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THE INDUSTRIAL REVOLUTION IN THE UNITED STATES: 1790-1870

Joshua L. Rosenbloom

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ABSTRACT

This chapter explores the distinctive trajectory of American industrialization up to 1870, emphasizing how the United States adapted and transformed British technologies to suit its unique economic and resource conditions. Rather than a straightforward transfer of innovations, the chapter argues that American industrial development was shaped by path-dependent processes and historical contingencies—such as the Embargo Act of 1807 and government sponsorship of firearms production—that enabled the emergence of a domestic innovation ecosystem. The chapter offers fresh insights into how high-pressure steam engines, vertically integrated textile mills, and precision manufacturing techniques evolved in response to labor scarcity, capital constraints, and abundant natural resources. A particularly novel contribution is the detailed analysis of how American manufacturers substituted mechanization and organizational innovation for skilled labor, leading to the development of technologies that were not only distinct from their British counterparts but also foundational for the Second Industrial Revolution. The chapter also highlights the democratization of invention, showing how economic incentives and institutional support fostered widespread innovation among ordinary citizens. By integrating technological, economic, and institutional perspectives, this chapter provides a compelling explanation for why the United States developed a robust manufacturing sector despite seemingly unfavorable initial conditions.

Joshua L. Rosenbloom
Iowa State University
Economics Department
and NBER
Jlrosenb@iastate.edu

1. Introduction

The British Industrial Revolution marks a turning point in world history, initiating a period of sustained technological innovation and economic growth. Identifying precisely when growth began in the United States is made difficult by the limited statistical data available before the beginning of the nineteenth century. It is indisputable, however, that the turning point came sometime between 1790 and 1830, and that the rate of growth accelerated across the nineteenth century. Although technological borrowing from Britain played an important role in the American take-off the emergence of a distinctive American system of technology was readily apparent by mid-century and provided the foundation for even greater growth after 1870.

A distinctive feature of the American growth experience was the combination of growth in per capita incomes with the expansion of the size of the U.S. economy. In the century after 1790, American population increased more than fifteen-fold. As a result, while real per capita GDP increased by a factor of about three, aggregate GDP increased by a factor of approximately fifty.[1] The ability to combine rapid intensive and extensive growth was a consequence of the resource abundant and labor-scarce conditions that characterized the U.S. economy in this period.

Bringing American resources into production required the application of technologies developed in Europe, especially Britain. In turn, this required that these technologies be adapted to American conditions. This adaptation was made possible by the emergence of a domestic community of innovators with the necessary technological skill. As this community emerged its members shifted increasingly toward the development of uniquely American innovations.

While there is a substantial literature concerned with the industrial development of the United States before the Civil War is has tended to focus either on the histories of leading industries, such as cotton textiles, or on those industries that would become important later in the nation's development, such as precision manufacturing and machine tool production. The primary concerns of this literature have been to explore the importance of tariff protection in promoting industry growth, and the role of relative factor proportions in explaining the emergence of a distinctive "American System" of manufacturing.[2] What is missing from this literature is a broader perspective on the interplay between technology transfer and domestic innovation in the development of the U.S. economy up to 1870. It is this gap that this chapter seeks to fill.

In view of the relatively rich literature on specific industries, the central question posed by the history of American economic growth before 1870 is less how it occurred than why the United States developed a significant manufacturing sector at all? Considering its resource abundance

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[1] All comparisons rely on data from http://measuringworth.com, retrieved 3/12/2024.

[2] On the role of tariffs see, e.g., Tausig (1931), Bils (1984), Harley (1992), and Irwin and Temin (2001). On the role of factor abundance see, e.g., Habakuk (1962), Rosenberg (1969), Temin (1971), David (1975, ch. 1), and Hounshell (1984)

and labor and capital scarcity, the country's comparative advantage would appear to have been in primary production and processing, not in manufacturing. Adam Smith (1776, pp. 347-48) made precisely this point in the *Wealth of Nations*, observing that:

> Were the Americans…to stop the importation of European manufactures, and…divert any considerable part of their capital into this employment [that is, manufacturing], they would retard instead of accelerating the further increase in the value of their annual produce, and would obstruct instead of promoting the progress of their country toward real wealth and greatness.

Although Alexander Hamilton, in his 1792 *Report on the Subject of Manufactures*, sought to refute Smith's negative assessment, and laid out a set of policy prescriptions intended to advance American manufacturing, his recommendations received little support in Congress, and there was no concerted government effort to promote the growth of industry (see Sylla 2024).

In the absence of a concerted government effort to promote manufacturing, I argue in what follows that American industrialization was the consequence of a combination of fortuitous accidents whose effects were compounded by the fundamentally path dependent nature of the process of economic development. I begin by briefly reviewing the evidence of the aggregate growth of the U.S. economy, before turning to an examination of the developments that gave rise to this economic growth. Key to the acceleration of economic growth was the trans-Atlantic diffusion of the key technologies of the British Industrial Revolution: steam engines, iron, and factory production of cotton textiles. Americans appear to have been well informed about developments in Britain, but their ability to apply these innovations was constrained by differences in the relative quantities and nature of factor inputs available as well the needs of American consumers. After describing the diffusion of British technologies, I turn to the development of precision manufacturing, which has been singled out as an exemplar of a distinctively "American System" of manufactures, before considering more general evidence about the innovation econmomy in the early nineteenth century. The chapter concludes with an effort to draw more general lessons from this history.

2. Aggregate Economic Growth

In the late 1700s, the American economy already enjoyed a comparatively high standard of living. According to the Maddison Project Database US per capita GDP in 1800 was $2,545 (in 2011 prices), about 75 percent of the level in the United Kingdom, the world's most advanced economy at the time.[3] International comparisons of this sort are quite sensitive, however, to decisions about how to convert between currencies and account for cross-country differences in relative prices of goods and services. Lindert and Williamson (2016, pp. 103-16) have argued that income per capita was higher in America than in the United Kingdom at this time because the costs of basic consumption goods were relatively lower in America, and luxury goods were more expensive.

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[3] The Maddison Project data can be accessed here https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2020 .

Continuous estimates of U.S. GDP per capita begin only in 1790. But the evidence for the years before 1800 suggests that GDP per capita was essentially constant, despite significant fluctuations over periods of 10-20 years. In the most careful analysis of the available data Mancall and Weiss (1999) concluded, for example, that per capita GDP increased only from $64 to $67 (In prices of 1840) between 1700 and 1774.[4]

In contrast to the stability of per capita GDP before 1790, the years after 1790 were characterized by sustained and accelerating increases in per capita GDP. Figure 1 traces this growth of Real Gross Domestic Product (GDP) per capita. The rate of growth was initially quite slow, averaging only about 0.6 percent per year between 1790 and 1830. After 1830, the growth rate accelerated to 1.1 percent per year from 1830 to 1870. It accelerated again after 1870, and reached almost 2.2 percent per year in the two decades from 1870 to 1890.

The growth accounting framework pioneered by Robert Solow (1957) and Moses Abramovitz (1956) provides a way to think about the proximate sources of this growth. In this approach, the growth of GDP per capita (y) can be decomposed into changes in aggregate inputs of labor (l) and capital (k) per capita and increases in the efficiency with which these inputs are converted into output. Mathematically, this decomposition begins by expressing aggregate output per capita, *y*, at time t as a function of per capita inputs of capital and labor (*k* and *l*), and a technology index, A:

$$(1) \qquad y_t = A_t * f(k_t, l_t)$$

If Equation (1) describes the determinants of output per capita at a point in time, the contributions to growth in output over time can be expressed as a simple linear approximation:

$$(2) \qquad y_t^* = A_t^* + \alpha k_t^* + (1-\alpha) l_t^*$$

Where the rate of growth of each variable is denoted by an asterisk, and a is the marginal product of capital.[5]

Equation (2) is widely used in the growth accounting literature to decompose the observed rate of growth into components attributable to increases in the factors of production per capita and Total Factor Productivity (TFP). TFP cannot be observed directly. Instead, the unobserved

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[4] It is true that the colonial economy grew rapidly in size due to rapid rates of population growth. Some earlier scholars interpreted this as signaling that there must have been an increase in per capita incomes. However, Mancall and Weiss show that any meaningful increase in per capita GDP would have been inconsistent with a variety of other evidence on colonial economic performance, a point that is reinforced by careful consideration of economic growth in the Lower South and Mid Atlantic regions (Mancall, Rosenbloom and Weiss 2004 and Rosenbloom and Weiss 2014).

[5] If the aggregate production function takes the Cobb-Douglas form, equation (2) is an exact representation of the contributions of labor, capital and technology. More generally, equation (2) can be interpreted as a first-order approximation to the true, but unknown, aggregate production function.

contributions of TFP are inferred by subtracting the contributions attributable to the growth of inputs per capita from the observed growth of output per capita. That is:

$$(3) \qquad TFP = y_t^* - \alpha k_t^* - (1-\alpha) l_t^*$$

It is tempting to equate the value of TFP calculated using equation (3) with the growth of A, the technology index in equation (1). That is to see it as a measure of the contribution of technological progress. However, it is important to note that TFP is measured as a residual derived by subtracting one set of measured quantities from another. As Abramovitz (1993, pp. 218-19) summarizes, TFP should be seen as a "measure of [our] ignorance about the source of growth." If, for example, inputs are mismeasured because we fail to adequately capture intangible forms of investment (such as education or on-the job training, that enhance the productivity of labor) then TFP will be overstated and the contribution of the growth of inputs will be understated. Although this suggests that TFP is an upper bound estimate of the contributions of technological progress, Abramovitz cautions that this is not the case because the underlying premise of equation (3) is that the sources of growth – factor inputs and technological progress – are independent of one another. More technically, that technological change is "factor neutral." If, instead, technological progress is not neutral, so that it differentially enhances the productivity of one or another input, this will encourage increases in the use of this factor and result in an understatement of the true contributions of technological change (Abramovitz 1993, pp. 221-22).

Despite these limitations of our ability to measure technological progress at the aggregate level, it is, nonetheless, helpful to begin by considering the available evidence about the growth of inputs and outputs for the economy. Table 1 reports one of the most careful efforts to decompose of the sources of growth over two successive eras of the nineteenth century. In contrast to the experience of the twentieth century, when comparable calculations have found that TFP is the dominant contributor to the growth of per capita GDP, Table 1 implies that between four fifths and three quarters of nineteenth century economic growth was attributable to increases in inputs per capita. In both subperiods, high rates of immigration, slowing fertility (which increased the proportion of the population of working age) and increased engagement in the market economy all combined to increase the labor force participation rate. Increased capital per person played a relatively modest role in the first half of the century (accounting for just 0.19 percent per year of growth before 1855). In the second half of the nineteenth century, however, capital investments emerged as the most important source of growth. The increase in capital was accompanied by a near doubling of the contribution of TFP to growth, and together these two factors help to explain the acceleration in growth rates over the century.

Put differently, the growth of the American economy in the nineteenth century reflected both technological advances that increased the efficiency with which inputs were converted into outputs and the accumulation of inputs, especially investments in physical capital. The relative contributions of factor accumulation and the residual was quite different in the nineteenth century than in the twentieth and twenty first centuries. While technological progress has been the dominant source of growth since the late nineteenth century, it made more modest contributions during the period that is the primary focus of this investigation. Even though the calculations underlying Table 1 imply that the contribution of TFP growth was relatively modest, we will see that technological innovations played an important part in making the aggregate expansion of the American economy possible and contributed to the accumulation of inputs per capita that were the more important source of growth in this period.

3. Technology Transfer and the Emergence of a Distinctive American Technology

The key technologies of the British Industrial Revolution centered around the application of steam power to a broadening array of uses, the substitution of iron (and later steel) for wood, the application of factory methods of production, and the mechanization of production, especially in cotton textiles, which was accompanied by a shift from domestic to factory production. The power of these innovations owed much to their interrelated nature. Steam engines unlocked vast stores of power available in fossil fuels (coal) that could power industrial processes and transportation. Iron was necessary both for building steam engines and for the construction of new industrial machinery driven by steam power. Factories were made possible and, in some cases, necessary by the centralized power source represented by the steam engine.

How and how quickly these British innovations diffused to other countries is a central question in the history of the Industrial Revolution. Over the course of the eighteenth century, the British Parliament passed several acts intended to prevent the international diffusion of novel technologies, especially those revolutionizing the manufacture of textiles (Henderson 1955, pp. 4, 7, 139-41). These acts made the export of plans, drawing and models illegal, and prohibited the emigration of skilled craftsmen. These efforts were largely ineffective, however. In most cases, it appears that the first overseas application of most new British technologies occurred within less than a decade of their introduction in Britain.[6]

United by a common language and long colonial relationship, technology transfer between Britain and the United States was typically quite quick. Indeed, in some cases Americans introduced British technologies ahead of continental Europe, even though doing so required subterfuge. A 1787 plan hatched by the American Tench Coxe to spirit plans for Richard Arkwright's water frame out of Britain, for example, was foiled by British customs officials, but Coxe was able to secure models of the machines by other means within a year (Licht 1995, p. 1).

Obtaining the information necessary to replicate British innovation, however, was in many cases the easy part of the process of diffusion. More challenging was making these new techniques profitable under circumstances that differed substantially from those for which they were first developed. This was especially true in the United States, where shortages of labor, both skilled

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[6] According to unpublished notes compiled by Gregory Clark, the first Newcomen Engine was in use on the continent in 1721 (9 years after its introduction in Britain), the first use of the Spinning Jenny on the continent was in 1772 (a 4 year lag), the Water Frame was first used on the continent in 1779 (a 10 year lag), the Mule first appeared on the continent in 1799 (a 20 year lag) and the Watt engine was introduced on the continent in 1778 (just 3 years after it was patented; and only 4 years after the first engine was put in use).

and unskilled, scarcity of financial capital, low population density, and differences in resource endowments meant that manufacturers faced very different combinations of factor inputs and product demands than in Britain.

As the remainder of this section details, American conditions produced a substantially different pattern of diffusion of steam power than Britain. Meanwhile resource constraints held back the growth of American iron production. Although American textile producers also confronted significant challenges, a series of chance events helped to launch the industry in the early nineteenth-century. Shaped by American circumstances and competition with already established British textile producers, the U.S. cotton textile industry followed a distinctive path of development, which, in turn, exerted an influence on other aspects of U.S. industrial development in the nineteenth century.

Steam Engines in North America

The first steam engine in North America was ordered from Britain in 1748 and erected five years later, in 1753. By the 1790s or earlier American mechanics and iron founders had begun to cast and assemble the parts of domestically produced atmospheric engines. By this time Americans had also begun to correspond with Boulton and Watt about their condensing engine, but the first order, from Robert Fulton, was not placed until 1803. By this time, however, British immigrants had brought the knowledge necessary to construct Watt engines to the U.S., and the majority of such engines were produced domestically. At first the firms established by these immigrant mechanics concentrated in New York and Philadelphia, but by the 1820s steam engine manufacturing was also taking place further west, in Pittsburgh (Tann and Breckin 1978, pp. 548, 550, 559).

Reflecting the emerging American mechanical ability in this domain, the American Oliver Evans introduced a high-pressure steam engine in the United States at roughly the same time that Richard Trevithick demonstrated the first high-pressure engine in Britain (Temin 1966, p. 188). Born in 1755, Evans had grown up on a Delaware farm and apprenticed as wheelwright. Wheels were the basic component not only of carts and wagons but of the machinery in mills and factories, making the transition to millwright a natural one for an ambitious young man. In the 1780s Evans developed a novel system of continuous process grain milling. By the 1790s, he had turned his attention to the design of steam engines, perfecting a small working model sometime before 1802. In 1804 he secured a patent for his design (Hunter 1985, pp. 34-37).

In comparison to the low-pressure Watt engines, Evans' high pressure engine design was compact and light, making it well suited to applications such as transportation. The smaller size also made it easier to construct. While only a few American machine shops in the 1820s were capable of machining the cylinder of a 24 horsepower low-pressure engine, most general machine shops at the time would have had the capacity to machine the much smaller cylinder of a comparably powered high-pressure engine (Halsey 1981, p. 729).[7] The ability to fabricate parts closer to where they would be installed lowered transportation costs and hence the overall purchase price of high-pressure engines. On the other hand, high-pressure engines were less fuel efficient, raising operating costs. As a result, the choice of high- vs. low-pressure engines came down to a trade-off between fixed and operating costs that was determined largely by the combination of interest rates and fuel costs at a particular location (Halsey 1981).

In most parts of the United States, the ready availability of low-cost firewood for fuel and the high cost of capital made the high-pressure engine the preferred choice. By comparison, in Britain at this time, capital was less expensive and fuel more expensive, slowing adoption of high-pressure engines. Not only were high pressure engines used to power steamboats on western rivers, but they quickly predominated among stationary engines as well. The small number of low-pressure engines in use were found primarily in more densely settled parts of the Northeast, where fuel was less accessible and capital more readily available to finance their construction.

Systematically tracking the diffusion of steam technology before 1850 is challenging because the existing sources are incomplete in their geographic coverage and are not entirely consistent with one another (Atack, Bateman and Weiss 1980, p. 283).[8] While steam engines were quickly adopted to power shipping on interior rivers, their use as a source of factory power grew much more slowly. Compared to Britain, waterpower sites capable of operating a factory were much more abundant in the United States, especially New England, where much early factory development took place. As a result, Atack, Bateman and Weiss (1980, p. 282) estimate that waterwheels likely outnumbered steam engines in industrial settings by 100 to 1 in 1820, when only about a dozen steam engines were being used in factories.

After 1820, rates of steam engine adoption accelerated. In 1838, responding to the growing number of accidents associated with steam engines, the Secretary of State sought to compile information on their numbers and location. At this time, roughly 64 percent of steam engines in use were employed in transportation, mostly powering steamboats. The remaining 36 percent were fixed engines, powering industrial uses, used municipal water supplies or other purposes. Table 2 summarizes data on the number of fixed steam engines by location. In some cases, the horsepower was also recorded, but in the absence of consistent methods to estimate horsepower it is not clear precisely how these estimates were compiled. Close to half of the steam engines and more than 50 percent of the horsepower at the time was found in western states. In terms of industrial distribution, American use of steam diverged substantially from that in Britain. Whereas steam engines in Britain were used widely in coal mining and textile

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[7] The cylinder bore was the largest machined surface of a steam engine. For a high-pressure engine rated at 24 horsepower, it would measure about 9 inches. In diameter and 40 inches in length. A comparable low-pressure engine cylinder would have had a diameter of about 26 inches and a length of 5 feet. Halsey (1981, p. 729) argues that in 1825 only a few machine shops in New York and Philadelphia would have been capable of handling such a casting.

[8] Hunter (1985, pp. 69-102) provides a detailed summary and discussion of the various efforts to catalog steam power in the U.S. before 1850.

production, in the U.S., steam engines were used primarily in processing raw materials – in grist mills, flour mills, sugar mills, tanneries, distilleries, sawmills and iron work. Textile factories relied primarily on waterpower (Hunter, pp. 74-75).

Atack, Bateman and Weiss (1980, pp. 285-88), used the data on from 1820, 1838, and the decennial Censuses of Manufactures beginning in 1850 to estimate regional diffusion curves for steam engines. Their calculations suggest that only between 10 and 20 percent of plants had adopted steam by 1840. Ten years later, when the census of manufacturers first collected systematic data on steam engines, the number of steam-powered plants was nearly equal to those relying on waterpower.

By the mid-1830s the ability to produce steam engines appears to have been relatively widely dispersed. Temin (1966, p. 190), observes that almost 250 distinct builders were identified as having produced the steam engines identified in the 1838 report. Most builders served local markets and had produced five or fewer engines. The major exception being in the South, which relied more heavily on suppliers outside the region. In terms of regional distribution, more than 80 percent of steam engines were concentrated in the northern part of the country.

The slow and uneven diffusion of steam in industrial production appears to reflect the competing costs of alternative power source. By the 1820s there were a number of contemporary estimates of the comparative costs of steam and waterpower, but, as Atack, Bateman and Weiss (1980, p. 288-89) caution, these were primarily produced by advocates for one power source or the other, so they should be taken with some degree of skepticism. As an alternative, Atack, Bateman and Weiss (1980, pp. 293-95) gathered data on fixed and operating costs of water and steam power at different dates and locations and then combined these costs using a Monte Carlo simulation to generate the likely distribution of cost for each power source by decade from 1830 through 1900. In each instance the range of costs of the two power sources overlap one another, suggesting that the relatively slow pace of adoption of steam was economically rational rather than a sign of entrepreneurial inertia. They also found that costs of both sources of power declined substantial over time.

Recently Hornbeck et al (2024) have revisited the question of the diffusion of steam power relying on newly compiled data on power sources used in lumber and flour mills drawn from the manuscript censuses of 1850 through 1880. Their analysis finds that the diffusion of steam power was driven by the decline in fixed costs of steam engines over time, which made them competitive at lower production scales. However, switching costs faced by incumbents who had already committed to waterpower resulted in inefficiencies in the diffusion process.

Although American industrial development in the first half of the nineteenth century was not greatly affected by the relative slow pace of diffusion of steam engines as a source of factory power, steam engines played a much more important role in accelerating improvements in transportation. Americans were quick to apply steam engines to power shipping on inland waterways. Steam powered shipping greatly lowered costs of upstream travel, and rapid improvements in ship design meant that the productivity of shipping improved substantially.

Rising utilization rates also contributed to falling unit costs (Mak and Walton 1972, pp. 628-35). According to Mak and Walton (1972, p. 624), the productivity of shipping on the Ohio, Mississippi and Missouri rivers increased more than 10-fold in the period 1815-1860. For the most part these advances seem to have arisen through learning-by-doing. And advances spread quickly because of the relatively rapid depreciation of capital and the correspondingly rapid rate of diffusion of advances in design.

Where water transportation was not viable, Americans were quick to deploy railroads. The first steam railway in the United States, The Baltimore and Ohio, began construction in 1827, essentially contemporaneous with the introduction of steam railroads in Britain. By 1830 the United States had 23 miles of track in operation. This figure increased to over 2,800 miles by 1840, and continued to grow rapidly thereafter, reaching more than 30,000 miles in 1860, on the eve of the Civil War (Carter et al 2006, series Df874). Although early steam locomotives were imported from Britain, U.S. manufacturers were soon turning out virtually all of the equipment used in North America.

Improvements in transportation by water and rail were a central contributor to the growth of the U.S. economy across the nineteenth century. Falling transportation costs and the increased speed of movement opened vast areas of the interior for settlement and integration into the national and global economy. The ongoing addition of land on the frontier created a persistent regional disequilibrium that attracted mobile labor and encouraged capital investments that were manifested in the nation's rapid extensive growth. This growth, in turn, encouraged the growth of urban centers and contributed to rising demand for products of the industrial sector.

Energy and Industry

An important aspect of the process of economic change initiated by the Industrial Revolution was that steam engines enabled the application of vastly more power per capita, which undoubtedly played a role in increasing the productivity of labor and capital. Associated with the rising energy intensity of production was the shift from traditional sources of power to fossil fuels (initially coal, and later petroleum). Malanima (2022) has sought to comprehensively measure energy consumption – including food and fodder by humans and animals, respectively – since 1820. The result is a set of estimates of total energy consumption expressed in terms of the caloric equivalent of tons of oil (Toe) consumed.

Reflecting the resource abundance of the United States, energy consumption per capita in in 1820 was 2,561 Toe, two- and one-half times that of the United Kingdom, and close to five times that of Western Europe (including the United Kingdom). On the other hand, the relatively small scale of the industrial sector in the U.S. and the longer reliance of industry on waterpower (excluded from these calculations) meant that the energy intensity grew much more slowly in the U.S. than it did in the United Kingdom or Western Europe for most of the nineteenth century. By 1870, U.S. energy usage per capita had increased only modestly, growing just 8 percent, to 2,778 Toe. By comparison energy use in the United Kingdom more than doubled, reaching 2,274 Toe, while it grew by almost 80 percent in Western Europe.

Iron and Steel

Iron was an essential ingredient of the Industrial Revolution. The substitution of iron for wood in industrial machinery, construction and other uses was an important contributor to technological advances across the economy, and the steam engine would not have been possible without it. Refining iron was, essentially, a chemical process. As such the characteristics of the product were highly dependent on other elements contained in iron ore and in the fuel used to extract the iron from this ore. Blast furnaces produced primarily pig iron or cast iron, both of which had relatively high carbon contents, making them relatively brittle. Converting pig iron to wrought or bar iron required removing the carbon by heating and hammering the heated metal.

The transition to cheap and abundant iron began in Britain with the substitution of coke for charcoal to fuel blast furnaces. Although the use of coke was introduced by Abraham Darby in 1709, this innovation did not diffuse widely until the last quarter of the eighteenth century.[9] Meanwhile, Henry Cort's introduction of the puddling and rolling process in 1783 greatly reduced the cost of converting pig iron into the more malleable wrought iron. These innovations transformed Britain from a major importer of iron at the beginning of the eighteenth century to the world's leading producer and a major exporter of iron by the beginning of the nineteenth century (Temin 1964, pp. 13-19; Allen 1979).

The earliest efforts to produce iron in North America date to the mid-1600s, and by 1700 American colonists were producing about 1,500 tons of iron annually, about two percent of world production. Output grew over the course of the 18th century, so that by the early 1770s, the colonies were producing about 30,000 tons of iron. Most of this was consumed domestically, but exports of bar iron were close to 2,500 tons and those of pig iron around 6,000 tons (Historical Statistics 2006, Eg706-709; Temin 1964, p. 13).

Despite the evident advantages derived from switching to coke to fuel blast furnaces and the adoption of puddling and rolling to produce wrought iron, American iron manufacturers continued to rely on traditional methods and fuels into the 1830s. While Americans were aware of the advantages of the new technologies, they lacked access to adequate supplies of cheap coal until the opening of the Lehigh Canal in 1818 provided access to the anthracite coal regions of northeastern Pennsylvania. Even then, however, efforts to utilize this fuel were stymied by the much higher carbon content of anthracite coal as compared to the bituminous coal used in Britain (Stapleton 1978, pp. 147-50; Knowles and Healey 2006, pp. 613-16).

Only in the early 1840s was a solution found, when the the Lehigh Coal and Navigation Company induced a Welsh iron producer, David Thomas, to help them introduce the newly developed hot blast method of making iron using anthracite coal. Other eastern Pennsylvania iron producers took notice of this innovation and soon erected anthracite furnaces. Meanwhile, the discovery of bituminous coal deposits in western Pennsylvania at around the same time

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[9] Some sources suggest that the first use of coke was not until 1713.

encouraged the emergence of mineral-fuel iron production in that part of the state (Knowles and Healey 2006, pp. 614-22).

Even after adopting mineral fuel, though, the U.S. iron industry remained uncompetitive on the world stage, and the U.S. relied heavily on imported iron. Robert Allen's (1979, pp. 920-24) analysis showed that around 1850 U.S. manufacturers faced considerably higher fuel costs per ton than their British competitors, as well as higher labor costs. Higher fuel costs reflected in large part differences in the chemical composition of iron ores and coal, which required more fuel to remove impurities. Allen attributed higher American labor costs primarily to the fact that U.S. manufacturers remained less mechanized than British producers. Only in the 1890s, did the competitive position of U.S. iron makers shift. This was due primarily to the drop of iron ore prices in the U.S. as a result of the opening of mining in the Mesabi range of Northern Michigan, while the costs of British iron ore were increasing (Allen 1979, pp. 928-29).

Cotton Textiles

In the years after 1760, the British cotton textile industry experienced a remarkable succession of mechanical innovations that vastly increased the quantity of cotton yarn that could be spun by one worker. The essential breakthrough was the introduction of machines that replaced human fingers in spinning cotton fibers into yarn. Richard Arkwright's water frame, patented in 1769, successfully employed a pair of rollers to accomplish this. James Hargreaves' spinning Jenny, patented in 1770, introduced an alternate approach relying on the spinning motion of the wheel itself. Crucially Hargreaves' device employed multiple spindles allowing an increase in the quantity of yarn spun. The resulting yarn was uneven in quality, however, and could be used only for the weft –the crosswise threads on the loom. In 1779, Samuel Crompton, combined the Arkwright rollers with the multiple spindles of the Jenny creating a device that could produce finer, stronger, and more uniform yarn which could be used for both the warp and weft. Because it combined the two earlier technologies his innovation was dubbed the "mule" (Mokyr 1990, pp. 96-98).

Recognizing the value of these innovations, Britain prohibited both the export of advanced machinery and the emigration of artisans skilled in the manufacture of textile machinery. These efforts to prevent the diffusion of cotton spinning technology were largely futile, however (Jeremy 2004, pp. 95-96). Within 5 years of Hargreaves' patent on the spinning jenny two 24 spindle jennies were in operation in Philadelphia—one built by an immigrant weaver, and another by a local craftsman.

Other aspiring manufacturers, including William Almy and Moses Brown in Providence, Rhode Island, actively sought to recruit British mechanics with knowledge of new spinning machinery. By 1790, they had entered a partnership with a British immigrant, Samuel Slater to establish a water powered spinning mill using a version of the Arkwright water frame. In contrast to the spinning jenny, which was hand powered and required a skilled operative, the water frame, as its name suggests, relied on water-power and largely dispensed with the need for skilled operatives, who were in scarce supply in the United States. The workforce of Slater's first mill, for example, consisted of 10 children drawn from surrounding farms and one adult supervisor (Ware 1931, pp. 20-21).

One measure of textile capacity is provided by the number of spindles in use to produce cotton yarn. Table 3 reports data on spindles in operation in the United States and Britain beginning in 1800. At that time, the U.S. industry had just two thousand spindles in operation, compared to 3.3 million spindles in Great Britain. Economies of scale and the lower costs of capital and labor in Britain meant that even after accounting for the costs of trans-Atlantic shipping British cotton cloth and yarn could be sold at lower cost in the United States than domestically produced products. Starting from this unpromising base, however, the United States emerged by the late nineteenth century as the world's second largest textile producer, and by the 1880s, it had roughly 1/3 as many spindles in operation as did Britain.

During the 1790s international developments increased pressure from imports on American producers. The start of Napoleonic Wars in Europe in 1793 prompted British producers to expand their North American export markets to compensate for the loss of sales on the continent. Between 1793 and 1807, the value of British exports to North American increased from £1.6 to £10.2 million. Irwin and Temin (2001) estimate that in 1807 the value of cloth produced by mills in New England was only about 8 percent of the value of cloth imported from Britain.

The situation faced by American textile firms shifted dramatically in December 1807, however, with Congress' passage of the Embargo Act, which prohibited trade with both Britain and France. Since the start of the British-French conflict in 1793, American merchants had exploited the opportunity created by American neutrality to greatly expand their trans-Atlantic shipping operations. By the early 1800s, however, British and French navies had begun to intercept American ships. Lacking the naval strength to protect American merchants, however, President Thomas Jefferson instead, sought to halt these attacks by blocking all trade with countries that threatened U.S. shipping.

The embargo did little to persuade the British and French to cease interfering with American ships, but it did provide domestic producers nearly complete protection from import competition while simultaneously preventing southern producers of cotton from exporting their crop to British producers. With export markets for raw cotton inaccessible, prices of this input fell while prices of finished cloth increased. The profit opportunities created by the widening gap between the prices of finished products and raw materials prompted a spate of new mill incorporations. Figure 2 illustrates these trends, tracing the near doubling in the ratio of cloth to cotton prices between 1807 and 1814 and the corresponding rise in the number of textile mills in operation.

Meeting growing domestic demand also prompted a spate of innovations. The shortage of skilled hand weavers needed to convert cotton yarn into finished cloth proved a particularly challenging bottleneck. Almy and Brown's mill, for example distributed yarn to weavers as much as 20 miles distant from their mill and then collected finished cloth. But securing regular deliveries from these weavers proved difficult. Almy and Brown observed in 1809 that “we have several hundred pieces now out weaving…but a hundred looms in families will not weave as much cloth as ten at least constant workmen” (Ware 1931, pp. 50-53).

Francis Lowell, a Boston merchant who had spent several years in Scotland where he had observed British textile technology took a different approach, developing plans for a water powered loom that would dispense with the need for hand weavers. In 1813, Lowell and several other partners established the Boston Manufacturing Company with the goal of integrating spinning, weaving and the other steps necessary to converting raw cotton into cloth within a single factory (Dalzell, 1987, pp. 5-25; Rosenbloom 2004, pp. 375-81). Automating weaving posed several challenges. Early mechanical looms required strong warps to avoid excessive breakage and could not easily be adjusted to accommodate a range of different yarns. Lowell’s decision to focus on producing a single type of fabric, a heavy sheeting made from relatively coarse yarn, can be seen as an adaptation to these constraints (Temin 1988, p. 894). Not only did the coarse yarn hold up better to the stresses of mechanized production, but focusing on a single product eliminated the need for flexibility either in spinning or in weaving. Another benefit of Lowell’s strategy was that the company’s product was well calibrated to meet the needs of the American market for a functional and long wearing fabric.

In addition to the narrowly technological issues that Lowell confronted in establishing the Boston Manufacturing Company, he also had to find a source of labor for his factory. His solution was to mobilize young women from rural parts of New England. As Field (1978) argues, competition from midwestern farms and the migration of young men out of New England created this potential pool of factory labor in the first half of the nineteenth century. The Boston Manufacturing Company and other textile producers in its wake actively recruited among these women and constructed dormitories near the factories to house them. In effect, by choosing to specialize, Lowell was able to substitute higher quality raw materials and special-purpose machinery for relatively scarce skilled labor.

The Boston Manufacturing Company commenced production in January 1815, putting a total of 2000 spindles into operation just as the Treaty of Ghent was ratified, bringing the War of 1812 to an end. The cessation of hostilities brought a flood of imported fabric, which caused the relative price of cloth to plunge (see Figure 2), although given the time involved in overseas trade it was not until 1816 that the full effects were felt.

The tariffs that Congress had enacted in 1812 to finance the military effort, and which provided domestic manufacturers with some level of protection, were set to expire one year after the end of the War. Without new tariffs, prices seemed likely to fall further, increasing the pressure on domestic producers. In early 1816 Congress began discussing a revised schedule of import duties. But the environment in which this discussion took place was fundamentally different from that before the war. Whereas before the war there were few domestic groups interested in import protection, now textile manufacturers throughout New England, who had made costly investments in manufacturing capacity, were dependent on continued protection from international competition. Many of them appealed to Congress seeking the imposition of protective tariffs on imported of cloth. At the same time, however, protective tariffs were opposed by consumers in other regions, who recognized that duties would increase the prices they paid for manufactures, and by Southern cotton growers who feared that continued tariffs would harm the British textile industry which was the major consumer of their product.

Confronted with these opposing interests, Lowell advocated for a relatively modest ad valorum duty, coupled with a minimum valuation for cotton imports of 25 cents per yard. The minimum valuation meant that the effective tariff on the low-priced fabric, coming mainly from India, that competed with cloth produced by the Boston Manufacturing Company was much higher than the ad valorum rate. Not only would such a tariff provide protection to the Boston Manufacturing Company, it did so with minimal effects on the British textile industry, allowing Lowell to secure support from key southern legislators, who recognized that the tariff Lowell advocated would encourage domestic demand for their crop without greatly affecting the British producers on whom the cotton growers' prosperity depended. Analysis of Congressional voting (Rosenbloom 2004, p. 384) shows that while Southern representatives opposed higher across-the-board tariffs, they were in favor of the minimum valuation approach that Lowell advocated.

After 1816, many traditional textile manufacturers closed when confronted with renewed British imports, but the Boston Manufacturing Company expanded its production rapidly. By 1820, its sales had increased to $260 thousand, more than ten times their level ($24 thousand) in 1816. At the same time, the company continued to make substantial improvements to its technology as it benefited from opportunities for learning-by-doing created by vertical integration of the different stages of production under one factory roof. In this setting bottlenecks and technological limitations could be quickly identified, and solutions adopted (David 1970).

During the 1820s, technological advances both in the United States and in Britain steadily lowered prices of cotton cloth, helping to stimulate demand. Falling prices also increased the effective protection for low-cost cloth, as prices fell relative to the minimum valuation. Protection further increased when Congress raised the minimum valuation to 30 cents per yard in 1824 and 35 cents per yard in 1828. Effective rates of tariff protection more than doubled between 1815 and 1830, reaching close to 60% of the value of imports, as illustrated in Figure 3, before beginning to decline. By 1830, the effective tariff on imported textiles had risen to 40 percent according to Irwin and Temin (2001). Not until 1846 were tariff rates reduced. By this time, American spindles in operation had reached roughly 1/6 the number in Britain, a level at which they held steady through the 1860s.

While the American industry had initially drawn on British technological advances, the characteristics of the American and British industries diverged over the course of the nineteenth century. U.S. producers were much more concentrated in production of coarser fabrics with yarn counts below 40, than were their British competitors. Moreover, the U.S. industry relied primarily on ring spinning, while mule spinning was the dominant choice in Britain. The latter difference in spinning technologies has occasioned a large literature. By the early 20th century, ring spinning had emerged as the superior choice, and some observers have sought to cast the persistence of mules in Britain as a reflection of entrepreneurial failure (see, among others, Saxonhouse and Wright 1984 and 2010; Sandberg 1969; Lazonick 1981).

More reasonably, however, it seems that the choices made by producers in each country reflected an optimal adaptation to the conditions they faced. Initially, mule spinning required more skilled operatives, but allowed lower quality cotton to be converted into yarn. Since there were few skilled mule spinners in the U.S. but abundant supplies of high-quality cotton, American producers opted to rely on ring spinning. With access to a much larger supply of skilled mule spinners but facing higher costs of raw cotton, however, their British counterparts relied primarily on mules. The American ring-spun yarn was coarser but stronger, making it well suited to mass production of cloth using mechanized looms. Focusing more on higher quality and fancier fabrics and having a greater supply of handloom weavers, British manufacturers were also slower to adopt power looms. Similarly, incentives to integrate spinning and weaving operations were greatest for producers of lower quality fabric using coarse yarn. While virtually all the American mills were vertically integrated the share of British mills combining spinning and weaving was much greater for those producing fabric with counts under 50 than for those producing finer products (Temin 1988, pp. 901-906).

The growth of factory produced textiles served to stimulate development of machine-making expertise. At its founding, the Boston Manufacturing Company was obliged to build all its own equipment. But as factories expanded, new firms were founded, and the technology of production stabilized, textile machine makers began to spin off from the textile manufacturers. In addition to supplying the textile industry, the expertise these machine builders acquired in metal working and the assembly of complex machinery led them to branch out into the construction of other types of machinery, such as steam locomotives (Thomson 2009, pp. 24-29; Rosenberg 1963, pp. 418-19). While expanding markets for machinery encouraged growing specialization, the ability of the machinery industry to apply solutions to production problems developed in one sector to challenges in other industries—what Nathan Rosenberg (1963, p. 426) has termed “technological convergence”—was an important factor accelerating the pace of technological progress in the middle of the nineteenth century.

Both the British and American textile industries were technologically dynamic, advancing productivity and reducing costs, but they were proceeding down distinct technological paths. The British industry relied on a "craft-like technology (the mule)" dependent on the skills of the operators, while the American approach relied on machinery that "reduced skill requirements and extended its capability along other dimensions" (Saxonhouse and Wright 2010, p. 536).

4. Precision Manufacturing

In much the same way that the U.S. textile industry followed a distinctive path of technological development in the first half of the nineteenth-century, American manufacturers of firearms, clocks, locks, and a range of other relatively complex machinery developed manufacturing technologies that diverged significantly from those in use in Great Britain. By the 1850s, American firearms manufacturers claimed to have perfected techniques that enabled them to produce guns using interchangeable parts, eliminating the need for the hand fitting of parts, on which British manufacturers relied. These American advances excited considerable interest in Britain.

In 1853, the British government sent several leading industrialists to the United States to learn more about American innovations in mechanized production. One of these visitors, Joseph Whitworth, a leading machine tool builder, visited factories in more than 15 U.S. cities before attending the New York Crystal Palace industrial exhibition that year. The observations of these experts attest to the novelty of American manufacturing techniques. Whitworth, for example reported that Americans "…call in the aid of machinery in almost every department of industry. Wherever it can be introduced as a substitute for manual labor, it is universally and willingly resorted to" (quoted in Hounshell 1984, p. 61). Another member of the British delegation observed that: "In consequence of the scarcity and high price of labor in the Unites States, and the extreme desire manifested by masters and workmen to adopt all labour-saving appliances…a considerable number of different trades are carried on… in large factories, with machinery applied to almost every process, the extreme subdivision of labour and all reduced to an almost perfect system of manufactures" (quoted in Rosenberg 1969, p. 128)

Prompted in part by these observations, in 1854 Parliament established a select committee to investigate the best method of producing guns for the military. The select committee heard testimony from the industrialists who had visited the U.S. and closely examined methods employed by the U.S. national armories in Springfield and Harpers Ferry as well as by private manufacturers including Samuel Colt. After an extensive review the select committee recommended that the Board of Ordinance establish an armory on the American model, and equipped with American machinery (Hounshell 1984, pp. 17-25).

Despite the detailed descriptions provided by British industrialists, characterizing precisely what was so novel about American manufacturing techniques has been challenging for scholars. Framed in terms of modern economic theory, the descriptions of nineteenth-century observers can be read in two different ways. One interpretation is that Americans had substituted capital for labor, selecting a different set of factor proportions along a commonly available isoquant. Another interpretation is that Americans had developed a different and superior technology from that in use in Britain (Habakkuk 1962; Temin 1966 and 1971; Fogel 1967; David 1975). In other words, they were producing on the isoquants of an entirely different production function.

One problem with the factor substitution interpretation is that both capital and labor was more expensive in the American context than in Britain, a fact that is explained by the abundance of natural resources in the U.S (Field 1983; James and Skinner 1985). As Peter Temin (1971) has demonstrated, once the set of inputs is broadened to include three or more inputs, conclusions about factor substitutions in response to differences in factor abundance become sensitive to model specification and do not yield clear-cut implications.

Setting aside the factor-substitution interpretation, the question is how and why did American manufacturers develop a distinct system of production from their British counterparts? This, of course, raises the question of how national technologies could have diverged for any extended period, especially given the seemingly rapid trans-Atlantic diffusion of technological innovations in this period. The answer, seems to be that, as was true in the case of the textile industry, the methods of manufacturing developed in the United States would not have survived in competition with imported goods. Rather the early development of the use of specialized machinery and the emphasis on interchangeable parts were made possible only because manufacturers received considerable support from the federal government. Not until perhaps the 1850s were American methods of producing firearms competitive with the hand methods in use in Britain, and, even then, it is not clear that they could be characterized as superior (Rosenbloom 1993).

Until the end of the eighteenth century the United States remained largely dependent on European suppliers to outfit its military. But with growing international tensions, the federal government began to invest in establishing more reliable domestic sources of weapons. Among the manufacturers who responded to this demand was Eli Whitney. From the outset the government promoted the principle of interchangeable parts production. The reasons for this are not entirely clear, but it appears that Thomas Jefferson was an early advocate. At a practical level, interchangeability would benefit the government by facilitating the repair of damaged weapons.

Progress toward the interchangeable parts ideal was slow and made primarily at government-run armories established in Springfield, MA and Harpers Ferry, WV. Seeking to reduce reliance on skilled-craftworkers, who were in especially short supply, the armories introduced better techniques of measurement and the use of an elaborate system of gauges and fixtures to measure critical dimensions of individual parts. The resulting division of labor in turn created opportunities to replace key steps in the production process with special purpose machinery designed to shape wooden and metal parts (Hounshell 1984, pp. 25-46), and stimulated advances in machine building.

It is important to emphasize that, like cotton textiles, firearms manufacturers not only introduced new production techniques but focused on producing a utilitarian product aimed at the mass of the market. In comparison, the product of British gunsmiths was a hand-crafted luxury good. Moreover, American methods of production were, in all likelihood, more expensive than British methods until at least the mid-1840s. This path of technological divergence would not have been possible without government sponsorship.

Outside of firearms, American manufacturers of clocks and locks also turned to the division of labor, greater reliance on precise measurement, and the use of special-purpose machinery to mass produce standardized products for a growing consumer marketplace in the first half of the nineteenth century. Much of this innovation centered in Connecticut, where a dense network of skilled craftsmen and workshops helped to facilitate the diffusion of new technologies (Thomson 2009, p. 50).

In the second half of the nineteenth century, metalworking techniques developed in gun manufacture were elaborated and improved by the machine tool makers in ways that made possible factory production of typewriters and sewing machines, and proved instrumental in the rapid diffusion of the bicycle. Each industry in turn contributed to further advances in machine tool design. The culmination of this process came with the application of these techniques to the mass production of automobiles pioneered by Henry Ford in the early twentieth century (Rosenberg 1963, Hounshell 1984).

5. The Broader Innovation Economy

Productivity Growth in Manufacturing

Developments in the production of steam engines, cotton textiles, and gun making clearly demonstrate the existence of a local community of innovators capable of understanding and adapting advances in European industrial technologies to the economic conditions that manufacturers faced in the United States. While developments beyond these leading industries have attracted less attention, there is considerable evidence that similar forces were at work across the American economy.

In the first half of the nineteenth century, most manufacturing activity took place in small, artisanal shops that employed perhaps a handful of assistants or apprentices working alongside the owner. The most numerous of these were small flour and sawmills, engaged in processing farm and forest products. Other important processing industries included tanneries, distilleries and iron forges. High costs of transportation, and low population density meant that these establishments were widely dispersed, small in size, and often worked only intermittently rather than year-round.

Table 4 summarizes data on the leading U.S. manufacturing industries in 1860, ranked by their contribution to value added. Reflecting its rapid growth trajectory, the cotton textiles industry was by 1860 ranked first. Many of the technological innovations developed in cotton had also been applied in the production of woolen goods, which ranked eighth, while machinery also made the list. With these exceptions, however, leading industries were concentrated in processing (lumber, flour and meal, iron, leather) or in small scale manufacturing (boots and shoes, men's clothing, carriages and wagons). Table 4 also illustrates the exceptional size of cotton goods factories (employing 144 workers on average) in comparison to most other industries at the time (ranging from 4 to 34 workers per establishment).

Despite the varied nature and characteristics of these industries, the manufacturing sector achieved quite rapid growth in both labor and total factor productivity. Drawing on Censuses of Manufacturing conducted in 1820, 1850 and 1860, as well as the McClane Report, which gathered information on manufacturing enterprises in 1832, Sokoloff (1986) was able to calculate the value of output, raw materials inputs, capital in use and the quantity of labor employed at a selection of manufacturing establishments in the Northeastern United States, where most manufacturing was concentrated. Adjusting for changes in output and input prices these data allow him to construct measures of output per worker and total factor productivity, as well as to measure the contributions of the different inputs to total output.

The results of Sokoloff's calculations are reported in Table 5. From 1820 to 1860, a weighted average of labor productivity across these industries grew at 2.5-2.7 percent per year, while total factor productivity growth was in the range of 1.8 to 2.2 percent per year. Table 5 also reports the results of decomposing the sources of labor productivity growth between factor substitution – increased capital (K/L) and raw materials (RM/L) per worker as well as increased efficiency of all inputs (TFP). Except for tobacco goods and tanning, the largest contributor was consistently TFP. More striking, however, is the relatively small role played by capital deepening in increasing labor productivity, which contributed no more than 16 percent of total productivity growth, and in many cases much less. In contrast, increases in raw materials per worker were a major contributor to rising labor productivity in this period.

Increased total factor productivity is, as noted earlier, a "measure of our ignorance" (Abramovitz 1992). It reflects advances in the ability to convert inputs into outputs that we cannot otherwise account for in terms of measured inputs. Examining histories of many of these industries, Sokoloff (1992, p. 359) concludes that their increased technical efficiency can be attributed primarily to "…improvements or refinements in the organization of production and from relatively subtle modifications of output and in traditional capital equipment." In other words, these were primarily process innovations arising from learning-by-doing.

The widespread nature of these advances suggests that they reflect broad based changes in the economy. Growing population and better transportation allowed establishments to increase in size, which may have enabled them to exploit economies of scale. Learning by doing, greater specialization, and more regular operations may also have contributed to more efficient use of all inputs. Whatever the sources, the rapid progress of productivity in manufacturing suggests that labor was being drawn into the manufacturing sector by the rising economic rewards offered in the sector, not by any stagnation in the agricultural sector.

Patenting and Innovation

Data on patenting offers important insight about the sources of innovation that produced rising levels of productivity. Not all innovations are patented, of course, and not all patents result in economically valuable innovations. Nonetheless patents are an important indicator of innovative activity. Both temporal and cross-sectional variation in patenting indicate that the innovative activity was responsive to economic incentives. The personal characteristics of patent holders suggest that, consistent with the emphasis on learning by doing, most innovations in this period relied more on direct experience than on highly developed technical expertise.

The U.S. Constitution, which came into effect in 1788, granted Congress the power to promote the progress of science and useful arts by granting inventors exclusive rights to their discoveries.

Within 2 years, in 1790, Congress passed the first patent statute, which vested authority to grant patents jointly with the attorney general, secretary of war and secretary of state, who were charged with determining whether the application was both novel and useful. Carrying out this responsibility quickly proved to be a burden on these officials, however, and in 1793 the patent act was replaced by new legislation that required only that the innovation be deemed useful, and established a fee of $35 to file the application. This fee, which was equivalent to perhaps 30 to 60 percent of per capita income in the pre-Civil War period, was at first a deterrent to frivolous patent applications. By 1836, however, rising levels of patenting were leading to increased litigation, and Congress enacted changes to the system establishing a staff of technical experts to review patent filings more carefully (Sokoloff 1988, p. 818).

Figure 4 graphs the number of patents granted from 1790 through 1850. Patenting rates exhibited substantial growth over this period, increasing from between 10-30 per year in the 1790s to over 750 per year at their peak in 1736, when the new more restrictive patent act took effect. This growth was episodic, however, increasing gradually from 1790 through 1807, accelerating with the economic stimulus caused by the Embargo Act of 1807, and then collapsing with the onset of the War of 1812. After a period of stagnation until the mid-1820s, patenting rose markedly until 1836. The drop in patenting after 1836 reflected both stricter patent examination and the effects of the financial crises that coincided with the dissolution of the Second Bank of the United States. But after 1840 the number of patents began to expand again and by 1849 exceeded the previous peak. After 1850 the number of patents issued shot upward, rising more than 4-fold by 1860, a development excluded here so that the pre-1850 fluctuations can be clearly seen in the graph. No doubt some of the growth in patenting reflected the expanding size of the U.S. economy, but over the period from 1790 to 1850 patenting increased nearly five times as fast as overall population.

Based on careful analysis of both temporal and cross-section variations in patenting Kenneth Sokoloff and Zorina Kahn (Sokoloff 1988, Sokoloff and Kahn 1999) argued that the data strongly support the view that innovation was responsive to economic incentives. Not only did the timing of patent applications track fluctuations in economic activity, but the locations of patent applicants correlated with the locus of manufacturing and commercial activity. Rates of patenting per capita increased substantially in Southern New England and New York after 1805, corresponding to the period of rapid expansion of textile production in these regions (Sokoloff 1988, p. 827). Sokoloff (1988, pp. 830-40) also found that as the transportation network expanded, providing low-cost market access to new regions, patenting rates increased. This effect is especially dramatic in the 1820s in the regions of upstate New York near the Erie Canal.

The characteristics of patent holders offer further insight about the character and sources of innovation in the U.S. Drawing on an analysis of a sample of about one-third of patents granted before 1846 as well as a study of 160 “great inventors” from the *Dictionary of American Biography* Sokoloff and Zorina Kahn (1990 and 1993), argued that the expansion of inventive activity was due to a “…disproportionate increase in invention by ordinary citizens operating with relatively common skills and knowledge rather than by an elite with rare technical expertise or extensive financial resources” (Sokoloff and Kahn1990, p. 364).

One reflection of this fact is the increase in the share of patents issued to individuals with just one or two patents, which increased from 67 percent in 1790-1804 to 78 percent in 1843-46 (Sokoloff and Kahn 1990, p. 367). Locating urban patentees in city directories, Sokoloff and Kahn (1990, p. 369) found that while merchants were the dominant group among early patent holders, their share shrank while that of machinists and toolmakers and other metal goods producers increased. More details about the personal characteristics of innovators can be gleaned from the data on great inventors. Among this group Kahn and Sokoloff (1993, p. 293-94) found that almost half had at most a few years of schooling. Even among this group of repeat inventors, commercial, artisanal, and professional careers predominated over more technical occupations. For the most part, these innovators had direct experience with the industries for which their innovations were intended (Kahn and Sokoloff 1993, p. 296-97).

6. An American Perspective on the Industrial Revolution

In 1790, the United States was still a small, largely agricultural economy, concentrated within a narrow band of settlement close to the Atlantic Ocean. In 1810, the earliest year for which data are available, just over 3 percent of the labor force were employed in manufacturing, and over 70 percent were employed in farming. By 1870, population had increased almost 10-fold to 38.6 million, spread across the entire continent, and manufacturing accounted for 19 percent of total employment. At this time, the United States still lagged Britain in the scale of its industrial production and GDP per capita. But the stage had been set for the surge of industrial expansion that would transform the United States into the world's industrial leader by the early twentieth century.

From the perspective of 1790, the transformation of the American economy that would take place over the next century would likely have seemed surprising. Considering the nation's abundant supplies of agricultural land, the absence of major urban centers, the low density of its population, and the high cost of capital, an observer ignorant of what actually happened would have concluded that the nation's comparative advantage was in agricultural production, not manufacturing. And it is important to bear in mind that the agricultural sector of the economy also experienced rapid absolute growth. It was just that manufacturing and commercial activities grew more rapidly.

The application of steam engine technology to transportation within the United States, first to power shipping on internal waterways, then by rail, and later to speed trans-oceanic shipping was an important factor in promoting the extensive growth of the American economy. Falling transportation costs were essential to expanding the frontier of settlement and bringing new land and resources into production. And this expansion created a persistent spatial disequilibrium that gave rise to economic opportunities and stimulated many of the processing industries that we have seen dominated the economy as late as mid-century.

The simple transfer of technology between Britain and the United States, however, cannot account for the transformation of the American economy over the course of the nineteenth century. It is apparent that technological ideas flowed relatively freely and quickly across the Atlantic, often embodied in the persons of skilled artisans or mechanics who emigrated from Britain to the United States. But British technologies were not well suited to American conditions. This was especially true in the iron industry, where differences in the chemical composition of iron ores and coal substantially slowed the transition to mineral fuel-based iron production. But it was true for steam engines, and cotton textiles as well.

American leadership in the introduction of high-pressure steam engines, and its success in cotton textiles and in precision manufacturing can be seen ultimately as a response to factor endowments. But this response was possible only because of the existence of an active community of inventors responsive to economic incentives created by protection from international competition or governmental subsidies. The development of cotton textiles and firearms production also serve to illustrate the importance of path-dependence, in which temporary historical "accidents" produced lasting divergence in economic development (David 1986; Arthur 1989).

In the case of cotton textiles, the temporary protection from imports provided by the Embargo Act of 1807 and the War of 1812, enabled Francis Lowell to introduce a novel model of integrated spinning and weaving. It is true that Lowell's approach employed increased mechanization to reduce the need for skilled labor. But his innovations were more complex than a simple capital-labor substitution. The output of the Boston Manufacturing company was both more coarse and less varied than the output of British manufacturers. At the same time, the Boston Manufacturing Company and subsequent Massachusetts textile mills replaced skilled labor with young women recruited rural New England and housed in purpose-built dormitories. As such, its success was dependent upon both technical and social innovations that allowed mobilization of a previously untapped source of labor.

Even with these innovations, the Boston Manufacturing Company would likely have failed in the face of flood of imported fabric had Lowell not been successful in securing tariff protection after the end of the War of 1812. Without the accident of temporary protection after 1807 it is unlikely that the Boston Manufacturing Company would have been established. And, in the absence of the Boston Manufacturing Company it is unlikely that there would have been an effective advocate for the protection the industry secured after the war ended.

In the 20th century, many developing countries adopted policies of import substituting industrialization: imposing tariff barriers to block imported manufacturers and protect nascent, or "infant," industries so that they could achieve economies of scale that would enable them to compete effectively on international markets. Advocates of such policies point to examples such as the American textile industry as demonstration of the effectiveness of this strategy. But the twentieth century record suggests that such protection is not sufficient in itself to stimulate sustained manufacturing development.

An important question about such policies is how long protection is required. The evidence in the American case is not clear cut. One early analyst, F. W. Taussig (1931), argued that by the early 1830s tariff protection was no longer necessary. Mark Bils (1984) and C. Knick Harley (1992) have contended, however, that the level of American prices suggest that protection was necessary until at least the 1850s. Further evidence in favor of this interpretation comes from the fact that American cloth was largely uncompetitive in a third market: Canada.

Douglas A. Irwin and Peter Temin (2001) argued based on econometric analysis of price movements that the American industry matured much earlier than Bils and Harley believe. Specifically, they suggested that because of product differentiation American and British manufacturers did not compete directly. As evidence of this, they point to the lack of responsiveness of American prices to fluctuations in tariff rates, which would affect the price at which British cloth was sold in the United States. The difficulty with this view is that the same result would be expected if tariff rates were redundantly high, as they likely were until the mid-1840s. After 1840, tariff rates did not change so there is no variation to examine.

Whether or not tariff protection remained necessary after the 1830s, an important feature of the American industry was the ability of American manufacturers to sustain rapid rates of technological progress. Although American manufacturers had solved the technical challenges of vertically integrated, mechanized production by the early 1820s, they continued to achieve substantial advances in productivity well after this. Paul David (1970) calculated that total factor productivity in textile production increased at an average rate of 6.67 percent per year in the 1830s. While a small portion of this increase was attributable to continued capital investment, he concluded that almost 1/3 of the advance in productivity was due to “learning by doing,” that is through the accumulation of knowledge about the production process and adjustments that are not embodied in any physical equipment.

We don’t know exactly why the American industry was able to lower costs of production so effectively, but it seems likely that an important factor encouraging productivity advance is that despite protection from international competition, American manufacturers were small relative to the market they served, and thus faced considerable competition from other domestic manufacturers. In many developing countries today, where only a small number of domestic firms serve a protected market, tariff protection in the absence of competition has often resulted in disappointing productivity performance.

The development of precision manufacturing techniques shares important similarities with cotton textiles. In particular, the main thrust of innovative efforts was the substitution of machinery and less skilled labor for workers possessing traditional craft-skills, who were in especially short supply in nineteenth-century America. In the case of firearms production, where many of the initial advances in mechanizing production were made, the impetus for innovation was demand from the military, which was prepared to pay a premium to support development of methods that increased the uniformity of components and minimized the need for hand fitting. Once again, mechanization was associated with changes in the definition of the product being made. Even so, the resulting output was not cost competitive with traditional manufacturing methods until the 1840s. So, again, it was a sustained period of protection in the form of military contracts that allowed the necessary techniques to develop.

In the long run, the methods of production pioneered in firearms manufacturing proved consequential. In particular, the needs of arms makers encouraged the emergence of a specialized machinery-building sector that facilitated the dissemination of innovations in metal working to a host of other industries. In the post-Civil War period these included the makers of typewriters, bicycles and eventually automobiles. The learning achieved in these industries helped establish interchangeable parts production and provided the foundation for the introduction of the moving assembly line in the production of automobiles by the early twentieth century.

7. Conclusion

By 1870, the United States was poised to become a leader in the so-called Second Industrial Revolution, centered around applications of electricity and the internal combustion engine, which would power the next stage of economic growth. By this time the nation possessed the manufacturing and machine-building expertise to both absorb innovations generated elsewhere and to make fundamental contributions to the development and application of these technologies. But the emergence of these technological capabilities was not a foregone conclusion in the 1790s, when the United States was still a relatively thinly populated and primarily agricultural economy.

A shared language and cultural connections with Britain established during the colonial period helped to facilitate the flow of technological knowledge from Britain during the early phases of the Industrial Revolution. And the abundance of natural resources and high living standards of Americans helped to attract mechanics and engineers with knowledge of these new technologies. British advances in steam power proved especially valuable in the American context, where they lowered transportation costs and helped to vastly expand the territory available for settlement. Reflecting differences in resource endowments, Americans turned more readily to high pressure steam engines than their British counterparts, producing a distinct technological path of development.

The growth of American manufacturing hinged on several important historical accidents. The Embargo Act of 1807 and the subsequent military conflict with Britain provided nearly complete protection from imports during which American textile manufacturing was able to expand substantially. Once the industry was established, textile manufacturers began to lobby for tariff protection that allowed the industry to continue its development. Again, reflecting the scarcity of labor and capital and abundance of resources the American industry followed a different path of development than in Britain, relying on ring-spinning rather than mules to produce a lower-quality and more homogeneous product. At least at first, American manufacturers could not compete on price with British imports, and protection provided the opportunity to realize the cost savings that this technological choice offered.

Similarly, government sponsorship of firearms production driven by military necessity stimulated investments in new manufacturing techniques. Producers at government armories relied heavily on precise measurement and mechanization to replace craft skills in short supply in the United States with less skilled labor. As with textiles, the evidence suggests that it was only after several decades of development that the novel American technologies became cost competitive. But in the process of their development, they nurtured the growth of machine-building skills that would prove essential to many of the industrial developments of the later nineteenth century.

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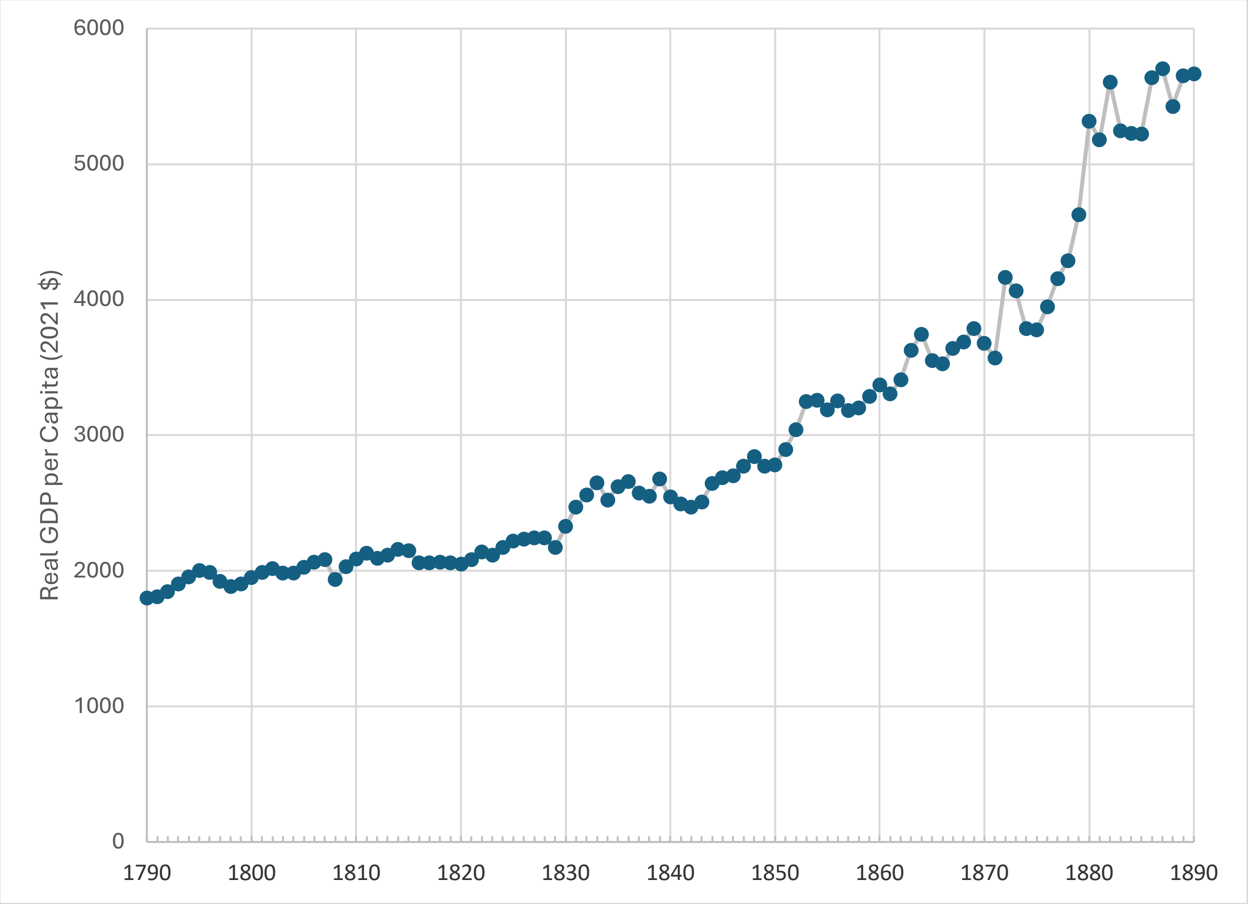
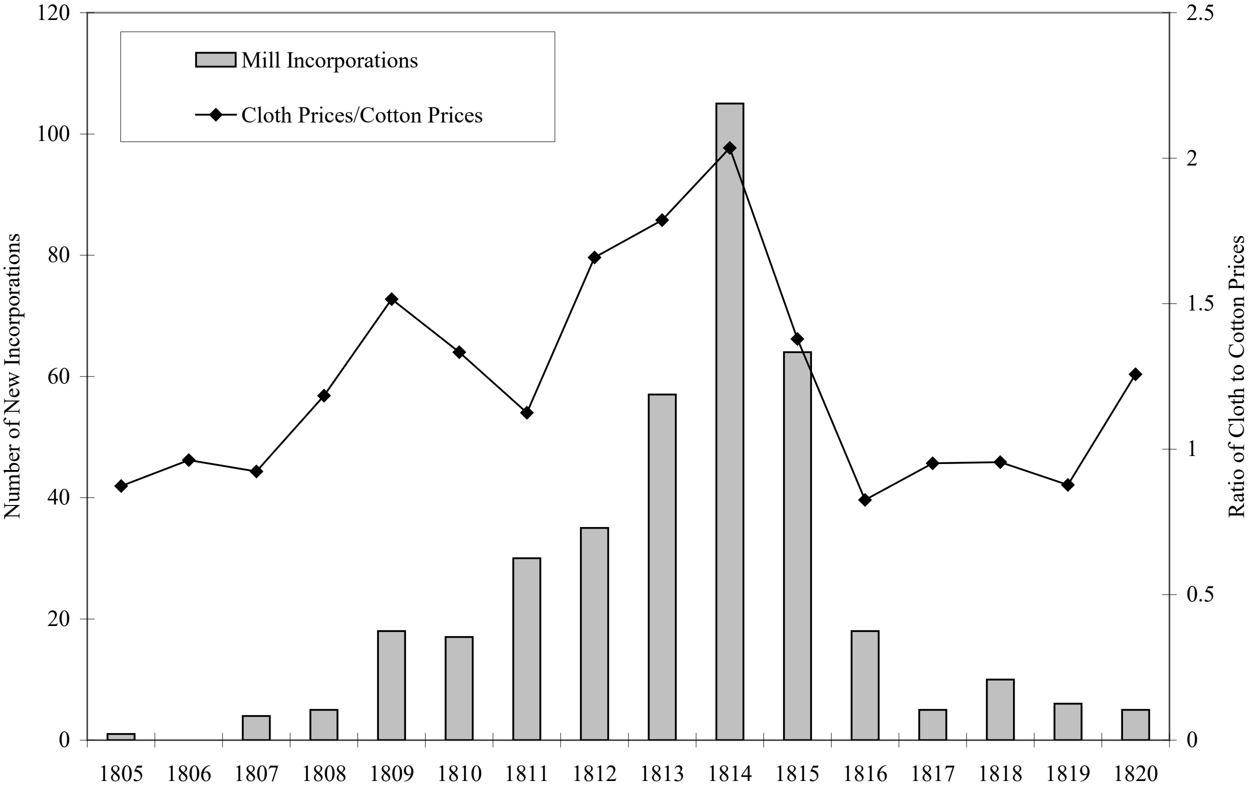
Figure 1
Growth of Real GDP per Capita, 1790-1890



Carter et al. (2006, series Ca9-19).

Figure 2

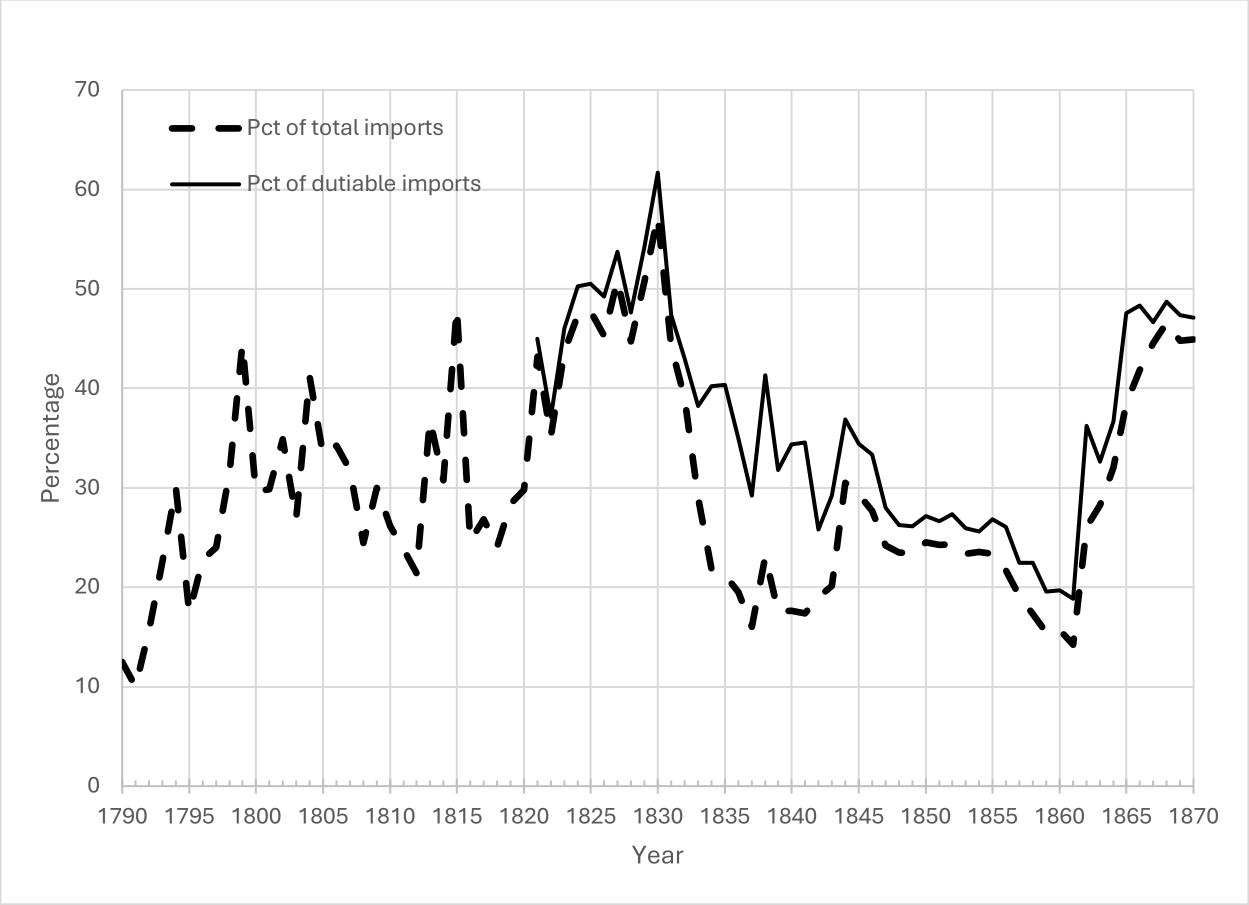
Mill Incorporations and Cloth/Cotton Price Ratio, 1805-1820



Source: Rosenbloom (2004, p. 375).

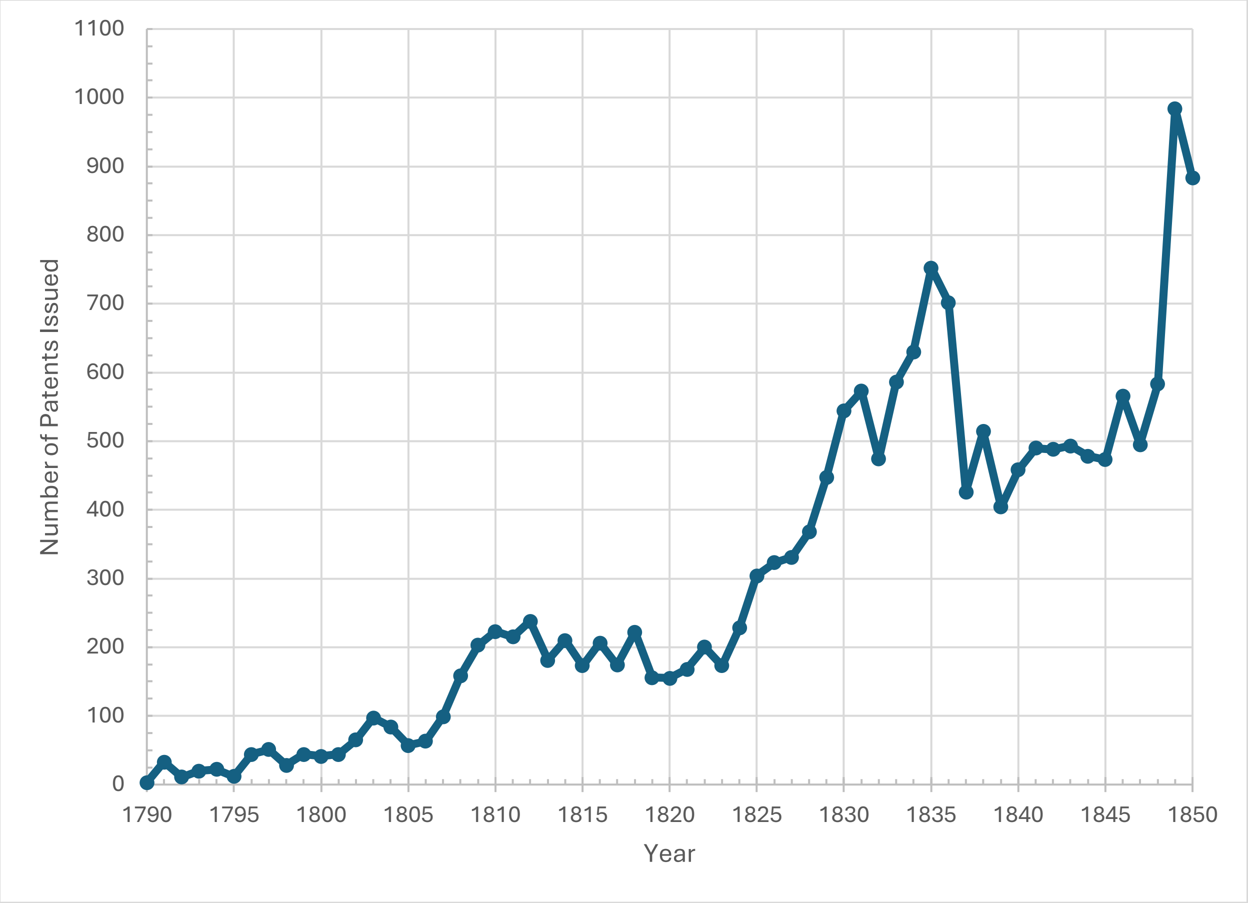
Figure 3

Tariff Revenue as a percentage of the value of imports and dutiable imports, 1790-1870



Source: Carter et al (2006, series EE 424-430).

Figure 4:
Number of Patents Issued Annually, 1790-1850



Source: Carter et al (2006, series Cg27-37).

Table 1: The Proximate Sources of Growth, U.S. 1800-1890

	Rates of Growth (% per year)				
Period	Real GDP Per Capita	Man Hours per Capita	Capital per Man Hour	TFP	TFP Share
1800-1855	0.87	0.48	0.19	0.20	23.0%
1855-1890	1.47	0.41	0.69	0.37	25.2%

Source: Abramovitz and David (2000, p. 14)

Table 2:
Location and Number of Fixed Steam Engines by Region, 1838

		Engines		Horsepower	
		N	PCT	N	PCT
East					
	New England	333	18	4754	14
	Middle Atlantic	437	24	5394	16
	South Atlantic	122	7	2733	8
West					
	Ohio Valley	392	22	8208	25
	Lower Mississippi	274	15	7399	22
	Not enumerated	244	14	4800	15

Notes: In some western states where returns were not available, Hunter has estimated an additional quantity of not enumerated engines

Source: Hunter (1985, p. 85)

Table 3
Cotton Textile Capacity in The United States and Britain, 1790-1895

	Millions of Spindles		Ratio
Date	Great Britiain	United States	US % of GB
1800	3.3	0.002	0.06
1810	6	0.096	1.60
1815	7.1	0.13	1.83
1820	8.4	0.22	2.62
1825	10.1	0.61	6.04
1830	11.7	1.1	9.40
1835	13.5	1.7	12.59
1840	15.3	2.4	15.69
1845	17.5	2.6	14.86
1850	20.98	4.1	19.54
1855	28	4.9	17.50
1860	30.4	5.4	17.76
1865	34.2	6.3	18.42
1870	34.7	7.4	21.33
1875	38.1	10	26.25
1880	39.75	11.3	28.43
1884	41.8	14.14	33.83

Sources: Farnie and Jeremy (2004, p. 21).

Table 4
Characteristics of Leading Manufacturing Industries in 1860

	Value Added			Number of Establishments		Workers Employed		
	Value ($millions)	% of total	per establishment	Number (1000s)	% of total	Number (1000s)	% of Total	Per establishment
Cotton Goods	55	6.4%	$68,750	0.8	0.6%	115	8.8%	144
Lumber	54	6.3%	$2,673	20.2	14.4%	76	5.8%	4
Boots and Shoes	49	5.7%	$3,920	12.5	8.9%	123	9.4%	10
Iron	46	5.4%	$20,000	2.3	1.6%	68	5.2%	30
Clothing	41	4.8%	$9,762	4.2	3.0%	121	9.2%	29
Flour and meal	40	4.7%	$2,878	13.9	9.9%	28	2.1%	2
Machinery	33	3.9%	$23,571	1.4	1.0%	41	3.1%	29
Leather	26	3.0%	$5,000	5.2	3.7%	26	2.0%	5
Woolen Goods	28	3.3%	$23,333	1.2	0.9%	41	3.1%	34
All Manufactures	854		$6,083	140.4		1311		9
		43.6%			43.9%		48.7%	

Source: Ratner et al (1993, P. 189)

Table 5
Productivity Growth in Northeastern Manufacturing, 1820-1860

	Labor Productivity Growth Rate		total Factor Productivity		Decomposition of labor productivity Growth (Shares attributable to)		
Industry	min	max	min	max	K/L	RM/L	TFP
Boots/Shoes	2.2	2.5	1.3	1.6	11	34	54
Coaches/Harnesses	1.7	2.2	1.3	1.3	9	29	61
Cotton Textiles	2.5	3.5	1.4	1.7	-2	48	54
Furniture/Woodworking	2.9	3	2	2.1	4	27	68
Glass*	2.8	2.8	1.6	1.6	5	37	57
Hats	2.7	3.1	1.4	1.6	5	48	46
Iron	1.7	2	1.1	1.1	3	42	55
Liquors	1.9	2.1	1.2	1.2	11	28	61
Flour/Grist mills	1.3	1.3	1	1	13	12	75
Paper	5.3	6.2	2.3	2.6	3	52	44
Tanning	2	2.6	0.9	1.1	11	43	46
Tobacco	1.5	2.7	0.7	1	16	59	25
Wool Textiles	3.6	3.7	1.8	1.9	4	44	51
Weighted Average	2.5	2.7	1.8	2.2			

Source: Sokoloff (1986), Tables 13.11 and 13.13, pp. 719, 723.
Notes: The ranges reflect the difference between aggregate and sample data in 1860. The decomposition uses firm level growth estimates.

*Only aggregate data in 1860