenth century Britain that prepared the ground for the Industrial Revolution. Not only did regional specialization deliver the standard gains from trade, but it also increased the supply of the skills that were crucial to a successful Industrial Revolution. Recent work has modeled “spatial take-offs” and regional specialization, but has not sufficiently highlighted the importance of human capital and skills in the process (Trew, 2014).

In modeling the British economy on the eve of the Industrial Revolution, we suppose that it consisted of two regions, North and South, and examine what happens when market integration between them took place as the result of falling transportation costs, of the sort that occurred in England during the eighteenth century.²⁰ The two regions have two sectors each, agriculture and manufacturing. Each sector has a specific factor: fertile land for agriculture, and skilled artisans for manufacturing, and there is a common pool of unskilled workers that can work in either sector. We suppose that the North has less fertile land and a larger supply of skilled artisans than the South.

Growing integration leads low-wage areas with large endowments of skilled workers to specialize in manufacturing while more prosperous areas with high agricultural potential de-industrialize. We test these predictions empirically in Sections 6 and 7. We begin with a textbook specific factors model. This leads to the familiar specific factors diagram in Figure 1 (depicting the North) where the supply of unskilled labour gives the length of the x-axis and the labour demand of each sector is drawn on opposite sides so that equilibrium wage and the employment levels of each sector are given by the intersection of the curves.

As transportation costs fall and trade between regions increases, the relative price of agricultural goods in the North falls, causing the labour demand curve for agriculture to fall. This has two consequences: the output of manufactures rises, and the income of skilled artisans in manufacturing, given by the triangle between the equilibrium wage and the labour demand

²⁰The model is similar in spirit to a literature that was generated by a seminal article by (Matsuyama, 1992).

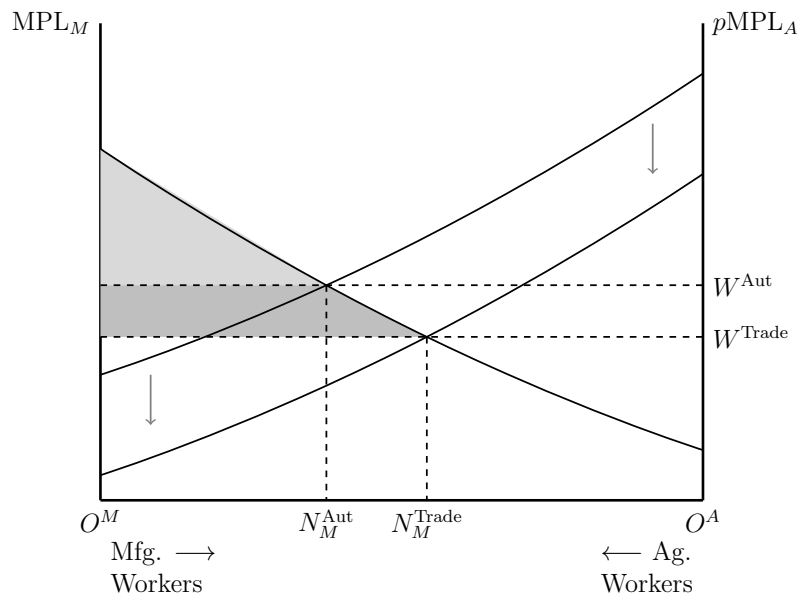


Figure 1: A fall in the relative price of agricultural goods caused by market integration leads areas with poor soil to specialize in various manufacturing activities. Some of these activities have the potential to generate new skills of the sort that underlay British industrialization.

curve, increases. The income of skilled artisans will rise further if there is an influx of unskilled workers—such as occurred into the north of England from the mid-seventeenth century onwards—which increases the length of the x -axis. But the supply of skills is endogenous. As the income of skilled artisans in the North rises, parents have a greater incentive and better capabilities to invest in the training of their sons, either by spending more time on them or to apprentice them to more expensive masters. In that way, the supply of high-skilled labor rises as the result of integration. At the same time, the South de-industrializes and increasingly specializes in agriculture.

The overall comparative statics result is that a region with poor agricultural productivity will accumulate increasing numbers of artisans with specific manufacturing skills, and some of these skills may be conducive to the subsequent development of new industrial technology of the sort that occurred historically in parts of England.

What about dynamics? In an Appendix below, we outline a process where market integration leads to a mutually reinforcing growth of skill

and production technology through parental investment and learning by doing, and show how this process can lead to a sudden transition from a low technology-skills steady state to a high one.

6 The Great Reversal and the Living Standards Puzzle: England 1760–1830.

To test this skills-driven model we will look at how well it explains the evolution of industrial employment across the 41 counties of England where, from the early eighteenth century market integration was driven by the rapid growth of transportation networks. By the time that Brindley built his first canal in 1760, England already had 1,400 miles of navigable rivers (compared with 950 miles in 1600) connecting places like Manchester and Sheffield to the sea, and by 1830 it had added a further 2,600 miles of canals (Satchell, 2017). Between 1750 and 1770, 10,000 miles of road, much previously only usable by pack horses, were turnpiked, increasing to 20,000 miles by 1830; and Bogart (2005) estimates that between 1750 and 1820, road freight charges fell by around 40 per cent.

One of the unsung heroes of the Industrial Revolution was, as already mentioned, coastal shipping, the “Cinderella of the transport world” (Armstrong, 1996). It seems plausible that here geography favored Britain provided it had the technology and resources to take advantage of the opportunities of specialization.²¹ In terms of the number of miles of coastline per square mile of territory, England led France at a ratio of 1:55 over 1:134 (Szostak, 1991, 59).

6.1 The Economic Geography of Pre-Industrial England.

Pre-industrial England fell into three regions. The first was the prosperous, high wage agricultural region of the south and east which for centuries had been the heartland of England’s main industry, the manufacture of woollen cloth. Next was the urban giant of London which, as well as being a port,

²¹Between 1760 and 1783, the tonnage of ships moving bulk goods around the coasts rose from 155,000 to 270,000 tons with the fastest growth outside London, and by 1824, now including Scotland and Ireland, this had risen to 833,000 tons. The cost of shipping a ton of coal to London relative to its price in Newcastle dropped by a quarter; and shipments of wheat rose from 63 to 170 thousand tons during this time (Armstrong and Bagwell 1983, Tables 15, 19–22; Hausman 1987, Table 2). Coastal vessels had to be as seaworthy as any ship built in Britain, and the coastal trade was among the first to adopt steamers in the 1820s.

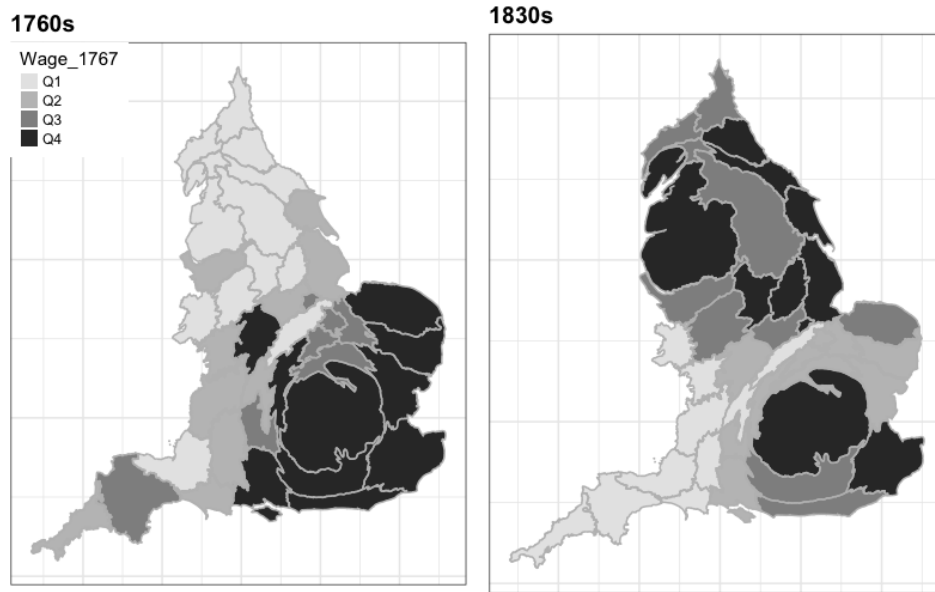


Figure 2: Cartograms of England in the 1760s and 1830s. The area of each county is scaled in proportion to its aggregate labour income (wage times population), and shaded according to its wage rate.

was a major industrial centre. By 1750, it contained over 10 per cent of England's population and was the largest city in Europe (Wrigley, 2010, 61).²²

The final region was the upland North and West. Despite low wages reflecting the region's poor agricultural potential, its population had been growing rapidly since the seventeenth century in response to the widespread non-agricultural employment opportunities offered by outwork and small-scale cottage industry. As well as fast flowing streams to provide water power they had ample supplies of "cheap and amenable female and child labour" (Humphries, 2013) that eventually became a vital input into the dark satanic mills of the Industrial Revolution, and a fairly well nourished population for undertaking heavy physical labour.

²²The classical reference is Jones (1968), extended in Jones (2010).

Above all, this region also possessed a large and flexible supply of workers with useful skills—clockmakers, mechanics, toolmakers—who would play a key role during the Industrial Revolution, and several of whom would become inventors and factory owners in their own right (Cookson, 2018). These artisans were concentrated in three districts that had been centres of skilled metalworking since the late sixteenth century—Birmingham, Liverpool, and Sheffield—and, as we have seen, it was within this triangle that the Industrial Revolution subsequently occurred.

Figure 2 shows a map of England where the counties are re-scaled in proportion to their aggregate labour income: the wage of agricultural labourers times population. Counties are shaded according to the wage rates of agricultural labourers in each period. Given the absence of any restrictions on mobility these are likely to have been close to the wages earned by unskilled labourers in other sectors.

In the 1760s, Figure 2 shows that the English economy was still dominated by London and its environs, and that southern wages were higher than northern ones, reflecting their higher agricultural productivity. By the 1830s we observe what can only be called a great reversal: Northern counties that were in the bottom quartile of wages are now in the top; and the aggregate income of the textile areas of Lancashire and West Yorkshire has become as large as London's. At the same time manufacturing in the old industrial district in the west counties such as Hampshire, Gloucestershire and Wiltshire had sharply declined, a phenomenon described by Jones (2010, pp. 47-50) as "the anomaly of the South". Against the widespread view that the early Industrial Revolution was less a revolution than a gradual adjustment of sectoral shares, Figure 2 highlights the abrupt change in the geographical structure of the British economy that took place within two generations.

6.2 The Standard of Living Puzzle.

This analysis also sheds light on one of the more durable puzzles of the British Industrial Revolution, the failure of real wages to increase appreciably despite the rapid rate of technological progress and industrialization (Mokyr 1999, 113–116; Feinstein 1998). Figure 2 shows that the puzzle is in large measure a statistical artefact caused by looking at national wages rather than regional ones. National real wages were indeed static between 1760 and 1830: weighted by population, the average national money wage rose by 50 per cent, as did the national CPI estimated by Clark (2011). However, this disguises the 80–90 per cent rise in nominal wages in industrial-

izing counties, compared with only 15 to 25 per cent in agricultural ones, so that northern wages not only caught up on southern ones but overtook them. Wage dispersion remained constant with a coefficient of variation of 13 per cent in both the 1760s and 1830s. One possible caveat here is that differences in the cost-of-living might account for (some of) the regional variation in wages. Yet Crafts (1982: 68) and Hunt (1986) have shown that regional cost-of-living differences in the 1840s were minor. What of earlier? Frederick Eden's *The State of the Poor* (1797) is a comprehensive source on regional price variations: it indicates little difference between the cost of provisions in northern and southern counties in the mid-1790s; if anything prices seem to have been slightly higher in the north. However, a dramatic reversal of fortunes is masked by this constant dispersion.

The differential labour demand that drove these wage rises led to very different patterns of population growth. Between 1761 and 1831, the population of the depressed agricultural counties in the south and east grew only 25–33 per cent, whereas that of the industrial counties and those around London more than doubled, with that of Lancashire more than quadrupling.

These different patterns of growth are tightly associated with industrialization. The correlation between the growth of aggregate labour income from the 1760s to the 1830s and industrial employment in 1831 is 0.82. What this suggests is that industrialization was not a narrow-based process confined to a few isolated sectors such as cotton and iron, but changed the entire geographical distribution of economic activity and living standards in Britain within two generations. Clearly, the great locational reversal affected internal migration, as a response to the changes in regional specialization. Migration would have heavily concentrated on unskilled workers, searching for work in the newly industrialized urban centers.

7 Data and Testing.

Although the regional specialization model we outlined above is extremely simple, it makes the very specific and testable prediction that areas that industrialize successfully will have two characteristics at the onset of industrialization: they had low wages associated with poor soil; combined with high endowments of pre-existing skills that could be repurposed if necessary to new manufacturing activities. It is straightforward to measure wages but the challenge comes in measuring the availability of skill at the beginnings of industrialization. We do have detailed data on the supply of

one type of skilled artisan in the mid-eighteenth century: watch and clock-makers, where the records of the London Watchmaker's Company (guild) detail every one of its apprentices during the eighteenth century (Moore, 2003). However, as Cummins and Ó Gráda (2019) demonstrate, roughly half of English watchmakers never apprenticed to the guild (and about 80 per cent in the main watchmaking region Lancashire), making this a potentially unreliable measure.

To test our hypotheses, we instead take advantage of the fact that the 1851 census details the numbers of workers in each occupation broken down by age. By examining elderly men (aged sixty and over, most of whom would have been apprenticed around age 14 in the late 1790s) we can get an idea of the geographical availability of skill at an earlier stage of the Industrial Revolution.²³ For nearly every county and every skill, the number of these men with a particular skill residing in a given area closely matches the cohort size of men with the skill born in that county, suggesting that most of these skilled workers were apprenticed locally and that inter-county migration does not confound the analysis.

We focus on the share of men over sixty born in each county who had potentially useful skills. Specifically we look at blacksmiths, millwrights (both traditional skills), watch- and instrument makers, gunsmiths and locksmiths, toolmakers, sheet-metal workers, and mechanics. These last workers made, assembled and maintained the machinery we associate with the Industrial Revolution.

Given their historical importance for early industrialization it might seem surprising at first that the number of watchmakers and lock- and gun-smiths has little explanatory power. It is important to remember, however, that specialized industrial skills were transformed and adapted rapidly: many of the men in our sample may have been trained by men who started out as watch tool makers or millwrights but by 1851 were making a living as industrial tool makers or machine builders.²⁴ The key to successful industrialization was that technical training in Britain was not only of high quality, but that it was relatively flexible and that highly skilled artisans adapted to the needs of different if related occupations (Cookson, 2018, pp. 106, 126). Terms such as millwright and blacksmith, moreover, by 1851 meant different things in different places. In agricultural areas they were largely engaged in traditional practices of maintaining water mills and making farm implements

²³Using men aged fifty and over gives practically identical results.

²⁴Cookson (2018, 80) feels that the central role of clockmakers as gear-cutters in the textile industry machine-tool making shops "ended before 1800.

and shoeing horses; whereas in industrial areas millwrights were increasingly engineers and blacksmiths forged heavy machinery parts.

8 Regression Results: Textiles.

As our historical survey showed, the two largest branches of the Industrial Revolution textiles and metallurgy, were driven by different factors. For textiles, the decisive contribution came from the existing availability of mechanically skilled artisans with a modest early role for coal as a source of power. In metallurgy, by contrast, we expect coal to be important as a fuel for working iron in forges, smelting brass and steel in reverberatory furnaces, and finally for smelting wrought iron. But in and of itself, coal was insufficient: although many parts of Britain had coal, metalworking grew in three centres where skill had accumulated over centuries.

Alongside the technologically dynamic of textiles and metallurgy, were large traditional sectors like shoemaking, woodworking, and garment making. We analyse these sectors as controls, because in those industries we would expect neither skill nor fuel to matter much.

We consider each sector in turn, starting with textiles. Here we look at the dependent variable textile employment using data from two censuses, 1831 and 1851. The 1851 census is highly reliable, but reports on a time later than the period that mostly concerns us from the 1780s to the 1830s; whereas the accuracy of the 1831 census for newer manufacturing sectors outside textiles is uncertain. What we observe, in Table 1 is that the distribution of textile employment is largely unchanged over this time: the regression results are very similar except that the coefficients in 1851 are around one standard deviation smaller.

8.1 The Supply of Skill.

The simple approach of Section 5 makes very specific predictions about the characteristics of regions that will be the first to industrialize. One is that they will have low agricultural potential and this, in a world where agriculture was the largest sector, this will translate into low wages. The second is that, among low wage regions, the ones that were most likely to succeed will have a large pool of trained artisans with malleable mechanical skills that could be applied to developing new technologies of the sort we saw above among Lancashire watchmakers and Staffordshire iron founders. Other factors, such as proximity to large markets, or the availability of kinetic energy

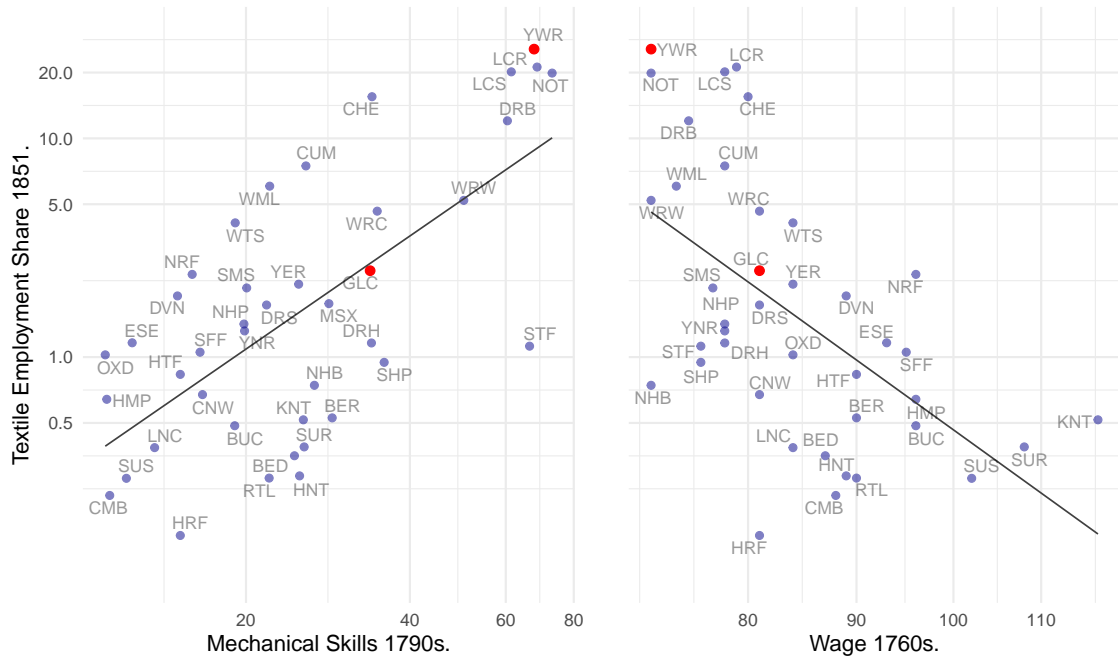


Figure 3: Supply of mechanical skill in the 1790s, and agricultural wages in the 1760s versus the percentage of males employed in textiles in 1851. Logarithmic axes. Note how the decline of Gloucestershire (GLC), the dominant woollen textile centre in the mid-eighteenth century and its eclipse by West Yorkshire (YWR) can be predicted from its lack of mechanical skills in the 1790s.

in the form of water or fuel (coal) may also be important. We proceed to test these predictions.

The broad pattern of the data are shown in Figure 3 which plots textile employment share in 1851 against the supply of mechanical skill in the 1790s, and the agricultural wage in the 1760s. It is immediately evident that successful regions were those that had combined low wages with high mechanical skills allowing them to adopt new machinery. What is particularly revealing are the points for Gloucestershire (GLC) and West Yorkshire (YWR). In the mid-eighteenth century Gloucestershire dominated the English woollen textile industry but it failed to mechanize and by 1851 had become a backwater, with the industry dominated by the factories of West Yorkshire.

<i>Dependent variable: Share of men employed in textiles.</i>								
	1831				1851			
Skills 1790s	2.033 (0.468)	2.208 (0.625)	2.075 (0.476)	2.232 (0.787)	1.660 (0.378)	1.676 (0.495)	1.646 (0.386)	1.837 (0.610)
Wage 1760s	-6.105 (1.861)	-6.768 (2.436)	-5.623 (2.011)	-6.692 (3.019)	-4.537 (1.455)	-4.601 (1.923)	-4.700 (1.583)	-4.259 (2.269)
Mkt Potential 1750	0.766 (0.288)	0.722 (0.309)	0.734 (0.294)	0.765 (0.664)	0.522 (0.227)	0.518 (0.243)	0.533 (0.233)	0.131 (0.501)
Distance to Coal		0.245 (0.570)		0.251 (0.645)		0.023 (0.439)		0.043 (0.474)
Water Power			0.181 (0.272)	0.244 (0.327)			-0.061 (0.215)	-0.060 (0.248)
Latitude	1.868 (1.590)	2.404 (2.036)	1.686 (1.625)	1.887 (2.267)	0.822 (1.252)	0.871 (1.583)	0.883 (1.287)	0.552 (1.695)
Literacy c1800				-1.431 (2.003)				-0.209 (1.519)
Pop Density 1700				0.087 (0.605)				-0.485 (0.453)
County Banks 1796				-0.076 (0.449)				-0.534 (0.340)
Lawyers 1730				0.032 (0.472)				-0.503 (0.358)
Booksellers 1761				0.117 (0.374)				0.271 (0.287)
R^2	0.701	0.703	0.705	0.715	0.656	0.656	0.657	0.697
Moran	0.388	0.381	0.421	0.391	0.184	0.180	0.113	0.090

Dependent variable is the employment share of textiles among all males over 20 in 1831, and among males aged 20–29 in 1851. Robust standard errors in parentheses. Mechanics 1790s is the share of males aged 60–69 listed as mechanics in 1851, by county of birth. Wage is the wage of agricultural labourers. Market potential is the sum of 1750 population times 1760s wages over all counties, weighted by the inverse squared distance to each county. Distance to coal is the distance from the county centroid to the centroid of the nearest county with coal. Latitude is measured in kilometers. Water flow for each square kilometer of England is based on the area that drains into it, multiplied by the tan of its slope. Each county is assigned a value equal to the 98th percentile of the flow across its squares. Literacy is the percentage of convicts that were literate. Density is the density of 1700 population relative to county farmland. Booksellers is the number of booksellers, lawyers is the number of attorneys, and banks is the number of county banks, all per capita. Moran denotes p value of Moran test for spatial autocorrelation of residuals. Regressions include a dummy for Shropshire in 1831, and Staffordshire in 1851. All other variables are in logs. 41 observations.

Table 1: Textile employment in 1831 and 1851, OLS.

8.2 OLS Results

Table 1 gives the results of regressing textile employment in 1831 and 1851 on a variety of possible explanatory variables. First is mechanical skill in the 1790s which we will treat as exogenous for now. Next we have agricultural wages to test if high wages in the 1760s drove regions to substitute machinery for expensive labour, or whether regions of poor agricultural po-

tential and low wages came to specialize in manufacturing as national markets integrated.²⁵ Given the importance of market integration to our story, alongside these we include the size of the potential market (measured as the product of 1760s wages and 1750 population, with weights declining with the square of distance) emphasized by Crafts and Wolf (2014): textiles are fairly bulky things so access to nearby markets would be desirable in the early stages of industry before canals even in the presence of coastal shipping. In addition to these we include measures of the supply of heat and kinetic energy: proximity to coalfields, and water flow.

The final column of each set of regressions includes a variety of other factors that occasionally mentioned in discussions of the causes of the Industrial Revolution. These are literacy around 1800, and booksellers per capita in 1761, as measures of human capital. The number of lawyers per capita in 1730 is added as a proxy measure of the security of property rights. Population density is the ratio of population in 1700 to agricultural land, in keeping with the story that areas of cottage industry (“protoindustry”) that were able to support large non-agricultural populations developed the skills and attitudes that subsequently drove industrialization. Finally, we include the number of County Banks in the 1790s. If industrialization was driven by a desire to replace expensive workers with energy-intensive machinery, this investment would have been facilitated in areas with extensive banking networks.

In any regression using spatial data there is a real possibility that the results are spurious. First, spatial data tend to show strong directional trends leading to strong correlation even in the absence of any economic relationship: in our case wages in the 1760s fall as one goes north, while 1831 textile employment falls as one goes south, so the two will tend to be correlated even if unrelated. To deal with this we include latitude as a proxy for any omitted variables that might explain employment. The second potential hazard is that the regression is fitting spatial noise. To test for this we include Moran’s I statistic as a diagnostic of spatial correlation in residuals.

What Table 1 indicates is that the growth of textile production occurred in areas with vigorous supplies of skilled metalworkers, and low wages, alongside access to substantial markets. The size of the coefficients is notable: the elasticity of textile employment in 1831 with respect to skill supply

²⁵For agricultural potential we experimented with a variety of measures that all correlate strongly with the wages of farm labourers in the 1760s: the correlation with the median county level of suitability for wheat, estimated by the FAO, is 0.5; with the average land tax per acre in 1707 (leaving out London) is 0.6; and their correlation with the age of the dominant rock type in each county — hard, ancient rock leads to less fertile soil — is 0.7.

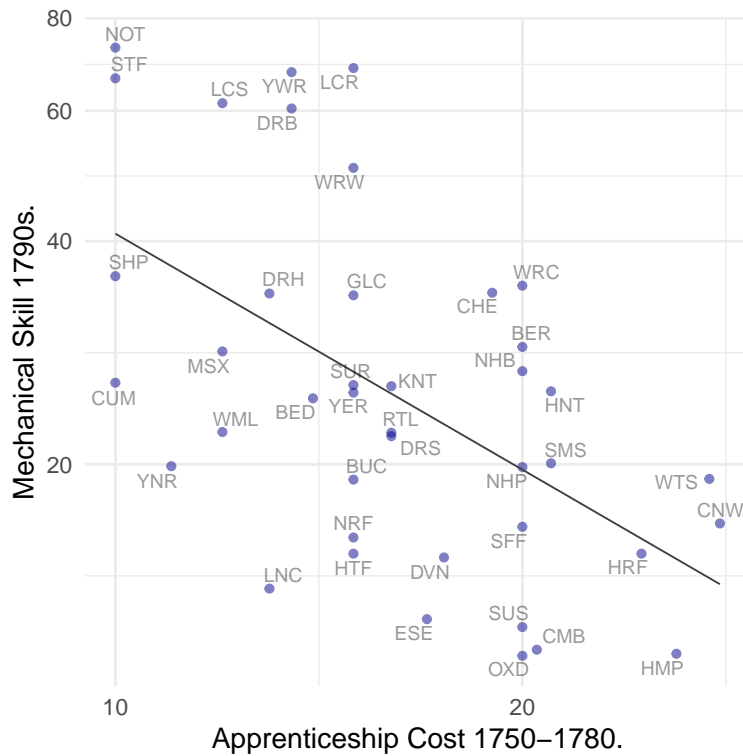


Figure 4: Apprenticeship fees for watchmaking 1750–1780, and the supply of mechanical skill in the 1790s. Logarithmic axes.

is in the region of 2, while wages have a negative elasticity of around 6. The significance of the latter is that it helps put to rest theories that relate the Industrial Revolution to high wages resulting from a supposed induced innovation mechanism. Latitude has no explanatory power and there is no evidence of spatial correlation in residuals.

Given the limited power needed to spin and weave textiles we noted earlier, the unimportance of coal and water power, once we control for skills, is not surprising. None of the other variables in the final column contributes much explanatory power. As Table 1 shows, then, textile production was strongly associated with mechanical skill in the 1790s.

8.3 An Instrumental Variable Approach

However, the supply of skills was potentially endogenous: new industries, even as early as the 1790s, may have encouraged inward migration of skilled workers, or caused men in traditional industries, like millwrights and blacksmiths, to become specialized machine builders. To address this concern, we employ an IV strategy where we instrument the measure of skills derived from old skilled workers in the 1851 census. We consider three potential instruments: apprenticeship fees in the mid-eighteenth century; the density of population relative to farmland in 1700; and the proximity of coal. We discuss the rationale for each in turn.

Our most important instrument for the supply of mechanical skill before the beginnings of industrialization from the cost of acquiring advanced mechanical skills measured by apprenticeship fees, in the mid-eighteenth century. In areas with heavy employment in skilled metalworking fees would have been lower, because a large number of masters would be competing for apprentices from the surrounding area. In predominantly agricultural areas, the low supply of masters would imply higher fees. We use the fees charged to become a watch- or clock-maker from the records of the Watchmakers' Company, assembled by (Moore, 2003). As Ben Zeev, Mokyr and van der Beek (2017) show, similar trades demanded similar apprenticeship fees, so we can be fairly confident that areas charging low fees, even if they did not have extensive watch industries, had extensive demand for similar skilled crafts such as whitesmiths (who filed castings into precise shapes), lock makers, gunsmiths, and instrument makers. The close relationship between mid-eighteenth century apprenticeship fees and the number of skilled workers trained in each county around 1800 is apparent in Figure 4.

Next, given the prediction that skill will accumulate in areas with poor land we consider the density variable of population relative to farmland in 1700. The idea here is that wherever rural cottage industries were common, the overall level of effective land to labor was lower (which drove workers to engage in alternative occupations), and possibly population growth was faster as argued by the models of protoindustrialization.

The final potential predictor of mechanical skill, as we discussed earlier, is the availability of coal. To repeat, coal was vital to early British success not so much for its ability to supply motive power but as a cheap source of heat that allowed metalworking to emerge to an extent unrivaled elsewhere. We introduce distance from coal as a potential instrument on the grounds that it strongly affected skill but had little direct impact on textile employment

Dependent variable: Share of men aged 60–69 described as mechanics and toolmakers in 1851.

Apprentice Fee	-0.705 (0.265)	-0.587 (0.215)	-0.650 (0.221)	-0.517 (0.179)	
Distance to Coal		-0.406 (0.087)		-0.339 (0.073)	-0.399 (0.073)
Pop Density 1700			0.792 (0.166)	0.627 (0.137)	0.610 (0.138)
Apprentice Fee/Wage					-0.463 (0.166)
Latitude	15.946 (61.723)	-166.856 (63.259)	-12.536 (51.544)	-149.575 (50.573)	-147.627 (50.866)
R^2	0.226	0.512	0.528	0.708	0.704
Spatial Autocorr.	0.126	0.544	0.001	0.059	0.127

Dependent variable is the share of males aged 60–69 born in the county who are listed as mechanics and toolmakers in the 1851 census: these men would have been trained as apprentices in the 1790s. Standard errors in parentheses. Apprentice fee is the average fee for a watchmaking apprenticeship in the county, 1750–1780. Distance to coal is the distance from the county centroid to the centroid of the nearest county with coal. Density is the density of 1700 population relative to county farmland. Apprentice Fee/Wage is the ratio of the apprentice fee to 1760s wage of agricultural labourers. Spatial Autocorr denotes significance level of Moran test for spatial autocorrelation of residuals. Regressions that include population density add a dummy for London. All other variables are in logs. 41 observations.

Table 2: First stage regressions for the availability of mechanical skill in the 1790s.

as a source of motive power, since much power was still supplied by water, and by 1851 (when steampower was applied widely) coal was available cheaply almost everywhere in Britain. Hence the presence of coal would not be expected to affect textile employment directly, but only through the supply of skill, so that it satisfies the exclusion restriction.

As Table 2 containing the 1st stage regressions shows, all of these variables have considerable explanatory power for the local availability of skill, but apprenticeship fees and coal especially. The final column of Table 2 uses the ratio of apprenticeship fees to local wages to control for the possibility that low apprenticeship fees simply reflected low wages and had nothing to do with skill availability, and shows that the explanatory power of the regression is largely unchanged.

Table 3 presents the 2nd stage regressions, focussing on the three main explanatory variables of low wages, market access, and skill supply in the

<i>Dependent variable: Share of men employed in textiles.</i>								
	1831				1851			
	OLS	IV ^a	IV ^b	IV ^c	OLS	IV ^a	IV ^b	IV ^c
Skills 1790s	2.125 (0.464)	3.178 (1.154)	2.502 (0.729)	2.559 (0.733)	1.703 (0.369)	2.466 (1.000)	1.955 (0.597)	1.531 (0.591)
Wage 1760s	-6.960 (1.722)	-5.169 (2.556)	-6.318 (1.981)	-6.300 (2.151)	-4.908 (1.330)	-3.686 (2.037)	-4.505 (1.533)	-5.214 (1.651)
Mkt Potential 1750	0.713 (0.286)	0.484 (0.380)	0.631 (0.313)	0.601 (0.320)	0.499 (0.222)	0.340 (0.303)	0.446 (0.244)	0.528 (0.247)
Hausman	.	0.286	0.503	0.395	.	0.388	0.594	0.704
Over-Identifying	.	.	0.373	0.470	.	.	0.462	0.201
Spatial Autocorr	0.497	0.305	0.465	0.505	0.505	0.436	0.355	0.273
Weak Instruments	.	0.007	0.000	0.000	.	0.015	0.000	0.000

^a Instruments for Skills: Fee for watchmaking apprenticeship, 1750–1780.

^b Instruments for Skills: Apprenticeship fee; distance to nearest coalfield.

^c Instruments for Skills: Apprenticeship fee; population density relative to farmland 1700.

Dependent variable is the employment share of textiles among all males over 20 in 1831, and among males aged 20–29 in 1851. Skills 1790s is the share of males aged 60–69 listed as mechanics and toolmakers in 1851, by county of birth. Wage 1760s is the wage of agricultural labourers. Market potential is the sum of 1750 population times 1760s wages over all counties, weighted by the inverse squared distance to each county. Standard errors in parentheses. 1831 regressions include dummies for Staffordshire, 1851 regressions use dummies for Shropshire. Regressions using 1700 population density as an instrument also include a dummy for Middlesex. All other variables are in logs. 41 Observations. Spatial Autocorr denotes p value of Moran test for spatial autocorrelation of residuals. Weak instruments denotes the significance level for a regression of mechanics on the relevant instruments. Hausman is the significance level of a Hausman test for the difference between OLS and IV. Over-Identifying is the significance level of a Sargan test of over-identifying restrictions. 41 observations. 41 observations.

Table 3: Textile Employment in 1831 and 1851: Instrumental Variables, 2nd stage.

1790s, instrumenting for skill. We deploy various combinations of the three potential instruments as shown.

The important thing that emerges from every column of Table 3 is that the results do not change materially from the OLS ones, regardless of the set of instruments used. The coefficient on skill rises somewhat compared with OLS, as does its standard error, but using no instruments, or apprenticeship fees, or apprentice fees and density, or even, if this is felt to be legitimate, adding coal leave the results unaltered. The regression diagnostics do not indicate any problems: as we would expect from Table 2 the instruments strongly explain the supply of skill, and a Sargan test of overidentifying restrictions indicates that the instruments are valid ones. The Moran statistic finds no spatial structure in the residuals: the regressions appear to be fitting more than spatial noise.

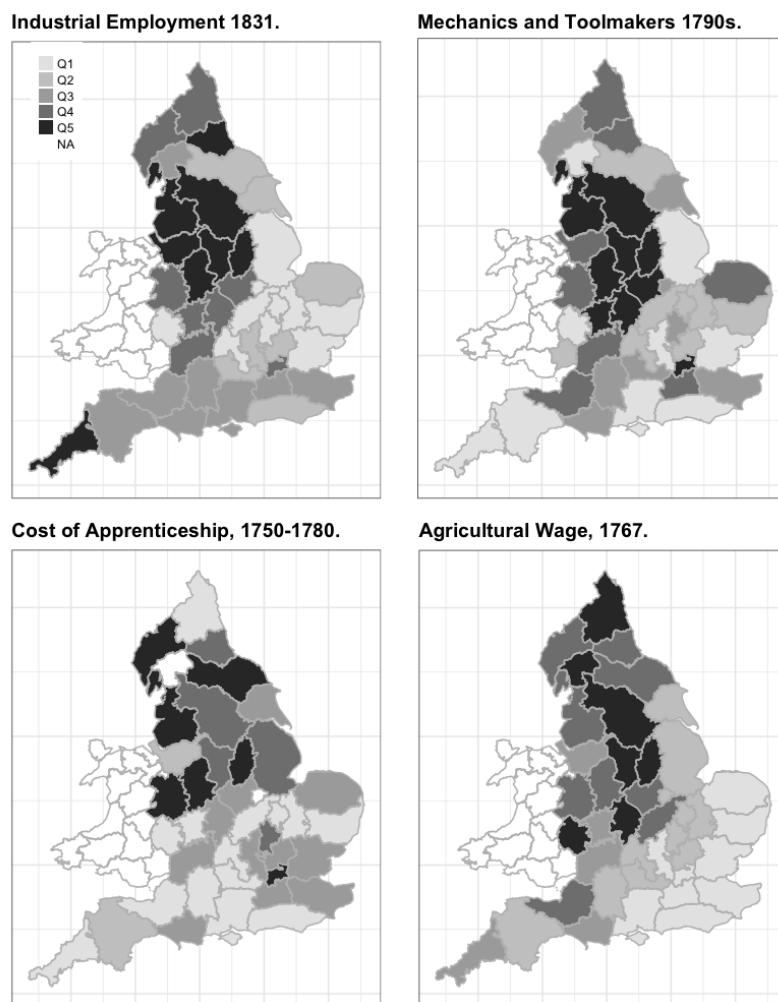


Figure 5: County levels, shaded by quintile, of industrial employment, the share of mechanics and clockmakers in the labour force, the inverse cost of becoming a watch-making apprentice, and the inverse wage of agricultural labourers.

9 Regression Results: Metallurgy

The indispensable role of coal in early British industrialization, we have argued, is in the skill in managing heat for metalworking—ranging from blacksmith work, to casting watch springs and pinions—that British artis-

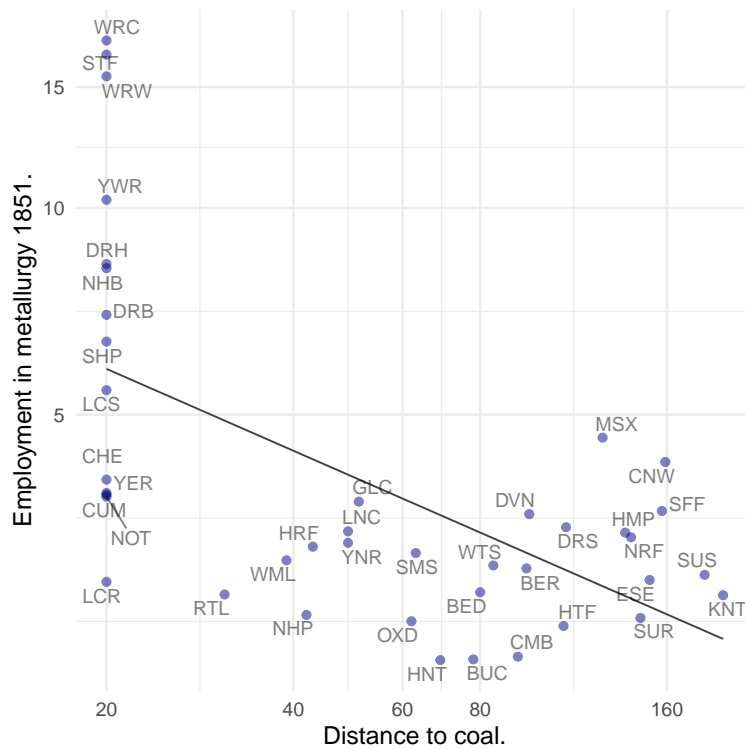


Figure 6: Distance to coal and employment in metallurgy 1851.

ans accumulated. Here we examine three heavy metalworking activities: metal manufacturing, metal products, and sheet metal. Whereas the 1831 estimates for textile employment are systematic, those for metals are chaotic reflecting the novelty of these activities, and we use 1851 data instead.

The relationship between total metal employment and coal distance is shown in Figure 6. Naturally, the relationship with coal proximity is strong but, what is equally important and again somewhat disguised by the logarithmic axes, is the concentration of the industry in three neighbouring counties in the West Midlands—Staffordshire, Warwickshire (which includes Birmingham), and Worcestershire—whose suitable coal had made them centres of metalworking skill since at least the sixteenth century.

Table 4 shows regression results for these three activities. It can be seen that for all three activities, proximity to coal, paired to being in the traditional metal centres of the West Midlands are strong predictors, especially for metal manufacturing. The mechanical skill variable adds no explanat-

ory power. Despite their importance to the modern sector, the metallurgical industries even as late as 1851 still depended heavily on traditional skills in forging and smelting, and the mechanical aptitude that was required in the construction and maintenance of machines was not important for the location of this industry. What is apparent, all the same, is how concentrated it was in areas where coal was available. The carbonocentric hypothesis sees coal as central to the supply of motive energy that replaced human and animal work. What really mattered here was coal as a source of heat, though as argued above, coal mines also generated some of the skills that were required for the new machinery. The other new industry reliant on coal for heat in the eighteenth century was pottery but it was overwhelmingly concentrated in Staffordshire, one country which had been a major centre for centuries, and whose heavy reliance on coal long pre-dated Josiah Wedgwood.

10 Regression Results: Traditional Industry

Having discussed textiles and metallurgy, the best known sectors of the Industrial Revolution, as a robustness check we consider how well the factors we have emphasized explain the location of traditional manufacturing activities: as John Burnett (1969, p.193) quipped, there were more cobblers than coalminers in 1851. The variables we stress here (mechanical skills, low wages, and coals as a source of thermal energy) explain modern industry but, as Table 5 shows, they do not correlated systematically with traditional manufacturing that had but mechanized little in the mid-nineteenth century. Table 5 shows that for the major traditional sectors of food, garments, shoes, and woodworking, wages are the only variable important variable for food and garments, and skills have no explanatory power.

11 Conclusions.

For the last generation the debate on the origins of the Industrial Revolution has been overshadowed by the realisation that its macroeconomic impact was at first modest, reflecting the fact that the sectors that grew fastest started out small (Crafts and Harley, 1992). From this grew a widespread belief that the Industrial Revolution was less of an epochal change in human history than a narrow event confined to a few sectors like cotton, iron, and

Dependent Variable: Employment in Metallurgy, 1851.

	<i>Total</i>	<i>Metal Mfg</i>	<i>Metal Prods</i>	<i>Sheet Metal</i>
Distance to Coal	-0.210 (0.099)	-0.596 (0.232)	-0.148 (0.089)	-0.101 (0.164)
Mkt Potential 1750	0.242 (0.070)	0.635 (0.194)	0.158 (0.063)	0.464 (0.116)
Traditional Metal Area	1.210 (0.181)	1.887 (0.429)	1.085 (0.163)	0.828 (0.302)
Skills 1790s	0.147 (0.144)	0.152 (0.349)	0.158 (0.130)	0.122 (0.240)
Latitude	0.580 (0.469)	1.402 (1.104)	0.434 (0.422)	0.750 (0.782)
R^2	0.811	0.771	0.791	0.546
Moran	0.083	0.116	0.133	0.415

Dependent variable is the share of males aged 20-29 employed in metallurgy. Standard errors in parentheses. Moran denotes p value of Moran test for spatial autocorrelation of residuals. Distance to coal is the distance from the county centroid to the centroid of the nearest county with coal. Market potential is the sum of 1750 population times 1760s wages over all counties, weighted by the inverse squared distance to each county. Traditional Metal Area is a dummy for three West Midland counties: Staffordshire, Warwickshire, and Worcestershire. Mechanics 1790s is the share of males aged 60–69 listed as mechanics and toolmakers in 1851, by county of birth. Metal Manufacturing contains a dummy for Rutland. All other variables are in logs.

Table 4: Determinants of employment in metallurgy in 1851.

steam in an economy that was otherwise fairly static (Clark, 1985).²⁶ However, recent findings have shown that this narrow view of industrialization is no longer tenable.

First, Broadberry et al. (2015) have demonstrated that slow but persistent output growth across a broad range of industrial sectors was under way by the late seventeenth century. Second, technological change is increasingly seen as sustained improvements, most of them anonymous and incremental, across many important activities—as varied as watch-making, shipping, ceramics, glass-making, brewing, road transport, paper making,

²⁶For early dissenting views, see Berg and Hudson (1992) and Temin (1997).

Dependent Variable: Share of men employed in traditional industries, 1851.

	Food	Garments	Shoes	Wood
Skills 1790s	0.029 (0.071)	0.130 (0.109)	0.029 (0.075)	0.038 (0.145)
Wage 1760s	0.624 (0.294)	-1.076 (0.453)	-0.531 (0.315)	0.374 (0.605)
Mkt Potential 1750	-0.039 (0.045)	-0.011 (0.069)	0.045 (0.047)	-0.119 (0.092)
Latitude	-0.054 (0.238)	0.465 (0.366)	-0.035 (0.251)	0.391 (0.489)
R^2	0.169	0.453	0.725	0.160
Moran	0.003	0.229	0.535	0.900

Dependent variable is the employment share of males aged 20–29 in 1851. Robust standard errors in parentheses. Mechanics 1790s is the share of males aged 60–69 listed as mechanics and toolmakers in 1851, by county of birth. Wage is the wage of agricultural labourers. Market potential is the sum of 1750 population times 1760s wages over all counties, weighted by the inverse squared distance to each county. Moran denotes p value of Moran test for spatial autocorrelation of residuals. Regressions include a dummy for Middlesex, and shoes includes one for Northamptonshire. All other variables are in logs.

Table 5: Employment shares of traditional industries in 1851.

candle-making, gas lighting, water- power and machine tools—in many cases innovations starting in the early eighteenth century, though the process shifted into high gear only after 1760. The Industrial Revolution saw some spectacular technological breakthroughs, documented in every textbook. But the practical exploitation and scaling-up of these insights depended on the cumulative and incremental microinventions that required artisanal skills, experimentation, and learning-by-doing.

Take, for instance, the large brewing sector where Mathias (1959, 13) saw the invention of porter—the first beer that could be produced on an industrial scale— as “exactly equivalent in its own industry to coke-smelted iron, mule-spun muslin or ‘pressed-ware’ in pottery.” Another example is in the small arms industry, where Hoffman (2011) estimates the growth in total factor productivity in the making of pistols at 1.1 percent a year (1556–1706) relative to a low-tech product such as spades. This, as he points out,

is an underestimate since it does not account for quality improvements in muskets and pistols. It is striking that his estimates for productivity growth in this industry are significantly higher for England than those for France. A very similar process is observed for the eighteenth century English watch-making industry (Kelly and Ó Gráda, 2016). For other examples, see Mokyr (2009, 134–144) and Tomory (2012).

This account is consistent with the importance that contemporary observers attached to Britain's large and diverse supply of mechanical skills in explaining its Industrial leadership. Britain's large advantage in the supply of mechanical competence before the Industrial Revolution was well known abroad, not least in France whose systematic efforts to poach British artisans have been described in details by many historians (Harris, 1998; Bertucci, 2017; Fox, 2009, p.143). Its many gifted inventors notwithstanding, Britain's advantage in invention is much smaller than its precocity in the Industrial Revolution would suggest.²⁷ The success of British artisans in developing technology from abroad, already noted by Daniel Defoe in the 1720s, is summarized succinctly in the often cited pronouncement of Jean Ryhiner (a Swiss manufacturer visiting Britain in 1766) "for a thing to be perfect it has to be invented in France and worked out in England" (Mokyr, 2009, 106-108).

In the new interpretation of the British Industrial Revolution we are offering, the role of tacit artisanal competence occupies center stage. Highly skilled craftsmen were needed to install, operate and maintain the new equipment, and it was the technical *savoir faire* of these engineers and mechanics that provided Britain with the crucial advantage. These artisans obviously were the elite of the distribution of skilled workers, and it is this upper tail human capital that mattered most.²⁸ A full explanation of the sources of this advantage would include above all the well-functioning market for apprenticeship training in Britain, which was widely regarded as more effective than elsewhere (Mokyr, 2019; Ogilvie, 2019). A simpler explanation would point to the higher overall productivity of British workers, resulting from their superior physical condition and better training (Kelly, Mokyr and Ó Gráda, 2014). If the distribution of skills among workers was symmetric,

²⁷In a list of major inventions by country of origin compiled by Giovanni Gozzini, Britain never accounts for half; during the critical years of the Industrial Revolution 1776-1825, its share is approximately 43 percent, falling to 29 percent in the years 1826-1850 (cited by Vries 2013, 22).

²⁸For recent research of the Upper Tail Human Capital interpretation, see for instance Mokyr, 2009; Meisenzahl and Mokyr, 2012; Squicciarini and Voigtländer, 2015; De la Croix et al., 2019; Dittmar and Meisenzahl, 2020.

even small differences in mean worker ability would be amplified and result in disproportionately larger differences in the density in the high upper tail of the distribution of competence.

The emphasis on the technical competence of British mechanics naturally raises the question of their education. There is an interpretation that sees the Industrial Revolution as driven by semi-literate “tinkerers,” and notable examples of such unlettered mechanical geniuses exist. Yet many of the leading industrialists (and not just leading inventors such as Smeaton and Watt) do not fit that description.²⁹ Even when they were themselves lacking in formal education, they had access to best-practice eighteenth-century formal science, such as it was. One of the channels through which this knowledge flowed was the new position of “consulting engineer,” associated with the career of John Smeaton, but which defined the work of many others, such as Watt’s scientific advisor John Robison, the above-mentioned John Whitehurst, and Peter Ewart (1767-1842), an Edinburgh-educated engineer and millwright whose work on energy was said to have influenced Joule. Scientific insights had various and often roundabout ways of informing inventors.³⁰

To replicate the Industrial Revolution, we propose a simple model where the gradual rise in the supply and ability of craftsmen led to a sudden transition to the basin of attraction of a high technology steady state: an Industrial Revolution. We test the empirical predictions of this model—that industrialization is driven by the supply of mechanical skill, and this in turn accumulates in regions that have low wages and existing industrial skills—across English counties, and find that its explanatory power is extremely high.

Naturally, we are not implying that artisans, no matter how skilled, could by themselves have brought about an Industrial Revolution. Such a pure-artisanal invention effort has its limits. After all, Asian craftsmen for centuries produced textiles, carpets, and ceramics that were the envy of Eu-

²⁹In the textile industry, to pick an example, Jedediah Strutt, Arkwright’s partner and himself an accomplished inventor, may fit this description, but his son William (1756-1830) was an educated man and was elected to the Royal Society. His contemporary, Charles Woolley Bage (1751-1822), who designed some of the largest textile mills of the Industrial Revolution, formulated the earliest known practical theory for the strength of cast-iron columns. John Kennedy, one of Manchester’s most successful cotton manufacturers, while lacking a formal education, was a serious intellectual and an active member of Manchester’s famed Literary and Philosophical Society and published a number of papers.

³⁰An example is Harrison’s famous marine chronometer, operating on a principle of triangulation developed by the Dutch mathematician Gemma Frisius in the middle of the sixteenth century.

rope yet no Industrial Revolution took place in India or China. The artisanal skills linked to metal working, which have been highlighted in this paper, underpinned the early stages of the Industrial Revolution, but they also depended on the new intellectual horizons opened by the likes of Torricelli, Huygens, Boyle, Desaguliers, and Joseph Black, to say nothing of Galileo and Lavoisier. It is the powerful complementarity between people who knew things and those who could make things, between savants and artisans, that opened the floodgates of progress. In terms of our model, if the maximum level of technology is too low, no amount of skill accumulation will lead to an industrial revolution. But it is equally true that without the necessary quality of well-trained and agile skills, no breakthroughs in mechanical engineering, chemistry, physics, and practical mathematics would have had much of an effect on the economy.

Appendix 1. Data Sources and Construction.

Measures of skill of men aged 60 and over born in each county or resident in each county are taken from the 1851 Census in the UK Data Archive <http://icem-nesstar.data-archive.ac.uk/webview/>. Workers are assigned by HISCO Code as follows: Blacksmiths 83120–83150. Toolmakers 83210–83400. Gunsmiths and Locksmiths 83210–83700. Mechanics 84110, 84130–84190. Millwrights 84120. Watch and instrument makers 84220–84290. Sheet metalworkers 87330–87390.³¹ These are expressed per 100,000 men over 60 who were working, retired, or unemployed.

Industrial employment in 1831 (defined as all workers not listed as being employed in the categories agriculture, retail and handcrafts, capitalists and professionals, or without a specific occupation) are from Marshall (1833, 10–11). Apprenticeship fees for the London Watchmakers Company are from Moore (2003).

Wages of agricultural labourers for the 1760s and 1833 are taken from Hunt (1986) with one obvious error corrected (Nottinghamshire in the 1760s where wage is given as 9 shillings instead of the 6 shillings that Young records). Population data are taken from Wrigley (2009).

Water flow for each square kilometer of England is based on the area that drains into it, multiplied by the tan of its slope; both from the USGS Hydro1k database. Each county is assigned a value equal to the 98th percentile of the flow across its squares. Coal distance is the distance of the centre of each county to the nearest county with a coal field. Counties with a coalfield were assigned a distance of 20 kilometers.

Literacy is the percentage of convicts from each county around 1800 that were literate from Nicholas and Nicholas (1992, Table 3) and height is the height of army volunteers from 1788 to 1805 from Floud (1986). Nutrition is the score given to each county by Horrell and Oxley (2012) based on information on labourers' diet collected by Eden in 1795 with values for two missing counties interpolated from a penalized spline of values from neighbouring counties.

Market potential is the sum of aggregate income (1760s wage times 1750 population) of each county weighted by the inverse distance to the centre of the county. Booksellers is the number of booksellers in 1751 measured by Dowey (2016) relative to county population in 1750. Lawyers are the number of attorneys in 1730 relative to county population from Aylett (1987).

³¹See <http://historyofwork.iisg.nl/major.php> for details of HISCO codes.

Appendix 2: Technology, Skills and Industrial Revolutions

The results of the partial equilibrium model in Figure 1 continue to hold in the general case as Anderson (2011) shows.³² There are I sectors in each region. For concreteness we can think of these as agriculture, traditional manufacturing, and skilled manufacturing. In the home region there are N unskilled workers and K skilled ones. Each sector i has $K_i = \lambda_i K$ skilled workers that are specific to it (for agriculture we can think of farmers as the skilled workers, whose number is proportional to the supply of land). It produces output

$$Y_i = A_i E_i N_i^\alpha K_i^{1-\alpha} \quad (1)$$

where A_i is the level of the sector's technology, E_i is the region's endowment of energy sources (water power, and possibly coal) available for the sector (for simplicity we suppose that energy sources are specific to sectors), and N_i is the number of unskilled workers it employs. The factor share coefficients are equal across sectors so reallocation of labour does not affect income distribution. The GDP of the home region is $\bar{Y} = GN^\alpha K^{1-\alpha}$ where the GDP "deflator" $G = \left(\sum_i \lambda_i (p_i A_i E_i)^{-1/(1-\alpha)} \right)^{1-\alpha}$. Trading with the home region is a foreign region (in this case the south of England), denoted by a star, which has its own values of skilled and unskilled labour, sectoral technology, and share of skilled workers in each sector. Between regions there are iceberg transportation costs: if the home region exports some good i then the foreign price is a multiple of the home price: $p_i^* = \theta p_i$. We set $G^* = 1$ so G denotes the terms of trade between the two economies.

Anderson (2011) demonstrates how the pattern of trade depends on the the relative productivity of sectors in the two regions

$$\Lambda_i = \left(\frac{A_i E_i}{A_i^* E_i^*} \right)^{\frac{1}{1-\alpha}} \frac{\lambda_i}{\lambda_i^*}, \quad (2)$$

and the home region will export a good i when this relative productivity is sufficiently high relative to transportation costs $\Lambda_i > G\theta$. Assuming that both regions have identical homothetic preferences, spending a fraction γ_i

³²To derive comparative statics results, Anderson assumes a continuum of sectors which is not necessary for our purposes here.

on each good and defining R as the ratio of home to foreign GDP, the GDP share of an exporting sector then equals

$$s_i = \gamma_i \left(\frac{R + 1}{R + (G\theta)^{1/(1-\alpha)} / \Lambda_i} \right) \quad (3)$$

where the bracketed term corresponds to the export intensity of the sector. We assume that the sector is sufficiently small that its growth does not affect terms of trade G or the GDP ratio R .

The crux of the dynamic part of this model is that A_i is a positive function of Y_i through learning by doing from a finer division of labor. The output share of high productivity sectors rises with market integration, and this process is self reinforcing as we will see below. Anderson (2011) shows that falling transportation costs increase factor incomes most in sectors with the highest relative productivity Λ_i while the skilled labour in the least productive, import competing sectors experience the largest falls. These rising incomes will lead to a gradual reallocation of specific factors into expanding sectors, a process originally modelled by Neary (1978), further increasing their relative productivity. Further rises in artisan numbers may occur if artisans move to the North from declining industries in the South.

We will focus on one exporting sector in the home economy (so we drop the i subscript, and also set the energy endowment equal to unity) which is a skilled manufacturing sector capable of technological progress. Specifically, its production technology A evolves according to a modified Nelson and Phelps (1966) process, depending on the gap between a frontier technology and the technology currently in use, and on the skill level of artisans S in adapting it for use in everyday production:

$$\frac{A_t}{A_{t-1}} = \begin{cases} \left(\frac{\tilde{A}}{A_{t-1}} \right)^\delta S_{t-1}^\eta & \underline{A} < A_{t-1} < \tilde{A} \\ 1 & \text{otherwise} \end{cases} \quad (4)$$

where $0 < \delta < 1, 0 \leq \eta$. The technology in use cannot exceed the frontier value \tilde{A} , and cannot fall below a minimum level \underline{A} which we can set equal to 1.

The skill of each artisan evolves according to a modified Ben-Porath (1967) equation

$$\frac{S_t}{S_{t-1}} = H_{t-1}^\sigma S_{t-1}^{-\mu} Y_{t-1}^\rho \quad (5)$$

where $0 \leq \sigma, \mu, \rho < 1$. E_{t-1} denotes investment in the young generation of workers in period $t - 1$ for acquiring technically useful skills. We think

of this primarily as some form of apprenticeship, but it may also include basic schooling. The size of the parameter σ reflects the ease of obtaining useful training, such as low barriers to apprenticeship associated with the weakness or absence of guilds. Finally we allow for learning by doing to influence skill acquisition by including sectoral output Y .

Output of the sector $Y = s\bar{Y}$. To derive a simple log-linear model we substitute equation 3 and take logs. For simplicity, we assume that the foreign economy is large relative to the home economy so R approaches zero in the sectoral share equation (3) but this does not affect the qualitative results. It follows that

$$\log Y_t = (1 - \alpha) \log A_t + \alpha \log N_t - \frac{1}{1 - \alpha} \log \theta_t + \log \lambda K + C_1 \quad (6)$$

where

$$C_1 = \left(\log \gamma - \alpha \log K - \frac{\alpha}{1 - \alpha} \log G - (1 - \alpha) \log A^* - \log \lambda^* \right).$$

It can be seen that an increase in the supply of unskilled labour N or a fall in transport costs θ will cause the output of the sector to expand. Output in this sector is higher the less productive is the foreign sector but diminishes as the number of skilled workers in other sectors rises, attracting unskilled labour away.

Each period an artisan has a single child and spends a fraction ϵ of their income on its education.

$$H = \epsilon \frac{(1 - \alpha) Y}{\lambda K}. \quad (7)$$

This education takes the form of an apprenticeship that takes place in another specialized teaching sector, and the greater the resources these masters receive the more effectively they can teach. Hence H appears directly in equation 5.

From (4) it follows that technology evolves according to the log-linear difference equation

$$\Delta \log A_t = -\delta \log A_{t-1} + \eta \log S_{t-1} + \delta \log \tilde{A} \quad (8)$$

and artisan skill evolves from (5) as

$$\begin{aligned} \Delta \log S_t = & (1 - \alpha) (\rho + \sigma) \log A_{t-1} - \mu \log S_{t-1} \\ & + (\rho + \sigma) \left(\alpha \log N_{t-1} - \frac{1}{1 - \alpha} \log \theta_{t-1} \right) + C_2 \end{aligned} \quad (9)$$

where

$$C_2 = C_1 + \rho \log \lambda K + \sigma \log (1 - \alpha) \epsilon.$$

To analyze the evolution of the system (8) and (9) it is easiest if we focus on low skills $L = 1/S$. The technology isocline $\Delta \log A = 0$ between the maximum and minimum technology levels is

$$\log L = -\frac{\delta}{\eta} \log A - \frac{\delta}{\eta} \log \tilde{A}. \quad (10)$$

while the equation of the low skill isocline $\Delta L = 0$ is

$$\begin{aligned} \log L = & -\frac{(1-\alpha)(\rho+\sigma)}{\mu} \log A - \frac{(\rho+\sigma)}{\mu} \left(\alpha \log N_{t-1} - \frac{1}{1-\alpha} \log \theta_{t-1} \right) \\ & - \frac{1}{\mu} C_2. \end{aligned} \quad (11)$$

As shown in Figure 7, the technology-skills system has four possible steady states, depending on the relative position and slope of these isoclines. In the first panel, the low skill isocline lies everywhere above the technology one so that the steady state of the economy is at the minimum skill point M where technology is at its lowest possible level $A = 1$ and skills are

$$\log S_t = \frac{(\rho+\sigma)}{\mu} \left(\alpha \log N_{t-1} - \frac{1}{1-\alpha} \log \theta_{t-1} \right) + \frac{1}{\mu} C_2. \quad (12)$$

In Panel (b) technology and skills have little impact on each other: the technology isocline is steeper than the low skill one or, equivalently, the own product terms in (8) and (9) are greater than the cross product terms. In that case the steady state is at the intersection of the two isoclines at point in which the economy is at an intermediate C .

In the third panel, by contrast, there is strong interaction between technology and skills that leads to two steady states, one at the minimum skills-technology state M and the other at the maximum level F . Which one the system converges to depends on its starting point.

Finally, in Panel (d) the technology isocline lies everywhere above the low skill one so the economy converges to the maximum technology level F .

Industrial Revolutions.

At this stage it should be evident from Figure 7 how this simple model gives rise to a rapid qualitative change in levels of skill and technology. We start

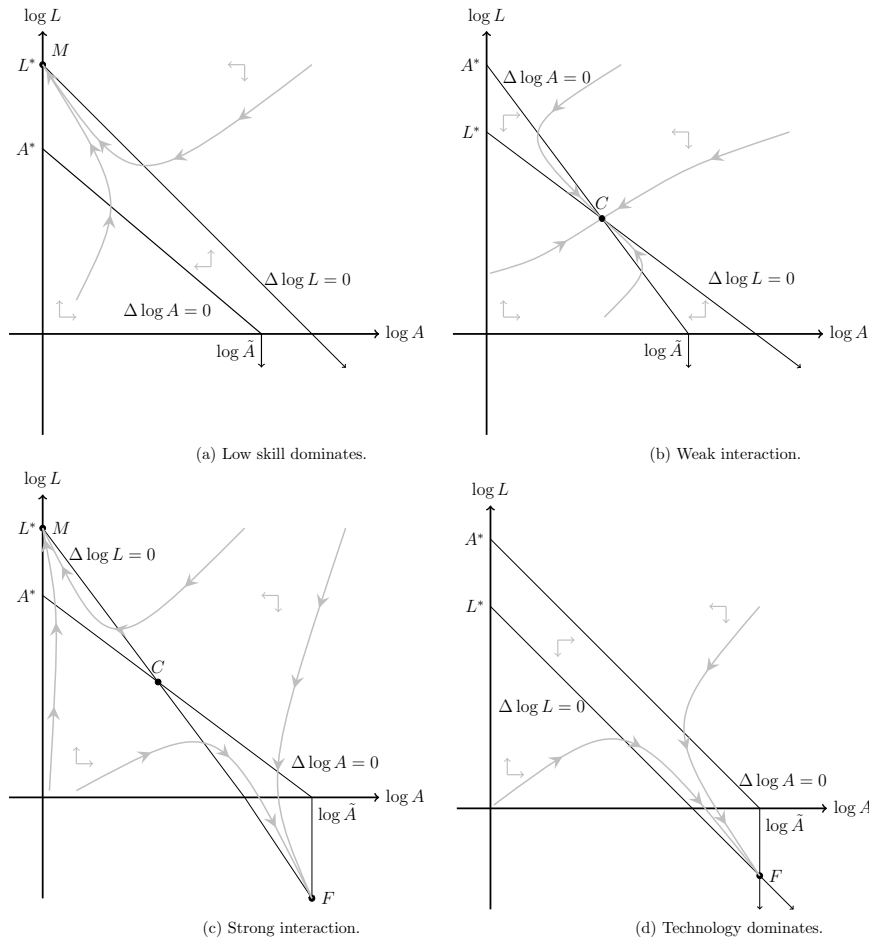


Figure 7: The four equilibria of the skill, technology system.

in the top-left panel where low skill dominates and the economy is at M , where the reciprocal of skills, L is at its highest at L^* . As transport costs θ fall and/or the supply of unskilled labour N rises the low skill isocline will shift downwards: artisan skill slowly rises.

In this setup it is easy to formally why the Industrial Revolution might be a slow and drawn-out process (as is still argued) as opposed to a more rapid and sudden process as the data suggest. What matters is the interaction between skills and technology, as shown in panels (b) and (c). In the case of a weak interaction between skills and technology in the second panel of Figure 7 this leads to a gradual rise in the level of technology and skill as

the steady state C moves down along the technology isocline: progress is incremental rather than revolutionary.

The most dynamic sectors of the Industrial Revolution, in which initial artisan skills and production technology strongly influenced each other's evolution, are described by panel (c). The course of the growth was by historical standards rapid and abrupt. The sector starts at the low skill point M (12). Skills gradually increase as transport costs fall and/or the supply of unskilled labour rises, but the economy remains stuck at the minimum technology point A^* . Eventually, the low skill isocline moves down sufficiently to intersect the technology isocline as in Figure 7c but, because the economy has started at the minimum skill point M it remains there.

Eventually, as skill continues to rise the low skill isocline falls below the technology one when $A^* > L^*$ in Figure 7d. At this stage the economy has moved into the basin of attraction of the high skill point F . In other words, the gradual accumulation of expertise eventually causes a qualitative discrete change in the economy, moving it to a high skill, high technology equilibrium.

A dynamic such as depicted in panel (b) describes sectors such as food-processing, construction, and apparel, that were less dependent on existing mechanical skills. These sectors experienced much more gradual and incremental growth. The modern sector consisted of cotton and other textiles, iron smelting and refining, engineering, machine tools, some heavy chemicals, mining, some parts of transportation, and a few consumer goods such as pottery and paper. At first, however, only segments of these industries underwent modernization, so that dualism existed within as well as between various products, which makes calculations about the performance of the modern sector rather tricky (Mokyr, 1999, pp. 12-13.) The actual experience of the aggregate British economy was, of course, a combination of such abrupt and incremental advances, and descriptions that emphasize this duality of a "modern" and "traditional" sector are consistent with this model.

Extensions.

To reduce the exposition to its bare essentials we have supposed that the only factor that changes is skill so that only the L isocline shifts. Historically however we would expect rising skill to increase the basic technology in use \underline{A} and perhaps also the frontier level \tilde{A} . A rise in the minimum technology level shifts the y axis in Figure 7 rightwards so that the technology in use will rise gradually before a jump to the high steady state. Similarly,

an increase in the frontier technology \tilde{A} will cause the technology isocline to rotate outwards, accelerating the transition to the high steady state. A main reason for the frontier technology to shift out is the closer integration of science with skills and production technology, the main thrust of the Industrial Enlightenment (Mokyr, 2009; Jacob, 2014; Wootton 2015).

Other extensions to the basic models are possible. As noted in Section 5 rising artisan income will attract in the specific factors from other, less successful sectors, in particular if it leads parents to apprentice their child in one of these successful sectors. This flow of skilled labour into successful sectors will, from (9) cause skills to rise faster in the industrializing region and the same process will accelerate the expansion of agriculture in the other region.

In addition to skilled manufacturing and agricultural sectors, we can add traditional manufacturing sectors where the specific factors are putting-out entrepreneurs who supply raw materials to unskilled workers and buy back the finished goods. It is then possible to allow improved technology to diffuse to these sectors once advanced ones have experienced a takeoff.

The assumption that the supply of unskilled labour N rises exogenously may also be relaxed. If the expansion of home manufacturing increases real wages then unskilled labour can be drawn in from the other region: as we have seen that population of industrializing regions of England rose rapidly and stagnated elsewhere. Labour supply may be further endogenized if a Malthusian component is added to the model but this is empirically irrelevant: as Kelly and Ó Gráda (2014) demonstrate, the positive check had long disappeared from England by the mid-eighteenth century.

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