The Rise and Fall of Great Technologies and Powers*

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Abstract

How do technological revolutions affect the rise and fall of great powers? Scholars have long observed that major technological breakthroughs disrupt the economic balance of power, bringing about a power transition. However, there has been surprisingly limited investigation into how this process occurs. Existing studies establish that a nation's success in adapting to revolutionary technologies is determined by the fit between its institutions and the demands of these technologies. The standard explanation emphasizes institutional factors best suited for monopolizing innovation in new, fast-growing industries (*leading sectors*). I propose an alternative mechanism based on the diffusion of general-purpose technologies (GPTs), which presents a different trajectory for countries to leapfrog the industrial leader. Characterized by their potential for continuous improvement, pervasiveness, and synergies with complementary innovations, GPTs only make an economy-wide impact after a drawn-out process of diffusion across many sectors. The demands of GPT diffusion shape the institutional adaptations crucial to success in technological revolutions. Specifically, I emphasize the role of education systems and technical associations that broaden the base of engineering skills associated with a GPT. To test this argument, I set the leading-sector mechanism against the GPT diffusion mechanism across three historical case studies, which correspond to historical industrial revolutions: Britain's rise to preeminence in the early 19th century; the U.S.'s overtaking of Britain before World War I; Japan's challenge to U.S. technological dominance in the late 20th century. Evidence from these case studies support the GPT diffusion explanation, shedding new insights into how emerging technologies like AI, which some regard as driving a fourth industrial revolution, will affect a possible U.S.-China power transition.

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1. Introduction

From the mechanization of the first industrial revolution in the 18th century, to the electrification of the second industrial revolution in the 19th century, to the informatization of the third industrial revolution in the 20th century, rounds of disruptive technological innovation have...fundamentally changed the development trajectory of human history...Today, we are experiencing a larger and deeper round of technological revolution and industrial transformation.
— Chinese President Xi Jinping, remarks at the BRICS Summit on July 26, 2018

How do technological revolutions affect the rise and fall of great powers? International relations scholars have long recognized that major technological advances often precede disruptions to the balance of power. As policymakers and scholars increasingly frame today's U.S.-China rivalry as a contest for technology leadership in the "Fourth Industrial Revolution," how will emerging technologies affect the U.S.-China power balance?[1]

While there are robust debates over the manifold consequences of power transitions, less attention is paid to the causes of power transitions. It is generally acknowledged that the rise and fall of great powers originates from, as Yale historian Paul Kennedy outlines, "differentials in growth rates and technological change, leading to shifts in the global economic balances, which in turn gradually impinge upon the political and military balances."[2] Historical analyses, spanning from the tenth to the 21st century in some cases, have established a connection between major technological innovations and the first outcome in Kennedy's causal chain — shifts in economic leadership.[3] Yet, few studies further explore the causal processes that link disruptive technological breakthroughs and disruptions to the economic balance of power.[4]

Among those that do, the standard account stresses dominance over critical technological innovations in new, fast-growing industries (*leading sectors*). By exploiting a brief window to monopolize profits in cutting-edge industries, the country that dominates innovation in these sectors rises to become the world's most productive economy. The leading-sector (LS) explanation cites prominent examples that supposedly bear out this phenomenon, including Britain's early lead in textiles during the Industrial Revolution and Germany's mastery of the emerging chemical industry in the late 19th century. As Drezner summarizes, "Historically, a great power has acquired hegemon status through a near-monopoly on innovation in leading sectors."[5]

The fit between domestic institutions and emerging technologies explains why the benefits of leading sectors tend to accrue in certain nations. Some scholars argue that national systems of political economy of rising challengers can more rapidly adapt to the demands of new, revolutionary

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[1] Doshi 2020.
[2] Kennedy 1987, xx.
[3] Akaev and Pantin 2014; Modelski and Thompson 1996; Thompson 1990.
[4] Modelski and Thompson 1996, 100.
[5] Drezner 2001, 7.

technologies. Leading economies, by contrast, are victims of their past success, burdened by powerful vested interests that resist adaptation to disruptive technologies.[6] Other scholars outline more specific institutional factors, such as the degree of government centralization and industrial governance structures, that account for why some countries monopolize leading sectors.[7]

Though specific interpretations vary, the general outlines of the LS explanation enjoy broad support across both academic and policy-making circles.[8] This influence is reflected in current discussions about how emerging technologies could influence China's rise, which emphasize China's capacity to innovate in new leading sectors and to capture monopoly rents from new discoveries.[9]

I challenge the LS interpretation of technology-driven power transitions on empirical, methodological, and theoretical grounds. I develop an alternative explanation centered on general-purpose technologies (GPTs), fundamental advances that can spur economic transformation. Distinguished by their potential for continuous improvement, pervasive applicability throughout the economy, and synergies with complementary innovations,[10] GPTs make a substantial impact on economic productivity only after a "gradual and protracted process of diffusion into widespread use."[11] Electricity, the prototypical GPT, followed this extended trajectory. The first electric dynamo practical for industrial use emerged in the 1870s, but the impact of electrification on overall productivity did not materialize until about five decades later.[12]

GPTs, therefore, affect economic power transitions in a pathway that differs significantly from the standard LS account. Specifically, these competing interpretations of technology-driven power transitions differ along three key dimensions: impact timeframe, relative phase of advantage, and breadth of growth. First, whereas the LS explanation emphasizes the impact of technological innovations in the early stages of their life cycle, the greatest boosts to productivity come late in a GPT's development. Second, the GPT explanation places more weight on diffusion. No one country dominates innovations in GPTs; rather, national success is determined by a state's effectiveness in adopting GPTs across a wide range of economic sectors. Finally, in contrast to the LS account's focus on a limited number of new industries' contributions to economic growth, GPT-fueled productivity growth is spread across a broad range of industries.

Clearly differentiating between these two pathways informs the institutional factors most crucial to economic leadership amidst technological revolution. If the LS trajectory holds, then the key institutional adaptations allow states to seize the market in new industries, such as scientific research investments that pioneer new technological paradigms and industry structures that

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[6] Gilpin 1996; Moe 2009.
[7] Drezner 2001; Kitschelt 1991.
[8] Gilpin 1981; Gilpin 1987; Kennedy 1987; Modelski and Thompson 1996; Rostow 1960; Schumpeter 1934; Schumpeter 1939; Tellis et al. 2000, 39; Thompson 1990.
[9] Kennedy and Lim 2018; Rapkin and Thompson 2003, 333; Tellis 2013, 112.
[10] Bresnahan and Trajtenberg 1995.
[11] David 1990, 356.
[12] Devine 1982.

monopolize LS innovation. If, however, the GPT model is operative, the key institutional complementarities facilitate widespread diffusion of GPTs, including education systems and technical associations that broaden the base of engineering skills associated with a GPT.

I test this argument with three historical case studies that set the GPT mechanism against the LS mechanism: Britain's rise to preeminence in the first industrial revolution (1780-1840); the U.S.'s overtaking of Britain in the second industrial revolution (1870-1914); and Japan's challenge to America's technological dominance in the information technology revolution (1960-2000). The case studies cover periods characterized by both remarkable technological change — the "three great industrial revolutions" in the eyes of some scholars[13] — and significant fluctuations in the global balance of economic power. Though all three cases favor the LS account in terms of both background conditions and prior theoretical discussions, the case study evidence reveals that GPT diffusion was central to how technological changes associated with each industrial revolution translated into differential rates of economic growth among the great powers.

This article proceeds as follows. I first outline the theoretical differences between the GPT and LS mechanisms. I then assess the explanatory power of these two mechanisms by tracing how technological changes affected economic power transitions in history's three industrial revolutions, finding in favor of GPT diffusion theory. I conclude by applying my findings to present-day debates over how major breakthroughs in emerging technologies like AI will affect the U.S.-China power balance.

2. Theories of Technology-driven Power Transitions

Existing studies establish that a nation's success in adapting to revolutionary technologies is determined by the match between its institutions and the demands of these technologies. Such analyses tend to fixate on the most dramatic aspects of technological change — "eureka" moments and first implementations of radical inventions. Consequently, standard explanations of technology-driven power transitions focus on the suitability of a rising power's institutional arrangements for cornering profits in leading sectors.

GPT diffusion theory, by contrast, draws attention to the less spectacular process by which fundamental innovations gradually diffuse throughout many industries. The rate and scope of diffusion is particularly relevant for GPTs. Recognized by economists and historians as "engines of growth,"[14] GPTs hold immense potential for boosting productivity. Realizing that promise, however, entails continuous changes across a wide range of technology systems. Under this pathway, the key institutional competencies are those that facilitate GPT diffusion. Specifically, I highlight the significance of education and training systems that widen the pool of engineering talent linked to new GPTs.

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[13] von Tunzelmann 1997, 2.
[14] Bresnahan and Trajtenberg 1995.

GPT Diffusion and LS Product Cycles

The dominant explanation for how technological change drives power transitions emphasizes a country's dominance in leading sectors, new industries that experience rapid growth on the back of new technologies. Cotton textiles, steel, chemicals, and the automobile industry form a "classic sequence" of "great leading sectors," developed initially by the American economist Walt Rostow and later adapted by political scientists.[15] Maintaining a monopoly on innovation in these emerging industries, according to the LS account, determines the rise and fall of lead economies.

This model of technological change and power transition builds on the international product life cycle, a concept pioneered by Raymond Vernon. Constructed to explain patterns of international trade, the product cycle begins with product innovation and the growth of sales in the domestic market. Once the domestic market is saturated, the product is exported to foreign markets, which eventually results in the diffusion of the manufacturing of the product, thereby eliminating the innovator's monopoly profits.[16] In fact, explicit references to the product cycle appear in many LS-based studies.[17] One scholar described Gilpin's *U.S. Power and the Multinational Corporation*, an influential text for the LS mechanism, as "[having] drawn on the concept of the product cycle, expanded it into the concept of the growth and decline of entire national economies, and analyzed the relations between this economic cycle, national power, and international politics."[18]

The product cycle's assumptions illuminate the differences between the GPT and LS mechanisms along three key dimensions. In the first stage of the product cycle, a firm generates the initial product innovation and profits from sales in the domestic market before saturation. Extending this model to national economies, the LS mechanism emphasizes the clustering of LS innovations and the attendant monopoly profits in a single nation.[19] "The extent of national success that we have in mind is of the fairly extreme sort," write Modelski and Thompson. "One national economy literally dominates the leading sector during its phase of high growth and is the primary beneficiary of the immediate profits."[20] The GPT trajectory, in contrast, places less value on the location where an innovation first takes place and more on where the GPT is more successfully diffused. I refer to this dimension as the *key phase of relative advantage.*

In the next stage of the product cycle, the product innovation spreads to global markets and the technology gradually diffuses to foreign competitors. Monopoly profits associated with a product innovation dissipate, as production of the innovation becomes routinized and transfers fully to other countries. This brief window of opportunity informs the LS mechanism's emphasis on the

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[15] Rostow 1978, 104-109. For an example of international relations scholars adopting Rostow's sequence of leading sectors, see Thompson 1990, which, with the exception of two new indicators, uses the same ten indicators proposed by Rostow as proxies for leading sectors.
[16] Vernon 1971.
[17] Gilpin 1975, 78, 197; Gilpin 1987, 234-237; Moe 2009, 207; Tellis et al. 2000, 37.
[18] Kurth 1979, 4.
[19] Rasler and Thompson 1994, 7.
[20] Modelski and Thompson 1996, 91. See also Thompson 1990, 217.

impact of technological innovations in the early stages of their life cycle. Modelski and Thompson write, "[Leading sectors] bestow the benefits of monopoly profits on the pioneer until diffusion and imitation transform industries that were once considered radically innovative into fairly routine and widespread components of the world economy."[21] Thompson states, "the greatest marginal stimulation to growth may therefore come early in the sector's development at the time when the sector itself is expanding rapidly."[22]

The GPT trajectory expects the opposite. A GPT's greatest marginal stimulation to growth comes later in its development. It is precisely the process by which diffusion transforms radical innovations into routine components of the economy — the stage at which Modelski and Thompson say the causal effects of leading sectors dissipate — that generates the productivity gap between nations. The impact timeframe of leading sectors is like "distributing money on the ground," write Newman and Zysman. "Some radically valuable possibilities, the larger bills, are picked up first; the smaller opportunities are captured later. But the original technological revolution loses force, as the most valuable opportunities are picked up and implemented."[23] In contrast, GPT-based growth is more like planting seeds in the ground. The radically valuable possibilities only flourish after a long period of germination. As the classic formulation by Helpman and Trajtenberg goes, there is "a time to sow" and "a time to reap."[24] I refer to this dimension as the *impact timeframe*.

The third dimension on which the two mechanisms differ is the *breadth of growth*. The product cycle tracks the life cycle of a product innovation within a singular industry. Similarly, the LS mechanism emphasizes the contributions of a limited number of new industries to economic growth in a particular period. Whereas LS-fueled productivity growth is driven by a small fraction of industries, GPT-fueled productivity growth is spread across a broad range of industries.[25] In the case of the latter, the extension of localized advances in GPTs across many sectors produces dispersed productivity increases.[26] Table 1 specifies how LS product cycles differ from GPT diffusion along the three dimensions outlined above. As the following section will show, the differences in these two technological trajectories also shape the institutional factors that are most important for national success in adapting to periods of technological revolution.

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21 Modelski and Thompson 1996, 52.
22 Thompson 1990, 211. Freeman et al. (1982, 80) describe this process as "a simultaneous or near-simultaneous explosive burst of growth of one or several major new industries and technologies."
23 Newman and Zysman 2006, 393-394.
24 Helpman and Trajtenberg 1994.
25 See Harberger 1998 for a related formulation of two views of long-term economic growth, which differentiates between mushroom-like and yeast-like growth.
26 Crafts 2001, 306; David and Wright 1999, 12.

Mechanisms	*Impact time-frame*	*Key phase of relative advantage*	*Breadth of growth*	*Institutional complementarities*
LS Product Cycles	Lopsided in early stages	Monopoly on innovation	Concentrated	Adaptations that deepen the skill base in LS innovations
GPT Diffusion	Lopsided in later stages	Edge in diffusion	Dispersed	Adaptations that widen the skill base in spreading GPTs

Table 1: Two Mechanisms of Technological Change and Power Transitions

Institutions for GPT Trajectories: GPT Skill Infrastructure

New technologies agitate existing institutional patterns. They appeal for government support, generate new collective interests in the form of technical societies, and induce organizations that train people in the relevant field. If the institutional environment is slow or fails to adapt, the development of new technologies is hindered. As Gilpin theorizes, a nation's technological "fitness" is rooted in the "extent of the congruence" between its institutions and the demands of evolving technologies.[27]

Which institutions fit best with the demands of GPTs? Institutional adaptations for GPT diffusion must solve two problems. First, the development of GPTs requires effective coordination between the GPT sector and numerous application sectors. Since the GPT sector is interacting with so many different application sectors, each end-user industry is uncertain about the likely direction of technical advance. Moreover, because they benefit from horizontal spillovers as the GPT develops, each application sector wants the other application sectors to bear more of the complementary innovation costs than is in their individual interest. This implies that application sectors will underinvest in the complementary innovations necessary to further spread the GPT.[28]

Second, GPTs demand human capital upgrading. Skilled labor is required for both innovation in the GPT sector and implementation of the new technology in each application

[27] Gilpin 1996, 413. See also Freeman and Louca 2001; Nelson and Winter 1982; Perez 2002.
[28] Bresnahan 2010; Bresnahan and Trajtenberg 1995.

sector.[29] Historical studies attribute the U.S.'s successful adoption of new electrical technologies to the "better match between the technologies advanced by electrification and the country's institutions of education and worker training."[30]

Education and training systems that foster relevant engineering skills for a GPT (*GPT skill infrastructure*) address both types of bottlenecks.[31] These institutions not only supply the needed engineering talent but also help systematize the new knowledge and organizational paradigms associated with GPTs, thereby coordinating information flows between the GPT sector and application sectors. Indeed, the emergence of distinct engineering specialties, such as chemical engineering and electrical engineering, have played an essential role in widening the knowledge base in the wake of a new GPT.[32] As the IR-1 case will show, British mechanical engineering talent was the key limiting factor that prevented France's ability to absorb innovations in machinery.[33] The impacts of new machines were not inevitably realized after they were bought or first implemented; they needed to be maintained and continually updated in different contexts. Centuries later, the growth of computer science, another engineering-oriented field, proved central to U.S. leadership in the information revolution.[34]

The institutional competencies for exploiting LS product cycles are different. Historical analysis informed by this frame highlights heroic inventors like James Watt and pioneering research labs at large companies.[35] For example, Drezner argues that decentralized government structures are necessary for technological leaders to maintain innovation in leading sectors.[36] In his study of which countries benefited most from emerging technologies over the past two centuries, Kitschelt emphasizes the match between the properties of new technologies and sectoral governance structures. Under his framework, tightly coupled technological systems with high causal complexity, such as nuclear power systems and aerospace platforms, were more likely to flourish in countries that allowed for extensive state support.[37] These approaches equate technological leadership with a state's success in capturing market shares and monopoly profits in new industries.

The example of chemical advances in the IR-2 crystallizes these differences. Under the LS model, institutional competencies in science and basic research gain priority. Drezner's analysis of technological leadership in the IR-2, for example, accredits Germany's late-19th century dominance in the chemical industry to its investments in scientific research and highly skilled chemists.[38] These

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29 Aghion and Howitt 2002.
30 David and Wright 2006, 154.
31 GPT skill infrastructure is one of many factors that could affect GPT diffusion. Other institutions, such as industry standards bodies, could also resolve coordination problems. Since human capital upgrading spills over to all these other institutions, GPT skill infrastructure serves as a useful indicator for other institutions that facilitate GPT diffusion.
32 Rosenberg 1998, 169.
33 Harris 1991.
34 Vona and Consoli 2014, 1403-1405.
35 Kennedy 2018, 54; Thompson 1997, 291.
36 Drezner 2001.
37 Kitschelt 1991; see also Kim and Hart 2001; Moe 2009.
38 Drezner 2001, 13-18; Moe 2007, 125.

institutional adaptations supported Germany's control over 90 percent of world production of synthetic dyes — a key segment of the chemical industry and a LS taken to explain Germany's overall industrial dominance.[39]

GPT diffusion spotlights another set of institutional complementarities. The key trajectory was the extension of chemical processes to a wide range of industries beyond synthetic dyes, such as food production, metals, and textiles. Under the GPT model, the U.S., not Germany, achieved leadership in chemicals because it first institutionalized the discipline of chemical engineering. Despite its disadvantages in synthetic dye production and chemical innovation relative to Germany, the U.S. was more effective in broadening the base of chemical engineering talent and coordinating information flows between fundamental breakthroughs with applied technology.[40]

My argument differs from existing explanations. Many scholars have investigated how institutional factors could account for the international competitiveness of nations.[41] Institutional factors commonly held up to explain technological competitiveness include: competitive democracy, decentralized government, industrial governance, national innovation systems, property rights, and varieties of capitalism.[42] Crucially, since this dissertation is limited to the study of shifts in productivity leadership at the technological frontier, many of these factors — such as those related to basic infrastructure and property rights — will not explain differences among technologically advanced nations.

In addition, many of the institutional factors put forth to explain the productivity of nations are technology-agnostic, in that they treat all forms of technological change equally. To borrow language from a former chairman of the U.S. Council of Economic Advisers, these explanations do not differentiate between an innovation in potato chips and an innovation in microchips.[43] In contrast, I am specific about GPTs as the sources of shifts in competitiveness at the technological frontier.

Other theories identify key technologies but leave the institutional factors at a high level of abstraction. Some scholars posit that the lead economy's monopoly on leading-sector innovation eventually erodes because of "ubiquitous institutional rigidities."[44] Unencumbered by the vested interests that resist disruptive technologies, rising challengers inevitably overtake established powers.

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39 Moe 2007, 253-255; Thompson 1990.
40 Rosenberg and Steinmueller 2013.
41 For reviews of the literature on institutions and the international political economy of technological change, see Breznitz 2009; Pedersen 2010.
42 Respectively, see Acemoglu et al. 2018; Drezner 2001; Kitschelt 1991; Nelson 1993; North 1990; Hall and Soskice 2001.
43 Michael J. Boskin once claimed, "It doesn't make any difference whether a country makes computer chips or potato chips." Thurow 1994.
44 Rasler and Thompson 1994, 81; see also Gilpin 1981, 179; Gilpin 1996; Moe 2009.

Because these explanations are underspecified, they cannot account for cases when established leaders sustain their advantage.[45]

3. Methodology

The universe of cases most useful for assessing the GPT and LS mechanisms are technological revolutions (cause) that resulted in an economic power transition (outcome) in the industrial period.[46] Following guidance on testing competing mechanisms that prioritize typical cases where the cause and outcome are clearly present, I investigate the first industrial revolution (IR-1) and second industrial revolution (IR-2).[47] Both cases featured periods of particularly disruptive advances, highlighted by many studies as "technological revolutions,"[48] and economic power transitions, when one great power sustains growth rates at substantially higher levels than its rivals.[49] I also study Japan's challenge to American economic leadership in the third industrial revolution (IR-3), which ultimately did not succeed. Still, deviant case analysis can disconfirm mechanisms and help explain why they break down.[50]

In each of these cases, I first deduce specific implications associated with each mechanism and then examine whether the empirical observations bear out these implications. Setting the GPT and LS mechanisms against each other generates diverging propositions regarding three dimensions of technological trajectories, which match on to different institutional complementarities. I organize the competing explanations "so that they are composed of the same number of diametrically opposite parts with observable implications that rule each other out."[51] I employ within-case congruence tests and process-tracing to evaluate the predictions of the two mechanisms against the empirical record.[52]

I adopt a consistent set of procedures for each case study. The first step is to identify the key technological drivers — the candidate leading sectors and GPTs of the period. I then investigate how these technologies developed in the leading economies, with particular attention to adoption timeframes, the technological phase of relative advantage, and the breadth of technological change — three dimensions which differentiate GPT diffusion from LS product cycles. After tracing

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45 Taylor 2004, 604.

46 I consider the first industrial revolution as a "unique break" in history, separating pre-industrial periods of extremely slow technological advance and modern times characterized by rapid rates of technological advance. Clark 2014, 220.

47 Beach and Pedersen 2019, 97-98; Goertz 2017.

48 Gilpin 1975, 69. Related terms include "technology waves" (Milner and Solstad 2021) and "long waves" (Goldstein 1988).

49 Many others have investigated economic power transitions. Related studies reference shifts in industrial leadership (Moe 2009), leading economies (Modelski and Thompson 1996; Reuveny and Thompson 2001), and the technological hegemon (Drezner 2001, 4). Other works examine differentials in relative economic growth among great powers as one part of a larger process of hegemonic transition. I use the term "economic power transition" because it concisely captures the outcome of interest while avoiding the associations of "industrial" with heavy industry.

50 Beach and Pedersen 2018, 861-863; Goertz 2017, 66.

51 Beach and Pedersen 2013, 15.

52 Blatter and Haverland 2012, 144; George and Bennett 2005, 181-204.

whether the historical evidence supports the GPT or LS trajectory in a particular period, I evaluate whether differences in the institutional competencies of leading industrial powers can explain why certain countries were better positioned to exploit the GPT or LS trajectory. I also weigh evidence for alternative explanations, including those specific to a particular case and those based on general theories. This process enables a structured, focused comparison of the mechanisms across cases.

Given space constraints, what follows is a full analysis of the IR-2 case and abridged summaries of the IR-1 and IR-3 cases. The supplementary appendix provides extended discussions of those other cases as well as a more comprehensive justification for case selection and process tracing.

4. Second Industrial Revolution

In the late nineteenth and early twentieth century, the technological and geopolitical landscape transformed in ways familiar to observers of today's environment. "AI is the new electricity," goes a common refrain that compares current advances in machine intelligence to electrical innovations that first emerged 150 years ago. Those fundamental breakthroughs, alongside others in steel, chemicals, and machine tools, constituted a "Second Industrial Revolution" (IR-2), which unfolded from 1870 to 1914.[53] The beginning of the period featured remarkable technological innovations, including the universal milling machine, the electric dynamo, the synthesis of indigo dye, and the internal combustion engine. In the view of some historians, possibly no other fifteen-year period had a higher density of important scientific breakthroughs than the years between 1859 and 1874.[54]

By the end of the period, there was a new balance of economic power, as captured in the decline of Britain and the rise of Germany and the United States.[55] Landes describes this as a "shift from monarchy to oligarchy, from a one-nation to a multi-nation industrial system."[56] Indicators of per-capita industrialization, per-capita GDP, and labor productivity all confirm that the U.S. overtook Britain in productivity leadership near the 20th century.[57] While Germany significantly narrowed the gap, it did not surpass Britain in productive efficiency. Departing from studies that focus on Anglo-German rivalry in this period, I prioritize explaining how the U.S. took advantage of the IR-2 to become the preeminent economic power.

[53] Though there is some dispute over the exact timeline of the IR-2, I follow the conventional periodization of the IR-2. Hull 1996; Mokyr 1998.
[54] Mowery and Rosenberg 1991, 22.
[55] Gilpin 2001,140; Buzan and Lawson 2015, 43. Drezner 2001.
[56] Landes 1969, 247
[57] Bairoch 1982, 294; Bolt and van Zanden 2020; Broadberry 2006, 110.

The IR-2 provides a good test of the GPT mechanism against the LS mechanism. For many scholars, the international contest for supremacy in this technological revolution functions as a key reference point for the effects of present-day technological advances on the balance of power.[58] The LS account of the IR-2 has strongly influenced thinking about the causes of power transitions. According to this perspective, Germany surpassed Britain in the IR-2 because it dominated innovations in key sectors such as electricity and chemicals. Being "the first to introduce the most important innovations" enabled Germany to pull ahead in terms of economic and industrial strength.[59] Literature on rising powers of today's era follow a similar template. Beckley's assessment of China's power resources, for instance, compares China's scientific and technological capabilities to Germany's ability to develop major innovations in the key chemical, electrical, and industrial dye industries of the IR-2.[60] Studying the IR-2 case is also substantively important, as some scholars view Britain's industrial decline as the ultimate cause of World War I.[61]

The IR-2 should constitute a most-likely case for the LS mechanism. New leading sectors in the electrical, chemical, and steel industries emerged in the early years of the IR-2, and they caught hold in the U.S. and western European countries in the 1880s.[62] Theoretically, this aligns well with the leading sector story. Groundbreaking clusters of technological innovations spurred the growth of new industries in Britain's rivals, which benefited from superior scientific and technical education systems, and an economic power transition occurred by the end of the period.

Historical evidence from the IR-2, however, challenges this conventional narrative. No country monopolized innovation in leading sectors such as chemicals, electricity, steel, and motor vehicles. Productivity growth in the U.S was not dominated by a few R&D-based sectors. Moreover, some of the most prominent technological breakthroughs, including in electricity and chemicals, required a gradual, protracted process of diffusion across many sectors before their impact was felt. This made them unlikely key drivers of the U.S.'s rise before 1914.

Instead, the IR-2 case study supports the GPT mechanism. The key GPT trajectory was embodied in the "American System of Manufactures" (ASoM), characterized by the sequential operation of special-purpose machine tools that enabled mass production. The U.S. did not lead the world in producing the most advanced machinery; rather, it had an advantage over Britain in adapting machine tools across almost all branches of industry. Though the ASoM's diffusion also required a long gestation period, the timing matches with America's industrial rise. Incubated by the growing specialization of machine tools in the 1830s and 1840s, the application of the ASoM across a broad range of manufacturing industries was the key driving force of America's relative economic growth in the IR-2.[63]

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[58] Allison 2017, xviii; Horowitz 2018, 51.
[59] Akaev and Pantin 2014, 869.
[60] Beckley 2011, 63-72.
[61] Gilpin 1975, 77; Organski 1958, 291-292.
[62] Rostow 1960, 175
[63] David 1975; Rosenberg 1972, 87-90.

A clarified trajectory of U.S. technological advantage points toward the institutional advantages that underpinned its rise. LS-based theories tend to highlight Germany's institutional competencies in scientific education and industrial R&D. In contrast, the GPT mechanism emphasizes the success of the U.S. in widening the base of mechanical engineering talent. This was a product of a diverse set of institutional adaptations, including educational institutes, specialized engineering programs at universities, technical high schools, and machine tool associations.

GPT vs. LS Mechanism in the IR-2

Which technological changes could have sparked the economic power transition before World War I? The IR-2 was an age of dizzying technological breakthroughs, including but not limited to the electric dynamo (1871), the first internal combustion engine (1876), the Thomas process for steel manufacturing (1877), and the synthesis of indigo dye (1880). Tracking down how every single technical advance could have affected the growth differentials among Britain, Germany, and the U.S. is an unmanageable task, so I focus on technological changes that could have initiated LS and GPT trajectories. Confirmed to meet the established criteria for leading sectors or GPTs, these technological drivers serve as the fields of reference for assessing the validity of the GPT and LS mechanisms in this case. Specifically, I study the chemicals, electrical equipment, automobile, and steel industries as candidate leading sectors, as well as chemicalization, electrification, the internal combustion engine, and interchangeable manufacture as candidate GPTs.[64]

Equipped with a better grasp of the possible technological drivers of economic power transition in the IR-2, I assess the explanatory power of the LS mechanism vis-à-vis that of the GPT mechanism for how these candidate leading sectors and GPTs affected the distribution of industrial power among leading powers in the IR-2. Concretely, the GPT and LS trajectories diverge along three dimensions: impact timeframe, key phase of relative advantage, and breadth of growth. Based on the differences between the LS and GPT mechanism across these dimensions, I test three sets of diverging propositions for how technological changes created opportunities for an economic power transition in this period.

Impact timeframe: gradual gains vs. immediate effects from new breakthroughs

GPT diffusion and LS product cycles present two competing interpretations regarding the IR-2's impact timeframe. Shortly after radical technological breakthroughs, the LS mechanism expects associated growth to be explosive. Under this view, new leading sectors emerged in the 1870s and 1880s off the back of major breakthroughs in electricity, chemicals, the internal combustion engine, and steel. Then, according to the expected timeline of the LS mechanism, these

[64] On justification for GPT and LS selection, see supplementary appendix.

new industries stimulated substantial growth in the early stages of their development, bringing about a pre-WWI upheaval in the industrial balance of power.[65] This leads to the first hypothesis:

H1.LS: The electrical equipment, chemical, automobiles, and/or steel industries made a significant impact on the U.S.'s rise to productivity leadership before 1914.

The GPT trajectory gives a different timeline for when the productivity benefits from major technological breakthroughs were realized on an economy-wide scale. Before stimulating economy-wide growth, the candidate GPTs that emerged in the 1880s — tied to advances in electricity, chemicals, and the internal combustion engine — required many decades of complementary innovations in application sectors and human capital upgrading. These candidate GPTs should have only contributed modestly to the U.S.'s industrial rise before World War I. If anything, the impacts of electrification, chemicalization, and the internal combustion engine should have materialized toward the very end of the period.

If the GPT mechanism was operational, the full impact of advances in machine tools should have taken effect during this period. By the start of the IR-2, mechanization spurred by advances in machine tools was at a later stage of development than other candidate GPT trajectories. While crude versions of machine tools were employed in national armories in the early decades of the 19th century, independent machinery-producing firms began to emerge in the leading industrial nations between 1840 and 1880. The mid-19th century saw many important innovations in machine tools, including the turret lathe (1845), the universal milling machine (1861), and the automatic lathe (1870).[66]

H1a.GPT: Electrification, chemicalization, and/or the internal combustion engine did not make a significant impact on the U.S.'s rise to productivity leadership before 1914.

H1b.GPT: The extension of interchangeable manufacture made a significant impact on the U.S.'s rise to productivity leadership before 1914.

Tracking the development timelines for all the candidate leading sectors and GPTs of the IR-2 produces two clear takeaways. First, innovations related to electricity, chemicals, and the internal combustion engine did not make a significant impact on U.S. productivity leadership until after 1914. Second, impact timeframes of advances in machine tools and steel align better with when the U.S. overtook Britain as the preeminent economic power.

If the LS mechanism was operational in the IR-2, advances in chemicals should have made a significant impact on relative industrial power before 1914. Summarizing the prevailing account, Moe writes, "The chemical industry is an important reason why industrially, by World War I,

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[65] Gilpin 1987, 98, 112; Thompson 1990, 226.
[66] Hobsbawm 1968, 147.

Germany was Europe's number one power."[67] Clearly, by the late 19th century, Germany took over leadership of the chemical industry from Britain. Germany was the first to incorporate scientific research into chemicals production, resulting in the synthesis of many artificial dyes before 1880.[68] The German chemicals sector drove much of the substantial increase in the global production of dyestuffs, which increased more than 4,000 percent from 1876 to 1913. Specifically, Germany produced 140,000 tons of dyestuffs in 1913, accounting for more than 85 percent of the world total.[69]

An accelerated impact timeframe, however, is less appropriate for the U.S. case. In 1914, there were only seven American dyemakers due in part to the lack of scientifically trained researchers.[70] Major U.S. chemicals firms did not establish industrial research laboratories like those of German counterparts until the first decade of the 20th century. Du Pont, for instance, opened its first industrial research facility in 1902.[71] It is very unlikely that advances in chemicals contributed meaningfully to U.S. productivity growth before WWI.

Moreover, while Germany's growth trajectory in synthetic dyes was impressive, the greatest impact of chemical advances materialized after 1914 through a different pathway: the "chemicalization" of multiple industries, or the spread of chemical processes across a ceramics, food-processing, glass, metallurgy, petroleum refining, etc.[72] At the heart of this process was the concept of "unit operations," inaugurated at MIT in the 1920s, which broke down any chemical process into a sequence of operations common for chemical processing across a number of industries.[73] Before this development, industrial chemistry was focused on the production of a very large variety of chemical products with little concern for the unifying principles across the manufacture of different products.[74] As Rosenberg notes, "The rapid expansion of chemical engineering in the twentieth century, however, was not so much due to the late-nineteenth-century growth of the synthetic dye industries but to other industries that were far more dependent on chemical engineering capabilities."[75]

The timing of electrification mirrored that of chemicalization. From 1880 to 1930, power production and distribution systems gradually evolved from shaft and belt drive systems driven by a central steam engine or water wheel to the electric unit drive system, in which electric motors

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67 Moe 2007, 426. Modelski and Thompson (1996, 69) date the period 1874-1914 as the high-growth period of the chemical industry.
68 Hull 1996, 195.
69 Drezner 2001, 12; Murmann and Landau 1998, 30.
70 Ilgen 1983.
71 For further discussion, see Bruland and Mowery 2006, 358-366.
72 Noble 1977, 18-19 identifies the following as chemical-process industries: petroleum refining, wood distillation, extractive and metallurgical, sugar refining, rubber, canning, paper and pulp, photography, cement, lime and plasters, fertilizers, steel, ceramics and glass, paints and varnishes, soap, leather, textiles, and vegetable oils.
73 Little 1933, 7.
74 Rosenberg 1998, 176.
75 Rosenberg 1998, 171.

powered individual machines.[76] Unit drive became the predominant method in the 1920s, after more machine tools were made to be compatible with electric motors, the rise of large utilities that made cheap electricity widely available, and vigorous debates about the relative merits of unit drive and group drive in technical associations.[77]

Various quantitative indicators of electrification support this timeline. In 1899, electric motors constituted less than five percent of total installed horsepower in American manufacturing industries; this share increased to 25 percent by 1909 but did not reach 55 percent until 1919.[78] Petralia analyzed the causal relationship between the adoption of electrical and electronic (E&E) technologies, operationalized as (E&E) patenting activity in individual American counties, and the per capita growth and wages of those counties over time. He finds that the effects of the adoption of E&E technologies on growth are not significant prior to 1914.[79]

Lastly, the impact timeframe of the internal combustion engine and automobile industry fulfill the expectations derived from the GPT mechanism. The commercialization and diffusion of internal combustion engines across many application sectors was a lengthy process. Despite its initial promise, the internal combustion engine never accounted for more than 5 percent of the generation of total horsepower in U.S. manufacturing from 1869-1939.[80] In 1900, 24 years after the introduction of the internal combustion engine, there were only 8,000 cars in the entire United States.[81] The U.S. motor vehicle industry did not overtake its French competitors as world's largest until 1904.[82] Furthermore, the installation of a moving assembly line for the mass production of Model Ts by Henry Ford, a key development, occurred in 1913.[83]

When assigning credit to certain technologies for major upheaval in global affairs, awe of the new often overwhelms the perseverance of the old. Yet, after carefully tracking when new breakthroughs in electricity, chemicals, and the internal combustion engine interacted with the broader economy, it is unlikely that these technologies were the key drivers of the IR-2's economic power transition. Accounts that attribute the economic rise of the U.S. and Germany to the new electrical and chemical industries have conflated the revolutionary nature of these innovations with instantaneous impact.

In contrast, careful tracing reveals the persevering impact of earlier developments in machine tools and steel — the remaining candidate GPT and leading sector, respectively. First, the GPT trajectory linked to machine tools was incubated much earlier than other candidate GPT trajectories.

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[76] This timeline describes the U.S. economy, which was the quickest to adopt electric power in manufacturing. Devine 1983.
[77] Devine 1982, 17-45; Devine 1983, 368-371.
[78] Devine 1982, 46-47; Rosenberg 1979, 48; see also Crafts 2002.
[79] Petralia 2020, 32.
[80] Du Boff 1967; Jovanovic and Rousseau 2005, 1188.
[81] Smil 2005, 121.
[82] Smil 2005, 136. In 1912, France exported more automobiles than America. (Locke 1984, 9fn18)
[83] Hounshell 1985, 218; Moe 2007: 166-168.

In contrast to breakthrough advances in chemicals and electricity early in the IR-2, technical advances in machine tools during the IR-2 were incremental, continuous improvements that helped disseminate transformative breakthroughs from an earlier period, such as the turret lathe (1845) and the universal milling machine (1861).[84] Accordingly, GPT diffusion theory predicts that interchangeable manufacture, unlike other candidate GPTs, diffused widely enough to make a significant impact on U.S. industrial productivity before 1914.

Profiles of key application sectors validate this expected timeline. Marking 1880 as the date when "the proliferation of new machine tools in American industry had begun to reach torrential proportions," Rosenberg outlines how three application sectors — sewing machines, bicycles, and automobiles — successively adopted improved metal-cutting techniques from 1880 to 1910.[85] Production of the McCormick reaper, a mechanical harvester that significantly improved agricultural productivity, also fully adopted interchangeable manufacture in the early 1880s.[86]

A range of quantitative indicators complement this timeline. Before 1840, the machine tool industry was nascent. By 1914, it had grown to 409 firms with a total output of around $31.5 million.[87] The number of potential machine tool users multiplied fifteen-fold from just 95,000 workers in 1850 to almost 1.5 million in 1910.[88] Leveraging indicators from company records, census data, and patenting by machine tool firms, Thomson identifies the last third of the 19th century as the stage when extensive technological convergence characterized the machine tool industry and application sectors.[89] In sum, the historical data backs up the GPT mechanism's expected impact timeframe for the machine tool industry — one that coincides with when the U.S. overtook Britain in economic power.

Of all the candidate leading sectors, the steel industry best fits the expectations of the LS mechanism regarding when industries transformed by radical innovations stimulated growth in the rising powers. The mid-19th century saw major breakthroughs in the steel industry, such as Bessemer's converter (1856), which allowed for the mass production of steel.[90] Over the course of the IR-2 period, the U.S. and Germany quickly exploited these breakthroughs in steelmaking to massively boost steel production.[91]

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84 Thomson 2010, 10.
85 Rosenberg 1963, 433. Singer, one of the largest sewing machine companies, did not fully adopt the ASoM until the 1870s. Hounshell 1985. The effects of mass production were made clear by World War I at the latest. Piore and Sabel 1984, 20.
86 Hounshell 1985, 182.
87 Census of Manufactures (1914), II, "Reports for Selected Industries," 269. For reference, this was more than the value of US automobile output in 1904 but less than automobile output in 1914 (around $503 million). Rosenberg 1963, 436.
88 Thomson 2010, 9.
89 Thomson 2010, 26.
90 Kuznets 1930, 10.
91 For a detailed study of this process in Germany's steel industry, see Wengenroth 1994.

Both Germany and the U.S. overtook Britain in total steel production by the early 1890s, which matches the timeline of Britain's overall economic decline.[92] German steel output in 1914, at 17.6 million tons, was larger than that of Britain, France, and Russia combined, which Kennedy references as a key factor driving Germany's industrial rise.[93] In 1910 U.S. production of basic steel alone almost doubled that of Great Britain's total steel.[94] During the IR-2 period, the ratio of U.S. to British steel output grew to a peak of 4.6 in 1912 from an initial starting point of .2 in 1871.[95]

Key phase of relative advantage

The second set of observable implications relate to the key phase of technological change that drove growth differentials among the leading industrial powers. While LS product cycles are primarily concerned with which country produced the initial breakthrough, GPT diffusion gives more priority to the ensuing process by which an innovation is adopted. The different emphases of the two models generate opposing, testable claims regarding how candidate leading sectors and GPTs affected the global balance of industrial power during the IR-2.

According to the LS mechanism, Britain's industrial prominence waned because it lost its dominance of innovation in the new industries of the IR-2. The U.S. and Germany benefited from the monopoly profits linked to being lead innovators in electrical equipment, chemical production, automobiles, and steel. Germany's industrial rise in this period garners a disproportionate share of attention. Many LS accounts attribute Germany's rise to its dominance of innovations in the chemical industry, "the first science-based industry."[96] Others emphasize the U.S.'s global lead in the share of fundamental innovations after 1850, which paved the way for it to dominate new industries and become the leading economy in the IR-2.[97]

GPT diffusion has different expectations regarding the key source of comparative advantage for productivity leadership. From this alternative perspective, where innovations are first introduced is not the most crucial; where they spread most successfully is the more important consideration. Therefore, the GPT mechanism expects that Britain lost its industrial preeminence because the candidate GPTs of the IR-2 spread more quickly and across a broader range of application sectors in the U.S. and Germany. This sets up the following hypotheses:

H2a.LS: Innovations in the steel, electrical equipment, chemical, and/or automobile industries were concentrated in the U.S.

H2b.LS: German and American advantages in the production and exports of electrical equipment, chemicals, automobiles, and/or steel were crucial to their productivity leadership.

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92 Sanderson 1972, 15.
93 Kennedy 1987, 210.
94 Hobsbawm 1968, 159.
95 Calculations based on crude steel output figures in Mitchell 1998, 466-467; Mitchell 1993, 356-358.
96 Moe 2007, 125. See also Drezner 2001, 11-18.
97 Thompson 1990.

H2a.GPT: Innovations in machine tools, electricity, chemicals, and/or the internal combustion engine were not concentrated in the U.S.

H2b.GPT: American advantages in the diffusion of interchangeable manufacture were crucial to its productivity leadership.

Tracking the technological trajectories of each LS illustrates that the U.S.'s true comparative advantages over other advanced economies was rooted in absorption and diffusion capabilities. In electric power technologies, for example, innovation leadership was fiercely contested among the industrial powers. The U.S., Germany, Great Britain, and France all built their first central power stations within a span of three years (1882-1884), their first electric trams within a span of 9 years (1887-1896), and their first three-phase AC power systems within a span of 8 years (1891-1899).[98] However, compared to the three other industrial leaders, American leadership in the diffusion of electricity was unquestioned. The spread of incandescent lighting in the U.S. nearly tripled the next closest competitor in 1887; there were ten times as many miles of electric trams in the U.S. than in the next closest competitor in 1900; and U.S. generating capacity in AC power more than doubled that of the next closest competitor in 1912/1913.[99]

Britain's relative backwardness in electricity was a failure of GPT diffusion, not LS innovation. In fact, Britain demonstrated the first steam turbine, invented by the British engineer Charles Parsons, for practical use in 1884, which one economic historian identifies as the most critical innovation for the commercialization of electric power.[100] Though many other electrical innovations were first introduced in Britain, industrial rivals adopted these innovations across a wide range of applications. One 1892 resolution by the British Institute of Electrical Engineers aptly captured this phenomenon, "Notwithstanding that our countrymen have been among the first in inventive genius in electrical science, its development in the United Kingdom is in a backward condition, as compared with other countries, in respect of practical application to the industrial and social requirements of the nation."[101]

The development of the chemical industry in the U.S. and Germany provides further evidence of the non-clustering of innovations in leading sectors. That both the U.S. and German chemical industries outpaced their British competitor during this period shows that no one country monopolized profits from innovation in this candidate LS. Germany's synthetic dye industries excelled not because it generated the initial innovations in aniline-violet dye processes – those were

[98] Taylor 2016, 189.
[99] Germany was the next closest competitor in all cases. Taylor 2016, 189.
[100] Field 2008, 23.
[101] *Electrician* 1902, 46; cited in Hughes 1962, 38.

first introduced in Britain — but because it had perfected these processes for profitable exploitation.[102] Similar dynamics characterized the U.S.'s chemical industry.[103]

Moreover, the limited role of electrical and chemical exports in spurring American growth casts further doubt on the significance of monopoly profits from being the first to introduce new advances.[104] In 1913, Britain had almost double the share of the U.S. in chemical exports.[105] As a whole the U.S. derived only eight percent of its national income from foreign trade in 1913, whereas the corresponding proportion for Britain was 26 percent.[106] Even though the U.S. was the leader in electrification, Germany captured around half of the world's exports in electrical products.[107]

If monopoly profits in any leading sector propelled the U.S. and Germany's industrial rise, it would be the steel industry. The German and American steel industries made remarkable gains in total output over this period, as both boasted growth rates at least three times higher than the British steel industry in the 1890s and 1900s.[108] Scholars commonly employ crude steel production as a key indicator of British decline and the shifting balance of industrial power in the decades before World War I.[109]

Inspecting the advanced economies' steel industries in further detail, however, undermines the significance of total steel output figures to this period's economic power transition.[110] In fact, Britain pioneered many major innovations in steelmaking.[111] As trade data shows, the British iron and steel industries maintained a revealed comparative advantage over their rivals throughout the IR-2.[112] How to square this with Germany's dominance in total steel output? In truth, new steelmaking processes created two separate steel industries. Britain shifted toward producing open-hearth steel, which was higher in quality and price. According to the British Iron Trade Association, Britain produced about four times more open-hearth steel than Germany in 1890.[113] Germany produced cheap Thomas steel and exported a large amount at dumping prices. Some of Germany's steel exports went to Britain, where they were processed into higher-quality steel and re-exported.

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102 Drezner 2001, 12; Hull 1996, 195; Trebilcock 1981.
103 Bruland and Mowery 2006, 362; Murmann 2003, 399.
104 Since the automobile industry developed so late in the period, I focus on potential innovation clustering and monopoly profits from the chemical and electrical industries.
105 Murmann 2003, 401.
106 Kennedy 1987, 244.
107 Henderson 1975, 189-190
108 Calculations based on Thompson 1990, 228. The British maintained comparable growth rates in steel output in the first two decades of the IR-2 (1870s and 1880s).
109 Kennedy 1987, 199-200; Thompson 1990, 213; Modelski and Thompson 1996, 87-88.
110 Relatedly, the most widely used indicator of national power resources, the Composite Indicator of National Capability (CINC), relies on steel production for the period 1900 to 2012 as one of six key factor variables. Greig and Enterline 2017, 45-46. For criticisms of CINC's usage of steel production as an indicator of industrial power, see Wohlforth 1999, 13; Beckley 2018.
111 Hobsbawm 1968, 159; Talbot 1900, 62.
112 Yearly Index of Forging and Heat Treating 1922, 357.
113 Wengenroth 1994, 384.

This evidence disassembles what one scholar deems "the myth of the technological superiority and outstanding productivity of the German steel industry before and after the First World War."[114]

In line with the implications of GPT diffusion, comparative estimates confirm a substantial U.S. lead in mechanization in the early 20th century. In terms of applied horsepower per hour worked, a proxy for machine intensity, in 1907 the U.S. figure was more than two times higher than the British equivalent and about 2.8 higher than the German equivalent.[115] In 1930, the earliest year for which data is available, Germany lagged behind the U.S. in installed machine tools per employee across manufacturing industries by 10 percent, with an even wider gap in the tools most crucial for mass production.[116]

This disparity in mechanization was not rooted in the U.S.'s exclusive access to special innovations in machine tools. In terms of quality, British machine tools were superior to their American counterparts throughout the IR-2 period.[117] Exploiting research from its institutes of technology, Germany also built higher quality machinery in certain fields, including sophisticated power technology.[118] Rather, the distinguishing feature of the U.S. machine tool industry was excellence in adapting innovations across industries.[119]

Reports by British and German study trips to the U.S. provide some of most detailed, reliable accounts of transatlantic differences in manufacturing methods. German observers traveled to the U.S. to learn from their American competitors and imitated their mechanization methods.[120] Reports from British visitors, including those by George Wallis and Joseph Whitworth (1854) and the "Report of the Committee on the Machinery of the United States of America (1855), authored by John Anderson, foresaw that the real threat to continued British industrial dominance was the systematic diffusion of special-purpose machinery across all branches of American industry.[121] America's industrial edge, according to these reports, was in "the adaptation of special apparatus to a single operation in almost all branches of industry"[122] and "the eagerness with which [the Americans] call in the aid of machinery in almost every department of industry."[123]

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[114] Wengenroth 1994, 390.
[115] Calculations based on data in Timmer et al. 2016. For a defense of applied horsepower per hour worked as a useful proxy for American methods of production in this period, see Timmer et al. 879-881. I thank Dr. Woltjer for sharing the link to this data.
[116] Ristuccia and Tooze 2013, 959-960.
[117] Great Britain Committee on the Machinery of the United States of America 1855, 32.; cited in Rosenberg 1963, 420fn12. See also Floud 1976, 68; Litterer 1961, 467.
[118] Braun 1984, 16.
[119] Saul 1960, 22; Rosenberg 1963, 417.
[120] Braun 1984; Nolan 1994; Timmer et al. 2016, 882-883.
[121] The travels of Wallis and Whitworth covered regions that employed 75 percent of the U.S.'s manufacturing workers. Rosenberg 1969, 24. Anderson was a prominent British engineer.
[122] Great Britain Committee on the Machinery of the United States of America 1855, 32.
[123] Whitworth 1969 (originally published in 1854), 387

While the new industries like electricity and chemicals take up much of the spotlight, developments in machine tools underpin the most important pathway between differential rates of technology adoption and the IR-2's economic power transition. After noting the importance of the electrical and chemical industries as two high-growth industries during the period, Hobsbawm elevates the importance of machine tools to the diverging trajectories of the US and UK, "Yet nowhere did foreign countries — and again chiefly the USA — leap ahead more decisively than in this field."[124] On the importance of interchangeable manufacture, Mokyr concludes:

> "[I]t could be argued that the most important invention was not another chemical dye, a better engine, or even electricity...There is one innovation, however, for which 'social savings' calculations from the vantage point of the twentieth century are certain to yield large gains. The so-called American System of manufacturing assembled complex products from mass-produced individual components."[125]

<u>Breadth of growth: the wide reach of interchangeable manufacture</u>

What were the sources of American productivity growth in the IR-2? The pattern of American economic growth is most pertinent to investigate because the U.S. overtook Britain as the preeminent industrial power in the IR-2. Regarding the breadth of economic growth, the LS trajectory expects that American productivity growth was concentrated in a narrow set of modernized industries, whereas the GPT trajectory holds that American productivity growth was dispersed across a broad range of industries. These differences produce the following testable hypotheses:

H3.1: Productivity growth in the U.S. was concentrated in the electrical equipment, chemical, automobile, and/or steel industries.

H3.2: Productivity growth was spread across a broad range of industries linked to interchangeable manufacture.

Historical data support the GPT model's predictions of pervasive U.S. productivity growth. Kendrick's detailed study of U.S. productivity growth in this period depicts a relatively balanced distribution. Among the industries studied, nearly 60 percent averaged between one to three percent increases in output per labor-hour from 1899 to 1909.[126] Per updates to Kendrick's estimates, "great inventions", which roughly correspond to the candidate leading sectors, accounted for only 29 percent of American TFP growth from 1899-1909.[127] From 1899 to 1941, 33 of 38 sectors averaged at least 1 percent annual TFP growth.[128] For instance, despite employing 40 percent of all research

[124] Hobsbawm 1968, 151.
[125] Mokyr 1990, 136.
[126] Kendrick 1961.
[127] Bakker et al. 2019, 2285. "Great inventions" encompass sectors that correspond to chemicals and pharmaceuticals, electricity, the internal combustion engine, and modern communications technologies. See also Bruland and Mowery 2006, 276.
[128] Bakker et al. 2019, 2288

scientists in 1920, the chemical industry's share of U.S. TFP growth over the course of the following decade was only 7 percent.[129]

Broad-based productivity growth in the U.S. economy does not necessarily mean that a GPT was at work. Macroeconomic factors or the accumulation of various, unconnected sources of TFP growth could produce this outcome. Therefore, if the GPT trajectory captures the breadth of growth in the IR-2, then the historical evidence should validate the second part of its core prediction: broadly distributed productivity growth in the U.S. is linked to developments in machine tools.

The extension of the American system of manufactures resulted in positive spillovers on the productivity of a wide range of sectors. Applications of this system of special tools reshaped the processes of making firearms, furniture, sewing machines, bicycles, automobiles, cigarettes, clocks, boots and shoes, scientific instruments, typewriters, agricultural implements, locomotives, and naval ordnance.[130] Its influence covered "almost every branch of industry where articles have to be repeated."[131] Per a 1930 inventory of American machine tools, the earliest complete survey, nearly 1.4 million metalworking machines were used across 20 industrial sectors.[132] The breadth of productivity spillovers from machine tools was not boundless. Machine-using industries constituted a fraction of manufacturing industries, which themselves accounted for less than a quarter of national income.[133] Still, progress in "certain types of new products developed by the machinery and other producer industries (that) have broad applications across industry lines" were a key source of the "broad, pervasive forces that promote efficiency throughout the economy."[134]

Institutional Complementarities: GPT skill infrastructure in the IR-2

With confirmation that the GPT trajectory characterized the pattern of technological change in the IR-2, the natural next step involves probing the variation among leading economies in adapting to the demands of GPT diffusion. Why was the U.S. more successful than Britain in this respect? According to GPT diffusion theory, the historical data should reveal that the success of the U.S. in diffusing machine tool advances was based on institutional adaptations that widened the base of mechanical engineering talent.

In contrast, LS-based theories tend to emphasize Germany's advantage in advanced scientific education as the reason Germany succeeded in science-based industries such as electricity and chemicals. To supplement my analysis of mechanical engineering skills, I also investigate the skill gaps related to chemical innovations. Although the widespread diffusion of chemical advances

129 Bakker et al. 2019, 2290.
130 Anderson 1877; Hounshell 1985; Rosenberg 1963; Thomson 2010.
131 Anderson 1877.
132 Thomson 2010, 6.
133 Harley 2003, 827.
134 Kendrick 1961, 181, 178

did not occur until after the end of the IR-2 period, tracing this process shows that the U.S. benefited the most from chemical breakthroughs because it most effectively institutionalized the chemical engineering discipline.

Skill gap in average mechanical engineers

Most agree that the build-up of human capital, by educational institutions, was a crucial aspect of how the U.S. was able to adapt machine tools and interchangeable manufacture across many industries. Less clear is which institutions and which forms of human capital were most valuable. Some point to general educational explanations. Others highlight the importance of higher education and science-based training. The historical evidence points to the U.S. advantage in producing semi-skilled mechanical engineers, as expected by GPT diffusion theory, as the crucial enabling factor for America's advantage in mechanization.

Some skill-based explanations are unconcerned with the specific pattern of technological change in the IR-2. They argue that the U.S. benefited from a general advantage over Britain in human capital.[135] Time series analysis of UK-U.S. trends from 1890 to 1991 shows that American advantages in human capital formation associated with higher education helped sustain U.S. industrial productivity leadership.[136] Other empirical evidence, more tightly bound to the IR-2 time period in question, casts doubt on this explanation. The years of education per worker increased by essentially the same proportion in both Britain (by a factor of 2.2) and America (by a factor of 2.3) between 1870 and 1929.[137] In his models of productivity convergence among members of the present OECD club from 1850 to 1914, Williamson finds that the contribution of schooling to growth in GDP per worker is "never statistically significant."[138]

Other skill-based explanations are more sensitive to complementarities with developments in specific technologies but focus on the wrong ones. One common explanation, which connects to LS-based interpretations of technological trajectories in the IR-2, is that Germany and the U.S. had an advantage in cultivating highly-skilled scientific talent in the new, science-based industries. Unlike Britain, these rising powers expanded scientific training in universities to prepare graduates for new, expanding industries such as chemicals.

These interpretations suffer from a misplaced attention to both the German case and science-based industries. If advances in machine tools drove the transition in economic leadership to the U.S. at the end of the 19th century, then a different type of institutional complementarity must be considered. The U.S. — the economic leader by the end of the IR-2 — trailed both Britain and

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135 Crafts 1989, 35; Mankiw et al. 1992, 432.
136 Greasley and Oxley 1998. In the context of industrial output per worker, the proxy for higher education is the proportion of 23-year-olds with degrees relative to the industry-wide workforce.
137 Romer 1996, 202. In 1913 the average years of primary and secondary schooling for the 15-64-year age group was higher in Britain than in the U.S. (Greasley and Oxley 1998, 185).
138 Williamson 1996, 296.

Germany in scientific achievements and talent.[139] In the U.S., the spread of machine tool advances across a broad range of metal-using industries was not dependent on scientific knowledge, university training, or industrial R&D laboratories.[140]

The U.S. machine tool trajectory relied, instead, on machinists and mechanical engineers. Machinists multiplied as mechanization advanced, as reflected in the growing ratio of machinists to blacksmiths, who were typically associated with craft methods. In 1870 there were less than half as many machinists as blacksmiths; by 1910 there were nearly two times as many machinists as blacksmiths.[141] The skills required were not found in scientific laboratories. Engineering science, "a translator between the languages of science and of technology," was central to advances in machine tools. According to a dataset of U.S. lathe patents from 1816-1929, the two largest groups of inventors were machinists and engineers (especially mechanical engineers).[142] The potential for technological convergence in the machine tool industry existed for decades before the IR-2, but it was constrained by a scarcity of skilled machinists and mechanical engineers.[143]

The key disparity between the U.S. and Britain in mechanical talent was also in engineering. Workmen of the engineering and machine-making trades were the critical bottleneck for the British Enfield Armory's attempts to adopt the American System of Manufacturing.[144] In 1906 the U.S. had approximately ten times as many engineering students as Britain.[145] Meanwhile in Britain, the University of Oxford "was probably the only first-rate university in the world without an engineering professorship."[146] While British mechanical engineers took pride in their apprenticeship system, which involved learning on the job and a good deal of self-training and experiential learning, American engineers increasingly began to systematically experiment with machine redesigns, benefiting from training at universities and technical institutes.[147]

It was the exploitation of engineering knowledge, not a comparative advantage in industrial scientists, that propelled the US from its "catching up" status to that of a leading nation in the early 20th century.[148] Around the turn of the 20th century, the estimated annual output of American engineers was about one thousand per year, with a total of 14,130 engineering students in 1906.[149] Fifteen years later in 1921, there were less than 7,000 researchers employed in American industry, according to the first survey of American industrial laboratories.[150]

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139 Hughes 1994, 433; Kocka 1980, 95-96; Nelson and Wright 1992, 1940.
140 Bruland and Mowery 2006, 359-360.
141 Thomson 2010, 9.
142 Thomson 2010, 11-12.
143 Locke 1984, 61; Thomson 2010, 14, 15
144 Anderson 1877, 28.
145 Sanderson 1972, 24.
146 Sanderson 1972, 39.
147 Locke 1984, chapter 2; Thomson 2010, 40.
148 Rosenberg and Steinmueller 2013, 1129.
149 Sanderson 1972, 24.
150 Chandler 1990, 84.

Institutional advantages in widening the base of GPT engineering skills

Just like Britain in the IR-1, the U.S. built a superior system of knowledge and skill diffusion in the defining GPT of the IR-2. Before 1870, mechanical engineering education in the U.S. was limited to informal apprenticeships.[151] Over the course of the IR-2 period, the U.S. developed a flurry of efforts to improve technical education in machine tools. There was a diverse GPT skill infrastructure in machine tools, including independent centers like Philadelphia's Franklin Institute, specialized engineering programs at universities such as the University of Cincinnati's cooperative engineering course, technical high schools, machine tool associations, and higher education institutions that favored the mechanical arts.[152] Stimulated by the passage of the Morrill Act, the number of engineering schools grew from six in 1862, when the act was passed, to 126 in 1917.[153]

Beyond boosting the number of academically-trained mechanical engineers, two interrelated developments improved knowledge flows between the machine tool industry and application sectors. First, inter-firm standardization in various machine processes and components, such as screw threads, helped spread mechanization across disparate markets and communities.[154] Second, the emergence and growth of professional associations of mechanical engineers helped build up the repository of engineering skills to translate advances in machine tools to production systems across many industrial sectors. The most prominent of these were The American Society of Mechanical Engineers (ASME), which was founded in 1880, the American Section of the International Association for Testing Materials (ASTM), set up in 1898, and the Franklin Institute, which became America's leading technical society around the start of the IR-2. Coordinated to share best practices and address labor supply issues, many of these national associations evolved from local institutions.[155] Consistent with this was a general trend of new associations and institutes dedicated to improving American skills in the mechanical arts.[156]

These two institutional adaptations were inextricably linked. On their own, individual firms would fail to capture the externalities associated with standardization. Associations like the ASME and ASTM helped promote standardization in machine-making in the broader interests of the industry as a whole. A vibrant cluster of machine tool manufacturers in Philadelphia and the Franklin Institute, especially, were essential to this process. The Franklin Institute played an influential role in establishing and disseminating manufacturing specifications.[157]

Work that attempts to quantify the impact of engineering capacity on American industrialization broadly supports these qualitative accounts. By collecting granular data on engineering density for the U.S. at the county level, Maloney and Caicedo can capture engineering

151 Lundgreen 1990, 55; Scranton 1997, 60.
152 Nelson and Wright 1992, 1942; Scranton 1997, 65-71
153 Noble 1977, 24; See also Maloney and Caicedo 2017, 12-13.
154 Hounshell 1985; Noble 1977.
155 For instance, in 1902 The Cincinnati Industrial Bureau and the local branch of the National Metal Trades Association helped to create the National Machine Tool Builders Association. Scranton 1997, 69. See also: Noble 1977, 76.
156 Rosenberg and Steinmueller 2013, 1130.
157 Morris 1987, 5-6.

talent across various U.S. counties in 1880 and parse the effect of engineering capacity on industrial outcomes decades later. They find that there is a statistically significant, positive relationship between the level of engineering density in 1880 and the level of industrialization decades later.[158] Notably, they also show that engineering density's effect on income is stronger than its effect on patenting, which they take to mean that engineering human capital is more connected to adoption and diffusion than generating novel technologies.[159]

LS-based Theories and Chemical Engineering

Thus far, the analysis of institutional factors has concentrated on explaining American advantage in systematizing machine tool advances because this GPT trajectory was the key driver of the IR-2's economic power transition. Though substantial, economy-wide benefits from the IR-2's chemical breakthroughs did not materialize until after the economic power transition I focus on, tracing which country best exploited these innovations through the interwar period supplements the primary analysis of institutional complementarities for machine tools. This section, therefore, provides a secondary test of which types of institutions are most apt for national success in technological revolutions.

LS-based explanations place high value on Germany's institutional advantages in scientific education and industrial research laboratories. These accounts emphasize Germany's relative edge over Britain in the chemical industry, often dubbed the first science-based industry, due to Germany's advanced scientific education system.[160] Germany's lead in synthetic dyes certainly benefited from its world-leading universities, which produced about two-thirds of the world's chemical research and twice as many academic chemists than Britain in 1890.[161]

Based on a different model of when and how advances in chemicals translated into substantial economic gains, GPT diffusion theory highlights a different set of institutional competencies. Highly skilled chemists were not the crucial asset, since Germany's dominance of synthetic dyestuffs did not meaningfully influence an economic power transition before World War I.[162] After a period of gestation, during which a broad range of industries outside synthetic dyes adapted chemical processes, the widespread diffusion of chemical processing was supported by the institutionalization of chemical engineering.

The historical evidence favors GPT diffusion theory. Despite lagging behind Germany in chemical innovation and top chemists, the U.S. captured the most benefits from the chemicalization

158 Maloney and Caicedo 2017.
159 Maloney and Caicedo 2017, 16.
160 Drezner 2001, 12(fn 33), 13; Henderson 1975, 186; Moe 2007, 4, 142. Other prominent LS accounts focus on industrial chemistry and related indicators such as sulfuric acid production (Modelski and Thopmson 1996; Rostow 1975, 734; Moe 2007, 131)
161 Sanderson 1972, 23. See also Locke 1984, 61.
162 For further support of these points, see the earlier section on the timeframe of impact in chemicals.

of industry because it was the first to institutionalize the discipline of chemical engineering.[163] LS accounts of Germany's dominance in industrial chemistry in the late nineteenth century miss the more significant expansion of chemical processing to a wide range of industries such as ceramics, food-processing, glass, metallurgy, petroleum refining, etc. A crucial step in this process was the emergence of unit operations, which broke down chemical processes into a sequence of basic operations (e.g. condensing, crystallizing, electrolyzing, etc.) that were common in chemical processing across a number of industries.[164] Enabled by unit operations, the development of chemical engineering broke down the siloed divisions of industrial chemistry, which had been primarily oriented around the production of a very large variety of chemical products with little concern for the unifying principles between the manufacture of different products.[165]

Challenging the priority placed on Germany's pre-WWI dominance of industrial chemistry, it was the U.S. that led in cultivating a chemical engineering discipline that facilitated the gradual chemicalization of many industries. American institutions of higher education, most notably MIT, quickly adopted the unit operations model and helped cultivate a common language and professional community of chemical engineering.[166] Rosenberg and Steinmueller conclude, "American leadership in introducing a new engineering discipline into the university curriculum, even at a time when the country was far from the frontier of scientific research, was nowhere more conspicuous than in the discipline of chemical engineering early in the 20th century."[167]

Germany was slow to develop an infrastructure for supporting chemical engineers. In the interwar period, in contrast to the U.S. case, "a unique occupation combining mechanical and chemical expertise failed to coalesce in Germany."[168] Chemical engineering did not become a distinct academic subject area in Germany until after the Second World War. German universities did not equip chemists with engineering skills, thereby shifting the burden of training to firms.[169] The German chemical industry maintained a strict division of labor between chemists and mechanical engineers. The lack of skill systematization resulted in more secrecy, less inter-firm communications, and a failure to exploit externalities from common chemical processes.[170]

Britain was more successful than Germany at cultivating a chemical engineering profession in the interwar period. In fact, controlling for the total population, there were more British

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163 LS-based explanations of Anglo-German differences in chemicals reflect the bias of contemporary British observers in the IR-2. Michael Sanderson, a historian of the British education system, describes British concerns about Germany's excellence in industrial science and chemistry to an "irrational fear" which was undoubtedly spurred by the "menace of Germany, her education, and commercial rivalry." Sanderson 1972, 22. Sanderson argues that outside of chemistry, German universities suffered from many of the same issues faced by British universities, including disengagement from industry.
164 Little 1933, 7; Rosenberg 1993, 176
165 Little 1933, 7; Rosenberg 1993, 176
166 Guédon 1980, 45-76; Noble 1977, 26-27, 192-195; Rosenberg 1998, 171; Trescott 1982.
167 Rosenberg and Steinmueller 2013, 1145
168 Divall and Johnston 1998, 204.
169 Rosenberg 1993, 192.
170 Guédon 1980

accredited chemical engineers than American ones. However, the weak links between British educational institutions and industrial practices limited the dissemination of technical knowledge, and the concept of unit operations did not take hold in Britain to the degree that it did in the states.[171] Unlike the U.S. case, it was not until after WWII that British chemical engineers saw themselves as "members of a professional group that shared a broad commonality cutting across the boundary lines of a large number of industries."[172]

Alternative Explanations

Like its predecessor, the IR-2 is the subject of countless studies. Scholars have widely investigated the decline of Britain and the rise of the U.S. and Germany, offering a diversity of explanations ranging from immigration patterns, cultural and generational factors, natural resource endowments, and labor relations.[173] My aim is not to sort through all possible causes of British decline. Rather, I am probing the mechanisms that underlie an established line of argument — that the technological breakthroughs of the IR-2 spurred an economic power transition. Thus, the contextual factors most likely to confound the GPT diffusion explanation are those that provide an alternative explanation of how significant technological changes translated into the U.S. overtaking of British economic leadership. Aside from the LS mechanism, which has been examined in detail, two other explanations, related to neorealist theories of threat and varieties of capitalism, deserve further examination.

How did external threats influence technological leadership in the IR-2? Scholars have argued that U.S. military investment, mobilized against the threat of a major war, was crucial to the development of many GPTs.[174] Likewise, in the early 19th century U.S. national armories subsidized the production of small arms with interchangeable parts, which some studies argue was crucial to the diffusion of the ASoM to other industries in the second half of the century.[175]

Though firearms production was an important experimental ground for mechanized production, military support was not necessary to the development of the ASoM. Based on his study of the development of interchangeable manufacture in four 19th century industries — clock manufacturing, axe manufacturing, typewriter manufacturing, and watch manufacturing — Hoke shows that government funding and subsidies were not vital to the development of interchangeable manufacture[176] In particular, the clock industry played a crucial role in diffusing mechanized production practices. The clockmakers, more attuned to the dynamics of the civilian economy than the small arms manufacturers, demonstrated that the American system of manufacturing could

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171 Divall and Johnston 1998, 212.
172 Rosenberg and Steinmuller 2013, 1146.
173 Kennedy 1987, 228.
174 Ruttan 2006.
175 Deyrup 1948; Smith 1985.
176 Hoke 1990.

drastically increase sales and cut costs.[177] In his definitive study of the history of American interchangeable parts manufacture, Hounshell concludes, "the sewing machine and other industries of the second half of the 19th century that borrowed small arms production techniques owed more to the clock industry than to firearms."[178]

Moreover, just like LS accounts, military-based explanations of America's rise during the IR-2 also over-emphasize innovation at the expense of diffusion. The spread of the ASoM, not its incubation, is the focal point for understanding how technological-institutional complementarities catalyzed an economic power transition. Over the course of the IR-2, the small arms industry was "an insignificant and diminishing item in the total of American manufacture," contributing to less than .3 percent of value-add in American industry from 1850-1940.[179]

Another threat-based argument posits that countries that face more external threats than internal rivalries will achieve more technological success.[180] In the IR-2 case, however, the U.S. was relatively isolated from external conflicts, while the UK and Germany faced many more threats (including each other).[181] Moreover, the U.S. was threatened more by internal rivalries than external enemies at the beginning of the IR-2, as it had just experienced a civil war.[182] This explanation, therefore, provides little leverage in the IR-2 case.

A second set of alternative explanations argues that giant managerialist firms were crucial to U.S. success. Related to the varieties of capitalism tradition, this explanation highlights U.S. industrial governance structures that enabled big business and the resulting economies of scale and scope that came from mass production.[183] This firm-centered approach contrasts with GPT diffusion theory's emphasis on educational institutions.

The firm-centered approach primarily views America's rise to industrial preeminence through the most visible actors in the American system of political economy: oligopolies in the automobile, steel, and electrical industries. But firms engaged in mass production represented only ten or twenty percent of American manufacturing's contribution to productivity growth.[184] From 1899 to 1909, sectors that relied on batch and custom production, including machine tools, accounted for a third of value added in manufacturing.[185] In fact, over this decade, the increase in

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177 Hounshell 1985, 50-61; Clockmaking also inspired an earlier generation of machine tool builders in Britain. Musson and Robinson 1989.
178 Hounshell 1985, 51.
179 Deyrup 1948, 6.
180 Taylor 2016
181 The Spanish-American War in 1898 is an exception, but this lasted one year and occurred late in the period.
182 Civil wars are categorized as "extreme cases" of high domestic tensions under Taylor's threat-based argument. Taylor 2016, 238.
183 Chandler 1977; Kim and Hart 2001.
184 Scranton 1997, 7.
185 Bureau of the Census 1913, 40-43.

value-add of batch and custom producers exceeded that for bulk and mass producers between 1899 and 1909.[186]

Second, there was significant diversity among leading firms. While many giant corporations did grow to take advantage of economies of scale and capital requirement in some mass-produced goods (e.g. automobiles), networks of medium-sized firms still dominated important segments of these new industries such as the production of electric motors. One third of the fifty largest manufacturing plants in the United States made custom and specialty goods.[187] "No single governance structure matched the requirements of production in all areas," notes Kitschelt.[188]

5. First Industrial Revolution

Few historical events have shaken the world like the IR-1. The contours and consequences of the IR-1 (1780-1840) were marked by extraordinary upheaval. For the first time in history, productivity growth accelerated dramatically, allowing large numbers of people to experience sustained improvements in living standards. Small towns transformed into large cities, new ideologies gathered momentum, and emerging economic and social classes reshaped the fabric of society. These changes reverberated in the international sphere where the ramifications of the IR-1 included the transition to industrialized mass warfare, the decline of the absolutist state, and the birth of the modern international system.

Among the manifold contours and consequences of the IR-1, two phenomena stand out. The first is the remarkable technological progress that inaugurated the IR-1 period. Everything was changing in part because so many things were changing — water frames, steam engines, puddling processes not least among them. The second is Britain's rise to unrivaled hegemony. Britain became the world's most advanced industrial power by the mid-19th century. Crucially, Britain's economic dominance was not based on the overall size of its economy — China was the world's largest economy during this period — but on its ability to take advantage of the technologies of the industrial revolution to become "the world's most advanced productive power."[189] Starting in the 1820s, Britain sustained productivity growth at levels substantially higher than France and the Netherlands.[190]

No study of technological change and power transitions is complete without an account of the IR-1. For both the LS and GPT mechanisms, the IR-1 functions as a typical case that is held up as paradigmatic of technology-driven power transitions. In existing international relations scholarship, the standard account attributes Britain's industrial ascent to its dominance of innovation

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[186] Scranton 1997, 17.
[187] Scranton 1997, 7.
[188] Kitschelt 1991, 472.
[189] Kennedy 2018, 53.
[190] Bairoch 1982, 322; Bolt and van Zanden 2020, 9; Crafts 1995, 752.

in the IR-1's leading sectors, including cotton textiles and the steam engine producing industry. Present-day scholarship and policy discussions often draw upon stylized views of the IR-1, analogizing present developments in information technology and biotechnology to the effects of steam power and cotton textiles in the industrial revolution.

The process-tracing evidence from the IR-1 case challenges many of these stylized views. Previous accounts of prominent technical advances conflated their significance with rapid diffusion. Many prominent advances, including the steam engine, only made limited contributions to Britain's rise to industrial prominence in this period due to their delayed diffusion.[191] The IR-1 case also demonstrates that Britain's advantage in adopting iron machinery across many sectors, as opposed to monopoly profits from innovations in cotton textiles, was crucial to its industrial ascendancy.[192] While the growth of British cotton exports was remarkable, British industrialization drew from widespread technological advances connected to access to cheap iron and mechanization.[193] Across these three dimensions, the GPT trajectory fits the IR-1 case better than the LS trajectory.

Since no country monopolized innovations in metalworking processes and Britain's competitors could also absorb innovations from abroad, why did Britain gain the most from this GPT trajectory? In all countries, as technical advances surged forward, institutional adjustments raced to cultivate the skills required to keep pace. As expected by GPT diffusion theory, Britain benefited from a superior system for disseminating GPT-related knowledge, especially its institutional advantages in widening the talent base of mechanically-skilled engineers. In contrast to the common refrain that Britain's leadership was rooted in the genius of individual innovators like James Watt, the historical data shows that Britain owed its success to the "tweakers" and "implementers" who facilitated mechanization across many industries.[194] In fact, France and other industrial rivals were far ahead in the institutions of higher technical education that trained expert scientists and engineers.[195] However, they lagged behind Britain with respect to a system that connected top engineers to a wider base of talent needed to diffuse the iron-based GPT.[196]

6. Third Industrial Revolution

In the two previous cases, an industrial revolution preceded a shift in global leadership. Britain established its economic dominance in the early 19th century, and the U.S. took the mantle in the late 19th century. During the last third of the 20th century (1960-2000), many recognized that the technological environment was undergoing a transformation akin to those of the first and second industrial revolutions. A cluster of information technologies, connected to fundamental breakthroughs in computers and semiconductors, disrupted the foundations of many industries. The

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191 Nuvolari et al. 2011, 292; von Tunzelmann 1978.
192 Berg 1985, 265; Macleod and Nuvolari 2009; Rosenberg 1970.
193 Horrell et al. 1994, 557; Nuvolari 2009, 223; Sullivan 1990, 354.
194 Meisenzahl and Mokyr 2011, 446; see also Cookson 2018, 154.
195 Mitch 1999; Moe 2007, 42-43.
196 Crouzet 1967, 239; Lundgreen 1990; Jacob 1997.

terms "Third Industrial Revolution" (IR-3) and "Information Age" came to refer to an epochal shift from industrial systems to information-based and computerized systems.[197] Amidst this upheaval, many thought Japan would follow in the footsteps of Britain and the U.S. to become the "Number One" industrial power.[198]

Of the countries racing to take advantage of the IR-3, Japan's remarkable advances in electronics and information technology garnered a disproportionate share of the spotlight. "[T]he more advanced economies, with Japan taking the lead in one industry after another, [were] restructuring their economies around the computer and other high tech industries of the third industrial revolution," Gilpin writes.[199] In the late 1980s and early 1990s, a torrent of works bemoaned the loss of U.S. technological leadership to Japan.[200] "Japan has...become the undisputed world economic champion," declared Clyde V. Prestowitz, Jr, a former U.S. trade negotiator, in his best-selling book on U.S.-Japan relations.[201]

Many perceived Japan's dominance in the IR-3's leading sectors as a threat to international security and the U.S.'s overall leadership of the international system. Prominent thinkers, including Henry Kissinger, warned that Japan would convert its economic strength into threatening military power.[202] Per a 1990 New York Times poll, 58 percent of Americans believed that Japan's economic power was more of a threat to American security than the Soviet Union's military power.[203]

Historical precedents loomed over these worries. U.S. policymakers feared that falling behind Japan in key technologies would, like relative declines experienced by previous leading powers, culminate in an economic power transition. Paul Kennedy and other historically minded thinkers likened the U.S. position in the 1980s to Britain's backwardness a century earlier: two industrial hegemons on the brink of losing their supremacy.[204] Often alluding to the LS mechanism, these comparisons highlighted Japan's lead in specific industries, such as consumer electronics or semiconductors, that were experiencing significant technological disruption. As Mowery and Rosenberg wrote in 1991, "Rapidly growing German domination of dyestuffs helped to propel that country into the position of the strongest continental industrial power. The parallels to the Japanese

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197 See Galambos 2013, 2-4 for a review of work on the history of the IR-3.
198 The most famous example is Vogel 1979. As Drezner (2001, 18) writes, "In 1985, Japan was the only credible challenger to US technological hegemony, and was thought to be an ideal candidate to overtake the United States."
199 Gilpin 1991, 15.
200 Dertouzos et al. 1989; Nelson and Wright 1992, 1932. Analyzing the situation from a long-wave perspective, Freeman et al. (1982, 166, 188) believed that Japan would become the leader of a new wave of transformative innovations.
201 Prestowitz, Jr. 1989, 2.
202 In 1987, Kissinger stated that Japan's decision to lift a ceiling on military spending "makes it inevitable that Japan will emerge as a major military power in the not-too-distant future (Kissinger 1987)." See also Gilpin 1996, 428.
203 Oreskes 1990; cited in Mastanduno 1991, 74
204 Freeman 1987; Kennedy 1987, 529; Nelson and Wright 1992; Piore and Sabel 1984.

strategy in electronics in recent decades are striking."[205] Many voices called for the U.S. to mimic Japanese institutional arrangements, viewed as critical to Japan's strength in leading sectors.[206]

However, the predicted economic power transition never occurred. To be sure, Japanese firms did take dominant positions in key segments of high-growth industries like semiconductors and consumer electronics. Additionally, the Japanese economy also did grow at a remarkable pace, averaging an annual 2.4 percent increase in total factor productivity (TFP) between 1983 and 1991. However, Japan's TFP growth stalled in the 1990s at an average of .2 percent per year — a period known as its "lost decade." By 2002, the per capita GDP gap between Japan and the U.S. was larger than it had been in 1980.[207] Becoming the world's leading producer in high-tech industries did not catalyze Japan's overtaking of the U.S. as the lead economy. Japan took advantage of the IR-3's opportunities by cornering the market in new, technologically progressive industries, fulfilling the conditions posited by the LS mechanism for Japan to become the foremost economic power. This makes the IR-3 case evidence particularly damaging for the LS theory.

From a different perspective, the case evidence shows that Japan did not lead the U.S. in the diffusion of general-purpose information and communications technology (ICT), which means the conditions for an economic power transition under the GPT mechanism were not present in the IR-3. During this period, Japan's TFP growth in ICT-*producing* sectors was similar to the U.S.'s trajectory; however, in sectors that intensively *used* IT, Japan's TFP growth lagged far behind that of its rival.[208] In particular, U.S. ICT-using service industries adapted better to computerization. In terms of labor productivity growth in these industries, the U.S. experienced the strongest improvement out of all OECD countries from the first half of the 1990s to the second half of the decade.[209] In contrast, the contribution of ICT-using services to Japan's labor productivity growth declined from the first half to the second half of the decade.[210]

Since there could be many reasons why an economic power transition does not occur, the absence of a mechanism in a negative case does not provide additional evidence that explains how and when technology-driven economic power transitions do occur. Still, the IR-3 case evidence does provide some, albeit muted, support for the GPT mechanism. The case shows that the LS mechanism expects an outcome that does not occur — a U.S.-Japan economic power transition — because it fails to account for the U.S.'s relative success in GPT diffusion. As supported by a bevy of evidence, this advantage stemmed from the U.S.'s superior ability to cultivate the computer engineering talent necessary to advance computerization. According to one estimate, relative to that

[205] Mowery and Rosenberg 1991, 80; cited in Drezner 2001, 18-19.
[206] Freeman et al. 1982, 198-199; Johnson 1982; Prestowitz, Jr. 1989. These institutional arrangements included the *keiretsu* system of industrial organization, lean production practices, and the organizing role of the Ministry of International Trade and Industry.
[207] Jin 2016.
[208] Fukao and Miyagawa 2007; Jorgenson and Motohashi 2005.
[209] Moe 2009, 219; Pilat et al. 2003, 60-61.
[210] Pilat et al. 2003, 61.

of Japan, the U.S. ICT talent pool was increasing by nearly three times as much per year.[211] Closer university-industry linkages in the U.S. system of higher education, compared to arrangements in Japan or Europe, provided a "thicker basis" for skill adjustments to computerization.[212] In this respect, the IR-3 case demonstrates that deviant cases can help form better mechanism-based explanations.[213]

7. Conclusion

My findings fill significant gaps in existing scholarship on how technological change affects the global balance of power, with broader implications for studying the effects of technological change on international politics. First, the thesis introduces a novel explanation of how and when emerging technologies affect economic power transitions. Scholars recognize that technological revolutions can disrupt the economic balance of power, but few have systematically investigated how this process occurs. GPT diffusion theory challenges the standard explanation based on leading sectors, which exerts enduring influence in policy and academic circles.[214] Since shifts in economic leadership often precede disruptions to the military balance of power and hegemonic conflict, this thesis also contributes to questions power transition scholars have long grappled with related to when and why hegemons come and go.[215]

Second, GPT diffusion theory refutes accepted thinking about how AI and other revolutionary technologies could affect the U.S.-China power balance. Drawing on the LS template, leading thinkers and policymakers in both the U.S. and China place undue emphasis on three points: the rapid timeframe of economic payoffs from AI and other emerging technologies, where the initial, fundamental innovations in such technologies cluster, and growth driven by a narrow range of economic sectors.

GPT diffusion theory suggests diverging conclusions on all three dimensions. The key technological trajectory is the relative success of the U.S. and China in adopting AI advances across many industries in a gradual process that will play out over multiple decades. The most important institutional factors, therefore, may not be R&D infrastructure or training grounds for elite AI scientists but rather those that widen the skill base in AI and enmesh AI engineers in cross-cutting networks with entrepreneurs and scientists. Based on the GPT diffusion framework, the U.S. is better positioned than China to implement AI at scale.

My aim is not to devalue institutions for advanced training and R&D spending. The conventional wisdom has rightly identified these as important variables for technological leadership.

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211 Arora et al. 2013, 771.
212 Hart and Kim 2002, 10.
213 Beach and Pedersen 2019, 102.
214 Drezner 2019, 289; Kennedy 2018; Tellis et al. 2000.
215 Reuveny and Thompson 2001; Wohlforth 1999, 32.

However, it has overlooked the underlying causal process by which R&D spending and higher education institutions influence the ability of rising powers to adapt to periods of significant technological upheaval: facilitating GPT diffusion as opposed to dominating LS product cycles.[216] This distinction makes a difference for precise and effective technology policy. Rebalancing investments toward applied R&D for commercializing and scaling up process innovations, for instance, would represent a national R&D strategy informed by GPT diffusion.[217]

More broadly, this thesis demonstrates a method to unpack the causal effects of technological change on international politics. One bottleneck to researching the technological drivers of changes in the international balance of power, which Harold Sprout articulated back in 1963, is that most theories either grossly underestimate the implications of technological advances or assume technological advance is the "master variable" of international politics.[218] This dissertation takes the middle ground. Technology does not determine the rise and fall of great powers, but some technological trends, like the diffusion of GPTs, do seem to gain an inertia of their own. Social and political factors, such as the domestic institutions highlighted in GPT diffusion theory, shape the pace and direction of these technological trends. This approach is particularly useful for understanding the social-shaping effects of technological change across larger scales of time and space.[219]

[216] R&D investments play an important role in technology transfer and adoption. Fagerberg 1987; Howitt and Mayer-Folkes 2002. As the IR-2 and IR-3 case show, higher education institutions can also help widen the base of engineering talent for spreading a GPT.
[217] For a similar argument about reforming U.S. R&D policies in the context of deliberations over the Endless Frontier Act, which proposes to significantly boost the National Science Foundation's budget, see Hammond 2021.
[218] Sprout 1983, 187.
[219] Dafoe 2015; Herrera 2006; Mayer et al. 2014.

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