The Rise and Fall of Technological Leadership: General-purpose Technology Diffusion and Economic Power Transitions

Jeffrey Ding

George Washington University, United States

Abstract

How do technological revolutions affect the rise and fall of great powers? Scholars have long observed that major technological breakthroughs disrupt economic power balances, yet they rarely investigate 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 institutions suited for monopolizing innovation in new, fast-growing industries (leading sectors). I outline an alternative pathway based on general-purpose technologies (GPTs), foundational advances that boost productivity only after an extended diffusion process across many sectors. Specifically, GPT diffusion demands institutional adaptations that widen the base of engineering skills associated with a GPT. To test this argument, I set the GPT mechanism against the leading-sector mechanism across three cases, which correspond to past 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. The findings support a novel explanation for technology-driven power transitions, directly bearing on how emerging technologies like AI, which some regard as driving a fourth industrial revolution, could influence a possible U.S.-China power transition.

Author's Note

This is an Accepted Manuscript of an article published by Oxford University Press in *International Studies Quarterly* on March 15, 2024, available at: https://doi.org/10.1093/isq/sqae013.

For helpful comments and feedback, I thank: Joslyn Barnhart, Michael Beckley, Stephen G. Brooks, Allan Dafoe, Adam Dean, Alex Downes, Daniel Drezner, Martha Finnemore, Ben Garfinkel, Charlie Glaser, Todd Hall, Yutao Huang, Stephen B. Kaplan, Iris Malone, Karolina Milewicz, Abraham Newman, Carina Prunkl, Toby Shevlane, Robert Trager, Sondre Solstad, participants at panels and seminars at the American Political Science Association, Oxford University, and Stanford University, two anonymous reviewers at *International Studies Quarterly*, and especially Duncan Snidal.

I. Introduction

Policymakers and scholars increasingly frame today's U.S.-China rivalry as a contest for technological leadership in the "Fourth Industrial Revolution" (Doshi 2021). How do technological revolutions affect the rise and fall of great powers? International relations scholars have long recognized that major technological advances often precede economic power transitions, with implications for global military and political leadership. As Yale historian Paul Kennedy has established, the rise and fall of great powers involves "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" (Kennedy 1987, xx). Yet, while scholars have debated how shifts in economic balances affect military power and geopolitical influence, few studies scrutinize the very first step of Kennedy's causal chain: the link between technological change and differentials in long-term growth rates among great powers (Ding 2023; Gilpin 1981; Kennedy 1987; Kirshner 1998).

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 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 technologies. Leading economies, by contrast, are victims of their past success, burdened by powerful vested interests that resist adaptation to disruptive technologies (Gilpin 1996; Moe 2009). Other scholars outline more specific institutional factors that account for why some countries monopolize leading sectors, such as the degree of government centralization or industrial governance structures (Drezner 2001; Kitschelt 1991).

I challenge the leading-sector (LS) interpretation of technology-driven power transitions on empirical 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 (Bresnahan and Trajtenberg 1995), GPTs make a substantial impact on economic productivity only after a "gradual and protracted process of diffusion into widespread use" (David 1990). Electricity, the prototypical GPT, followed this extended trajectory. The first electric dynamo practical for industrial use emerged in the 1870s, but its impact on overall productivity took five decades to materialize (Devine 1983).

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, phase of relative 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 mechanism 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 the contributions of a few key industries 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 mechanism is operative, 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 monopolize LS innovation. Alternatively, GPT diffusion theory highlights institutions that facilitate widespread diffusion of GPTs, including education systems and technical associations that broaden the base of relevant engineering skills.

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 (von Tunzelmann 1997, 2) — 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 each technological revolution translated into differential rates of economic growth among the great powers.

By deepening our understanding of how technological revolutions cause power transitions, this article makes three primary contributions. First, it introduces and defends GPT diffusion theory as a novel explanation for how and when technological change can lead to a power transition. The evidence herein supports the explanatory power of GPT diffusion theory over the standard explanation of technology-driven power transitions based on leading sectors, which exerts enduring influence in policy and academic circles (Drezner 2019, 289; Gilpin 1975; Kennedy 1987; Kennedy 2018; Tellis et al. 2000). In doing so, this article answers the call for the international relations field to devote more attention to the causes of power transitions, not just their consequences (Beckley 2020; Kroenig 2020). Second, GPT diffusion theory revises accepted thinking about how emerging technologies could influence the existing U.S.-China balance. Existing work on this topic emphasize China's capacity to innovate in new leading sectors and capture monopoly rents from new discoveries (Allison and Schmidt 2020; Beckley 2011; Kennedy and Lim 2018). This article highlights the importance of institutions that widen the pool of engineering skills linked to GPTs, which are often ignored by innovation-centered accounts of U.S.-China technological competition.

More broadly, this paper demonstrates an approach to unpack the causal effects of technological change on international politics. One obstacle to researching the technological drivers of changes in the international balance of power is that most theories either grossly underestimate the implications of technological advances or assume technological advance is the "master variable" of international politics (Sprout 1963, 187). This article 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 institutional adaptations to build GPT skill infrastructure, shape the pace and direction of these technological trends. This approach is particularly useful for understanding the effects of technological change across larger scales of time and space.

II. Theories of Technological Change and Power Transition

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," GPTs hold immense potential for boosting productivity (Bresnahan and Trajtenberg 1995). Realizing that promise, however, entails continuous changes across a wide range of technology systems. Understanding the demands of GPTs helps filter which institutional factors are most salient for how technological revolutions bring about economic power transitions. Oriented around institutions that enable GPT diffusion, this explanation highlights the significance of education and training systems that widen the pool of engineering skills and knowledge linked to new GPTs.

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 economist Walt Rostow and adapted by political scientists (Rostow 1978, 104-109; Thompson 1990). 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 (Vernon 1971). In fact, explicit references to the product cycle appear in many LS-based studies (Gilpin 1975, 78, 197; Gilpin 1987, 234-237; Moe 2009, 207; Tellis et al. 2000, 37). 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" (Kurth 1979, 4).

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 attendant monopoly profits in a single nation (Rasler and Thompson 1994, 7). "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" (Modelski and Thompson 1996, 91). The GPT trajectory, in contrast, places more value on where technologies are diffused than where an innovation is first pioneered (Ding 2023). I refer to this dimension as the *phase of relative advantage*.

In the next stage, 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. Mirroring this logic, 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" (Modelski and Thompson 1996, 52). 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" (Thompson 1990, 211; Freeman et al. 1982, 80; Gilpin 1987, 112).

The GPT trajectory assumes a different *impact timeframe*. As noted earlier, because GPTs require major structural changes across countless industries, their greatest marginal stimulation to growth comes decades after their emergence (David 1990; Helpman and Trajtenberg 1994). It is precisely the period when diffusion transforms radical innovations into routine components of the economy — the stage which LS scholars say the causal effects of leading sectors dissipate — that generates the productivity gap between nations.

The product cycle also reveals differences between the LS and GPT mechanisms regarding the *breadth of growth*. Like the product cycle's focus on an innovation's life cycle within a singular industry, the LS mechanism emphasizes the contributions of a limited number of new industries to economic growth in a particular period. GPT-fueled productivity growth, on the other hand, is dispersed across a broad range of industries (Crafts 2001, 306). Table 1 specifies how LS product cycles differ from GPT diffusion along the three dimensions outlined above. Crucially, these technological trajectories shape the institutional factors that are most important for national success in adapting to periods of technological revolution.

Table 1: Two Mechanisms of Technological Change and Power Transitions

Mechanisms	*Impact timeframe*	*Phase of relative advantage*	*Breadth of growth*	*Institutional complements*
LS Product Cycles	Lopsided in early stages	Monopoly on innovation	Concentrated	Deepen skill base in LS innovations
GPT Diffusion	Lopsided in later stages	Edge in diffusion	Dispersed	Widen skill base in spreading GPTs

INSTITUTIONS FOR GPT DIFFUSION: 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 relevant fields. If institutional environments fail to adapt, the development of new technologies is hindered. As Gilpin articulates, a nation's technological "fitness" is rooted in the "extent of the congruence" between its institutions and the demands of evolving technologies (Gilpin 1996, 413; Perez 2002).

If GPTs drive economic power transitions, which institutions fit best with their demands? Institutional adaptations for GPT diffusion must solve two problems. First, since the economic benefits of GPTs materialize through improvements across a broad range of industries, capturing these benefits requires extensive coordination between the GPT sector and numerous application sectors. Given the sheer scope of potential applications, it is infeasible for firms in the GPT sector to commercialize the technology on their own, as the necessary complementary assets are embedded with different firms and industries (Teece 2018).[1] Thus, coordination between the GPT sector and other organizations that provide complementary capital and skills, such as academia and competitor firms, is crucial. In contrast, for technologies that are *not* general-purpose, this type of coordination is less significant and sometimes detrimental to a nation's competitive advantage, as innovating firms could leak technical secrets (Goldfarb et al. 2021).

Second, GPTs place demands on human capital. In describing the connection between skill formation and technological fitness, scholars often delineate between general skills and industry-specific skills. According to this perspective, skill formation institutions that optimize for the former are more conducive to technological domains characterized by radical innovation, while institutions that optimize for the latter are more favorable for domains marked by incremental innovation (Hall and Soskice 2001; Culpepper and Finegold 1999). GPT diffusion entails both types of skill formation. The skills must be specific to a rapidly changing GPT domain but also broad enough to enable GPT adoption across many industries (Aghion and Howitt 2002, 312-313; Streeck 1992, 16). Strong linkages between R&D-intensive organizations at the technological frontier and application areas far from the frontier also play a key role in GPT diffusion. This draws attention to interactions between researchers who produce innovations and technicians who help absorb them into specific contexts (Mason et al. 2020; Rincon-Aznar et al. 2015).

Education and training systems that foster relevant engineering skills for a GPT, or what I call *GPT skill infrastructure*, address both constraints. These institutions not only supply engineering

[1] In the AI domain, as one example of a potential GPT, firms that develop general machine learning algorithms will not have access to all the industry-specific data needed to fine-tune those algorithms to particular application scenarios.

talent but also standardize best practices 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 proved essential in widening knowledge bases in the wake of a new GPT (Rosenberg 1998, 169). Computer science, another engineering-oriented field, was central to U.S. leadership in the information revolution (Vona and Consoli. 2014). While GPT diffusion is dependent on many other factors, I limit my analysis to institutions of skill formation because their effects permeate across other institutional arrangements (Thelen 2004, 285-286; Goldin and Katz 2008).

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 (Kennedy 2018, 54; Thompson 1997, 291). Studying which countries benefited most from emerging technologies over the past two centuries, Herbert Kitschelt prioritizes the match between the properties of new technologies and sectoral governance structures. By way of illustration, under his framework, tightly coupled technological systems with high causal complexity, such as nuclear power systems and aerospace platforms, are more likely to flourish in countries that allow for extensive state support (Kitschelt 1991; Kim and Hart 2001). In other studies, the key institutional factors behind LS product cycles are education systems that subsidize scientific training and R&D facilities in new industries (Drezner 2001; Moe 2009, 216-217). These approaches equate technological leadership with a state's success in capturing market shares and monopoly profits in new industries.

Competing interpretations of leadership in chemicals during the IR-2 crystallize these differences. Based on the LS template, the standard account accredits Germany's late-19th century dominance in the chemical industry — with control over 90 percent of global production of synthetic dyes — to its investments in scientific research and highly skilled chemists (Drezner 2001, 13-18; Moe 2007, 125). GPT diffusion spotlights other institutions that complemented the extension of chemical processes to a wide range of industries beyond synthetic dyes, such as food production, metals, and textiles. Under the GPT mechanism, 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 research, the U.S. was more effective in broadening the base of chemical engineering talent and coordinating information flows between fundamental breakthroughs and industrial applications (Rosenberg and Steinmueller 2013).

It is important to note that some parts of the GPT and LS mechanisms can co-exist. A state's capacity to pioneer new technologies can correlate with its capacity to absorb and diffuse GPTs. Countries home to cutting-edge R&D infrastructure might also be fertile ground for education systems that widen the pool of GPT-linked engineering skills. However, these aspects of the LS mechanism are not necessary to the GPT mechanism. A state can capitalize on GPTs to become the most powerful economy without monopolizing LS innovation. Moreover, there is direct conflict between the mechanisms' expectations regarding impact timeframe and breadth of growth. Thus, while there is some overlap between these two mechanisms, they can still be set against each other in a way that improves our understanding of technological revolutions and power transitions.[2]

My theoretical framework differs from related work on the political economy of technological change (Breznitz 2009; Katzenstein 1985; Olson 1982; Taylor 2016; Weiss 2003). Scholars attribute the international competitiveness of nations to broader institutional contexts, including democracy, national innovation systems, and property rights enforcement (Acemoglu et al. 2018; Nelson 1993; North 1990). Since this paper is limited to the study of shifts in productivity

---

[2] It should be emphasized that this paper owes much to the efforts of LS theorists to flesh out specific linkages among certain technological changes, institutional adaptations, and more highly aggregated economic changes. After all, both mechanisms share a basic premise: To fully uncover the dynamics of technology-driven power transitions, it is essential to specify which new technologies are the key drivers of economic growth.

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. Additionally, most institutional factors put forth to explain the productivity of nations are technology-agnostic, in that they treat all forms of technological change equally. 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 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" (Rasler and Thompson 1994, 81; Gilpin 1981, 179; Gilpin 1996; Moe 2009). Unencumbered by vested interests that resist disruptive technologies, rising challengers inevitably overtake established powers. Because these explanations are underspecified, they cannot account for cases when established leaders sustain their advantage (Taylor 2004, 604).

III. Assessing GPT Diffusion Across Industrial Revolutions

The differences between the GPT and LS explanations yield diverging observable implications for how technological revolutions produce economic power transitions. First, I observe whether emerging technologies generate growth differentials among leading economies through GPT diffusion or LS product cycles. Under the GPT diffusion pathway, there should be an extended lag between initial breakthroughs and their ultimate impact on economic productivity. Additionally, dominating innovation in new industries is not essential for a state to effectively capitalize on a technological revolution; rather, it must lead in the diffusion of GPTs across the entire economy. By extension, that state's productivity growth should be dispersed across a broad range of industries, not concentrated in a few leading sectors.

In mapping these technological trajectories, one key issue is identifying which technologies count as leading sectors and GPTs. Conflicting and expanding lists of GPTs have raised questions about the concept's validity (Field 2008; Ristuccia and Solomou 2014), and definitions of leading sectors are inconsistent across existing studies.[3] To address these concerns in each case study, I first compile a list of all technologies highlighted by key texts and then filter out technologies that do not meet a stable set of criteria for GPTs and leading sectors. For example, while some accounts include the railroad and the automobile as GPTs , I do not analyze them as candidate GPTs because they lack a variety of uses (Field 2008, 12; Mokyr 2006, 1073). I also support my choices with data from studies that identify GPTs with patent-based indicators (Petralia 2020). Taken together, these procedures limit the risk of omitting certain technologies while guarding against GPT and LS concept creep.

Second, I assess whether institutional competencies can account for certain countries' success in exploiting GPT diffusion or LS product cycles. If GPT diffusion holds, the state that gains or sustains economic leadership should have an advantage over its rivals in GPT skill infrastructure. Examples include institutions that widen the repository of engineering skills linked to GPTs, standardize best practices associated with a GPT, and strengthen university-industry linkages in the GPT. Additional evidence of the GPT diffusion theory's explanatory power would be that other countries had advantages in institutions that complement LS product cycles, such as scientific research infrastructure and sectoral governance structures.

I employ within-case congruence tests and process-tracing to evaluate the predictions of the two mechanisms against the empirical record (Blatter and Haverland 2012, 144; George and Bennett 2005, 181-204). The universe of cases most useful for assessing the GPT and LS mechanisms are technological revolutions (cause) that produced an economic power transition (outcome) in the industrial period. Following guidance on testing competing mechanisms that prioritize typical cases

[3] Field 2008; Ristuccia and Solomou 2014. For instance, some studies select leading sectors based on the size of the industry (Kurth 1979, 3), while others maintain that size does not matter (Thompson 1990, 211).

where the cause and outcome are clearly present, I investigate the first industrial revolution (IR-1) and second industrial revolution (IR-2) (Beach and Pedersen 2018; Goertz 2017). Both cases featured periods of particularly disruptive advances, highlighted by many studies as "technological revolutions" (Gilpin 1975, 69),[4] and economic power transitions, when one great power sustains growth rates at substantially higher levels than its rivals (Drezner 2001, 4; Modelski and Thompson 1996; Moe 2009; Reuveny and Thompson 2001).[5] I also study Japan's challenge to American economic leadership in the third industrial revolution (IR-3), which ultimately failed. This deviant case can disconfirm mechanisms and help explain why they break down (Beach and Pedersen 2018, 861-863; Goertz 2017, 66).

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 and the research design.

SECOND INDUSTRIAL REVOLUTION

In the late nineteenth 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 from 150 years ago. Those fundamental breakthroughs, alongside others in steel, chemicals, and machine tools, sparked a "Second Industrial Revolution" (IR-2), which unfolded from 1870 to 1914 (Hull 1996; Mokyr 1998). According to some scholars, one would be hard-pressed to find another period with a higher density of important scientific advances (Mowery and Rosenberg 1991, 22).

[4] Related terms include "technology waves" (Milner and Solstad 2021) and "long waves" (Goldstein 1988).
[5] Productivity is the most important determinant of economic growth in the long run. This aligns with recent scholarship on power measurement, which centers economic efficiency, to check against distorted measures of national power based on gross economic output (Anders et al. 2020; Beckley 2018).

By the end of the period, Britain's decline and the rise of Germany and the U.S. yielded a new balance of economic power. As Kennedy's influential account states, Britain was "in third place," and "in terms of industrial muscle, both the United States and imperial Germany had moved ahead" (Kennedy 1987, 228).[6] Yet, while the U.S. overtook Britain in productivity leadership around the turn of the 20th century, Germany narrowed the gap but ultimately did not surpass Britain in productive efficiency. This is supported by indicators of per-capita industrialization, per-capita GDP (Figure 1), and labor productivity (Bairoch 1982, 294; Bolt and van Zanden 2020; Broadberry 2006, 110). A clarified picture of the outcome helps structure the case analysis, which focuses on whether the GPT or LS account better explains why the U.S. became the preeminent economic power.

Insert Figure 1 here

The IR-2 case favors the LS mechanism in terms of background conditions and existing theoretical explanations, making it a most-likely case for the LS mechanism and a hard test for the GPT mechanism. In the 1880s, major technological innovations spurred the growth of electrical, chemical, and steel industries in Britain's rivals, which matches the general outlines of the LS explanation (Rostow 1978). Many international relations scholars hold up the IR-2 as a classic case of power transitions caused by LS product cycles (Gilpin 1981; Gilpin 1987; Kennedy 2018, 51; Modelski and Thompson 1996). According to this perspective, Germany supposedly surpassed Britain in the IR-2 because it was "the first to introduce the most important innovations" in key sectors such as electricity and chemicals (Akaev and Pantin 2014, 869). Scholarship on today's rising powers follows a similar template, comparing China's scientific and technological capabilities to Germany's ability to develop major innovations in chemicals (Beckley 2011, 63-72; Horowitz 2018).

[6] Linking World War I to Germany's challenge to British economic power, international relations scholarship has directed most of its attention to the Anglo-German rivalry and marginalized the rise of the United States. Chan 2008, 21; Vazquez 1996, 41.

Historical evidence from the IR-2 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 supports the GPT mechanism. Spurred by inventions in machine tools, the industrial production of interchangeable parts, known as the "American system of manufacturing," embodied the key GPT trajectory. 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 American system'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 interchangeable parts across a broad range of manufacturing industries was the key driving force of America's relative economic growth in the IR-2.

Since a nation's success in adapting to technological revolutions is determined by how well its institutions complement the demands of emerging technologies, the GPT-based explanation of the IR-2 highlights institutional factors that differ from those featured in standard accounts. LS-based theories tend to emphasize Germany's institutional advantages in scientific education and industrial R&D. In contrast, the IR-2 case analysis points toward the U.S.'s edge in education and training systems that widened the skill base and standardized best practices in mechanical engineering. These institutional advantages enabled the U.S. to address engineering talent shortages and ineffective coordination between the GPT sector and application sectors — two key constraints on GPT diffusion.

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 unmanageable, 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, and interchangeable manufacture as candidate GPTs.[7]

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. In the 1870s and 1880s, new leading sectors emerged off the back of major breakthroughs in electricity, chemicals, and steel. According to the LS mechanism's expected timeline, these new industries should have stimulated substantial growth in the early stages of their development, bringing about a pre-WWI upheaval in the industrial balance of power (Modelski and Thompson 1996, 69; Moe 2007, 426; Thompson 1990, 226).[8]

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-

[7] Some technological innovations can produce both LS and GPT trajectories. On justification for GPT and LS selection, including overlap between candidate GPTs and leading sectors, see supplementary appendix.
[8] When discussing the impacts of leading sectors on the rise and decline of hegemonic powers, Gilpin (1987, 108) hones in on "the years prior to the First World War (1897-1913)."

wide growth, the candidate GPTs that emerged in the 1880s — tied to advances in electricity and chemicals — 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, with impacts, if any, materializing toward the very end of the period.

Critically, 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, including the turret lathe (1845) and universal milling machine (1861) was at a later stage of development than other candidate GPT trajectories (Hobsbawm 1968, 147).

Developments in chemicals and electricity provide evidence against the LS interpretation. In 1914, the U.S. was home to only seven dye-making firms (Ilgen 1983). Major U.S. chemicals firms did not establish industrial research laboratories like those of German counterparts until the first decade of the 20th century (Bruland and Mowery 2006, 358-366). Thus, it is very unlikely that chemical innovations made a meaningful difference to growth differentials between the U.S. and Britain before 1914.

At first glance, the growth of the German chemical industry aligns with LS expectations. Germany was the first to incorporate scientific research into chemicals production, resulting in the synthesis of many artificial dyes before 1880 (Hull 1996, 195). Overtaking Britain in leadership of the chemical industry, Germany produced 140,000 tons of dyestuffs in 1913, more than 85 percent of the world total (Drezner 2001, 12).

While Germany's rapid growth trajectory in synthetic dyes was impressive, the greater economic impacts of chemical advances materialized *after* 1914 through a different pathway: "chemicalization," or the spread of chemical processes across ceramics, food-processing, glass, metallurgy, petroleum refining, and many other industries (Noble 1977, 18-19). Prior to key chemical engineering advances in the 1920s, industrial chemistry was focused on making chemical products, such as synthetic dyes, with limited attention to unifying principles across the manufacture of different products. The rapid expansion of chemical-based industries in the 20th century owed more to these later improvements in chemical engineering than earlier progress in synthetic dyes (Little 1933, 7; Rosenberg 1998, 171-176).

Electrification's impact on U.S. productivity growth mirrored that of chemicalization. From 1880 to 1930, power production and distribution systems gradually evolved from systems driven by a central steam engine to electric unit drive, a system where electric motors powered individual machines. Unit drive did not become the predominant method until the 1920s (Devine 1983). Estimates of electric motors' share of horsepower in manufacturing as well as the causal effects of electrical patenting activity on per capita growth, along with other quantitative indicators, confirm that electrification's impact on U.S. economic productivity became significant only after 1914 (Crafts 2002; Devine 1983; Petralia 2020).

When assigning credit to certain technologies for major upheaval in global affairs, awe of the new often overwhelms respect for the old. Yet, careful tracing reveals the persevering impact of earlier developments in machine tools. During the IR-2, technical advances in machine tools were incremental, continuous improvements that helped disseminate transformative breakthroughs from the mid-19th century, such as the turret lathe and the universal milling machine (Thomson 2010, 10).

Profiles of key application sectors and quantitative indicators validate the timeline expected by GPT diffusion theory. Marking 1880 as 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 (Rosenberg 1963, 433; Hounshell 1985; Piore and Sabel 1984, 20). The number of potential machine tool users multiplied fifteen-fold from just

95,000 workers in 1850 to almost 1.5 million in 1910 (Thomson 2010, 9). Patenting data identifies the last third of the 19th century as when extensive technological convergence characterized the machine tool industry and application sectors (Thomson 2010, 26).

Phase of relative advantage: the American system's diffusion

When spelling out how the IR-2 produced an economic power transition, the two mechanisms also stress different phases of technological change. 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 electricity, chemicals, automobiles, and steel. For instance, many LS accounts attribute Germany's rise to its dominance of innovations in the chemical industry, "the first science-based industry" (Moe 2007, 125; Drezner 2001, 11-18).

GPT diffusion has different expectations regarding the key driver of growth differentials. Where innovations are adopted more effectively is more important than where they are first introduced. The GPT mechanism expects that Britain lost its industrial preeminence because the IR-2's candidate GPTs diffused more intensively in the U.S. and Germany.

Cross-country historical evidence on the 2IR's technological drivers illustrates that the U.S.'s true comparative advantages over other advanced economies were rooted in absorption and diffusion capabilities. In electricity, for example, innovation leadership was fiercely contested among advanced economies. The U.S., Germany, Britain, and France all built their first central power stations, electric trams, and AC power systems within a span of nine years (Taylor 2016, 189), but the U.S. clearly led in diffusing these systems: U.S. electricity production per capita more than doubled that of Germany, the next closest competitor, in 1912.[9] Britain, despite introducing the

[9] Author's calculations based on the Cross-country Historical Adoption of Technology dataset (Comin and Hobijn 2009).

steam turbine and other significant electrical innovations, lagged behind in adopting electrification at scale (Committee of the Institution of Electrical Engineers on Electrical Legislation 1902).

In chemicals, the success of both the U.S. and German chemical industries suggests that no one country monopolized innovation in this sector. Germany's synthetic dye industry excelled not because it generated initial breakthroughs in aniline-violet dye processes — in fact, those were first pioneered in Britain — but because it had perfected these processes for profitable exploitation (Drezner 2001, 12; Hull 1996, 195). Similar dynamics characterized the U.S. chemical industry (Bruland and Mowery 2006, 362; Murmann 2003, 399).

Moreover, the limited role of electrical and chemical exports in spurring American growth casts further doubt on the significance of monopolizing innovation. The British share of global chemical exports almost doubled the U.S. share in 1913 (Murmann 2003, 401). Overall, 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 (Kennedy 1987, 244). Even though the U.S. led in electrification, Germany captured around half of the world's exports in electrical products (Henderson 1975, 189-190).

If monopoly profits in any leading sector propelled the U.S. and Germany's industrial rise, it would have been the steel industry. Germany and the U.S. made remarkable gains in total steel output over this period, and 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 (Kennedy 1987, 199-200; Thompson 1990, 213; Modelski and Thompson 1996, 87-88). Nonetheless, Britain pioneered major innovations in steelmaking and maintained a revealed comparative advantage in iron and steel industries (Hobsbawm 1968, 159).

How to square this with Germany's dominance in total steel output? In truth, new steelmaking processes created two separate steel industries. Shifting toward a type of steel that was higher in quality and price, Britain produced about four times more open-hearth steel than Germany in 1890 (Wengenroth 1994, 384). 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. This evidence exposes what one scholar calls "the myth of the technological superiority and outstanding productivity of the German steel industry before and after the First World War" (Wengenroth 1994, 390).

In line with the implications of GPT diffusion, comparative estimates confirm a substantial U.S. lead in mechanization in the early 20th century. In 1907, machine intensity in the U.S. was more than two times higher than rates in Britain and Germany.[10] In 1930, the earliest year for which data on installed machine tools per employee is available, Germany trailed the U.S. in this metric by 10 percent, with an even wider gap in the tools most crucial for mass production (Ristuccia and Tooze 2013, 959-960).

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, German firms also had advantages in certain fields like sophisticated power technology (Great Britain Committee on the Machinery of the United States of America 1855, 32; Floud 1976, 68; Braun 1984, 16). Rather, the distinguishing feature of the U.S. machine tool industry was excellence in adapting innovations across industries (Saul 1960, 22; Rosenberg 1963, 417). British study trips to the U.S. reported that America's competitive edge came from the "adaptation of special apparatus to a single operation in almost all branches of industry" (Great Britain Committee on the Machinery of the United States of America 1855, 32) and "eagerness with which [the Americans] call in the aid of machinery in almost every department of industry" (Whitworth 1969, 387). When evaluating the significance of certain technological

[10] Author's calculations based on Timmer et al. 2016.

innovations to economic leadership in this period, economic historians also elevate machine tools and the American system above chemical and electrical innovations (Hobsbawm 1968, 151; Mokyr 1990, 136).

Breadth of growth: the wide reach of interchangeable manufacture

Finally, regarding the breadth of growth, the third dimension on which the two mechanisms diverge, the LS trajectory expects that a narrow set of new industries accounted for productivity differentials, whereas the GPT trajectory holds that a broad range of industries contributed to productivity differentials. The U.S.'s growth pattern serves as the best testing ground for these diverging predictions, since the U.S. overtook Britain as the economic leader in this period.

Historical data support the GPT mechanism'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 industries studied, nearly 60 percent averaged between one to three percent increases in output per labor-hour from 1899 to 1909 (Kendrick 1961). Per updates to Kendrick's estimates, "great inventions," roughly corresponding to the candidate leading sectors, accounted for only 29 percent of American total factor productivity (TFP) growth from 1899-1909 (Bakker et al. 2019, 2285; Bruland and Mowery 2006, 276). From 1899 to 1941, 33 of 38 sectors averaged at least 1 percent annual TFP growth (Bakker et al. 2019, 2288). Despite employing 40 percent of all research scientists in 1920, the chemical industry was responsible for only 7 percent of U.S. TFP growth throughout the following decade (Bakker et al. 2019, 2290).

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 connect broadly distributed productivity growth in the U.S. to developments in machine tools.

Although spillovers from interchangeable manufacturing were not boundless, the extension of the American system boosted productivity in 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 (Hounshell 1985; Rosenberg 1963; Thomson 2010). Its influence covered "almost every branch of industry where articles have to be repeated" (Anderson 1877). Per a 1930 inventory of American machine tools, the earliest complete survey, nearly 1.4 million metalworking machines were used across 20 industrial sectors (Thomson 2010, 6). 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" (Kendrick 1961, 181, 178).

Institutional Complementarities: GPT skill infrastructure in the IR-2

Which institutions for skill formation were most central to the U.S.'s ability to diffuse new advances in machine tools? Previous studies of economic rivalry among great powers in the IR-2 attribute Germany's technological success in this period to its investments in R&D facilities and advanced scientific and technical education (Drezner 2004, 13; Moe 2009, 216-217). American leadership in adoption of interchangeable manufacturing methods was beholden to a different set of institutions for skill formation. It rested, instead, on a broad base of mechanical engineering skills.

With the development of more automatic and precise machine tools throughout the 19th century, mechanization demanded more of machinists and mechanical engineers. Before 1870, U.S. firms relied on informal apprenticeships at small workshops for training machine tool designers and users, as engineering education at traditional colleges did not prioritize mechanical engineers (Lundgreen 1990, 55; Scranton 1997, 60). Yet, craft-era methods and skills were no longer sufficient to handle the enhanced sophistication of machine tools (Thomson 2010, 9). Thus, in the mid-18th century, the need for more formal technical instruction in mechanical engineering presented a strong constraint on the U.S.'s potential for mechanization.

Over the next few decades, advancements on three main fronts met this need for a wider pool of mechanical engineering expertise. First, in 1862, the U.S. Congress passed the Morrill Act, financing the creation of land-grant colleges dedicated to the agricultural and mechanical arts. With support from land-grant funds, the number of U.S. engineering schools multiplied from six in 1862 to 126 in 1917 (Noble 1977, 24; Maloney and Caicedo 2017, 12-13). In 1900, 88 percent of students pursuing mechanical engineering at U.S. higher education institutions were enrolled in land-grant colleges (Dalby 1903, 39).

Second, new technical institutes also served demands for mechanical engineering training. Pure technical schools like the Worcester Polytechnic Institute, founded in 1868, and the Stevens Institute of Technology, founded in 1870, developed mechanical engineering curricula that would become templates for other engineering programs (Seely 2004, 61). Embedded with local and regional businesses, technical institutes developed laboratory exercises that would familiarize students with real-world techniques and equipment. In this respect, these institutes and land-grant colleges "shared a common belief in the need to deliver a practice-oriented technical education" (Seely 2004, 61).

Another significant development in the spread of mechanical engineering knowledge was the emergence of professional engineering societies that created industrial standards. Standardization in various machine processes and components, such as screw threads, helped spread mechanization across disparate markets and communities (Hounshell 1985; Noble 1977). The American Society of Mechanical Engineers and other similar associations coordinated to share best practices and improve knowledge flows between the machine tool industry and application sectors (Noble 1977, 76; Scranton 1997, 69).

Both Britain and Germany fell short of the U.S. standard in GPT skill infrastructure. For Britain, the key gap was in the supply of mechanical engineering talent. In 1901, around 2,600 students were enrolled in full-time higher technical education in the UK (Wickenden 1930, 43). By comparison, in mechanical engineering programs *alone*, the U.S. had 4,459 students enrolled in higher technical education in 1900 (Dalby 1903, 39). Controlling for population differences, the U.S. substantially outpaced Britain in engineering density, as measured by the number of university-educated engineers per 100,000 male laborers (Ahlström 1982; Maloney and Caicedo 2017).

While Germany developed a more accessible form of mechanical engineering education than Britain, it struggled to link this training with industrial applications. From 1870 to 1900, enrollments in German technical colleges increased nearly fourfold (Rose 1903, 51). Key German standards bodies and technical colleges prioritized scientific and theoretical education at the expense of practical skills — a trend "most pronounced in mechanical engineering" (Gispen 1989, 122). The Journal of the Association of German Engineers lamented that German institutions were not equipping students with practical skills and the ability to manage factories and workshops. Compared to their German peers, American students spent less time with theoretical schooling and far more time with exercises in technical laboratories (Figure 2) (Bureau of Education 1894, 193).

Insert Figure 2 here

Crucially, and contrary to the LS mechanism's expectations, the U.S.'s institutional adaptations to new opportunities presented by interchangeable manufacture were not rooted in cultivating scientific experts. The best and brightest American researchers furthered their education at European universities. According to one study of the National Association of German-American Technologists, an organization that regularly facilitated technical exchanges between the two countries, Germany technical institutes held an edge over their U.S. peers in terms of research on mechanical engineering techniques (Braun 1983, 16). Even proponents of American engineering education concluded that "strictly scientific and intellectual education in American technological schools" did not even match "the average of a secondary industrial school" in Germany (Bureau of Education 1895, 676).[11]

FIRST INDUSTRIAL REVOLUTION

Few historical events have shaken the world like the IR-1 (1780-1840). Among the manifold contours and consequences of the IR-1, two phenomena stand out for my purposes. 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 based not on being the world's largest economy — China held that title — but on its ability to take advantage of technological advances to become "the world's most advanced productive power" (Kennedy 2018, 53). Starting in the 1820s, Britain sustained productivity growth at levels substantially higher than France and the Netherlands (Bairoch 1982, 322; Bolt and van Zanden 2020, 9).

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 in the IR-1's leading sectors, most notably the cotton textiles industry (Gilpin 1975, 67-80. Thompson 1990). Present-day scholarship and policy discussions often draw upon a LS account of

[11] While my priority is on demonstrating the explanatory power of GPT diffusion theory relative to the LS account, the supplementary appendix assesses alternative factors in the IR-2 case.

the IR-1, analogizing developments in information technology and biotechnology to the effects of steam power and cotton textiles in the industrial revolution.[12]

The historical evidence challenges many of these assumptions. Time-series data on output growth of 26 industries helps differentiate the growth schedules of the cotton textiles and iron industries. Expanded uses of iron in machine-making — a gradual process compared to the growth of cotton textiles — matched the timeline of when British industrialization outpaced its rivals. In contrast, Britain's cotton textile industry grew exceptionally fast following major technological innovations in the 1760s but experienced a deceleration in output growth from the 1780s onward. Based on this early peak, it is unlikely that the cotton industry was the main driver of the post-1815 upsurge in British productivity growth (Greasley and Oxley 2000, 114. Farnie 2003, 734).[13]

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 (Berg 1985, 265; MacLeod and Nuvolari 2009). While the iron industry accounted for a much smaller proportion of Britain's exports and national income, its impact on productivity materialized through the diffusion of iron machinery across a wide range of sectors (Moe 2007, 86). British industrialization drew from widespread technological advances connected to access to cheap iron and mechanization (Horrell et al. 1994, 557; Nuvolari 2009, 223; Sullivan 1990, 354). Overall, 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, institutional adjustments raced to

[12] For instance, Chinese leader Xi Jinping has analogized China's current efforts to lead a new round of "disruptive technological innovation" to Britain's leadership in IR-1 (Doshi 2021).
[13] Previous accounts also conflated the significance of some advances, including the steam engine, with their rapid diffusion. von Tunzelmann 1978.

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 "tweakers" and "implementers" who facilitated mechanization across many industries (Meisenzahl and Mokyr. 2011, 446; Cookson 2018). In fact, France and other industrial rivals were far ahead in higher technical education institutions that trained expert scientists and engineers (Moe 2007, 42-43). 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 (Crouzet 1967, 239; Lundgreen 1990; Jacob 1997).

Notably, these institutional features — tied to widening the base of mechanical expertise — differed from those more linked with heroic inventions in cotton textiles, the classic leading sector of the IR-1. Collating information from biographies of British engineers, online databases, and detailed economic histories, Ralf Misenzahl and Joel Mokyr constructed a database of 759 British engineers and mechanics who made improvements to existing inventions during the Industrial Revolution (Meisenzahl and Mokyr 2011). Based on analyzing interactions between these tweakers and their institutional surroundings, they found that the textile industry was an outlier in terms of protectiveness over intellectual property rights and reluctance to share information about new techniques. While two-thirds of tweakers in mechanically-inclined fields shared their knowledge with a broader audience or joined professional societies, less than one-tenth of tweakers in textiles did the same.[14]

[14] Author's calculations based on the following four sectors as proxies for mechanical expertise: road and rail and canals, instruments, iron and metallurgy, and other engineering (Meisenzahl and Mokyr 2011, 472).

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 term "Third Industrial Revolution" (IR-3) came to refer to an epochal shift from industrial systems to information-based and computerized systems (Galambos 2013). Amidst this upheaval, many thought Japan would follow in the footsteps of Britain and the U.S. to become the "Number One" industrial power (Vogel 1979).

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. In 1991, Gilpin wrote, "[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 1991, 15). This aligned with a torrent of works published in the late 1980s and early 1990s that bemoaned the loss of U.S. technological leadership to Japan (Freeman et al. 1982, 166, 188; Nelson and Wright 1992, 1932; Prestowitz 1989).

Past precedents loomed over these worries. Paul Kennedy and other historically minded thinkers likened the U.S. position to Britain's backwardness a century earlier: two industrial hegemons on the brink of losing their supremacy (Freeman 1987; Kennedy 1987, 529; Nelson and Wright 1992; Piore and Sabel 1984). Often alluding to the LS mechanism, these comparisons highlighted Japan's lead in technologically progressive industries, such as consumer electronics or semiconductors. 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 strategy in electronics in recent decades are striking" (Mowery and Rosenberg 1991, 80). Many voices called for the U.S. to mimic features of Japan's innovation system, such as the *keiretsu* system of industrial organization and the activist role of the Ministry of International Trade and Industry, viewed as critical to its strength in leading sectors (Freeman et al. 1982, 198-199; Prestowitz, Jr. 1989).

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 (Ding and Dafoe 2021, 199-207). Additionally, Japan's economy did grow at a remarkable pace, averaging an annual 2.4 percent increase in 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 (Jin 2016). Becoming the world's leading producer in high-tech industries, fulfilling the conditions posited by the LS mechanism, did not catalyze Japan's overtaking of the U.S. as the lead economy. This makes the IR-3 case evidence particularly damaging for the LS theory.

On the other hand, 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 absent. 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 (Fukao and Tsutomu 2007). 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 (Moe 2009, 219; Pilat et al. 2003). Conversely, Japan regressed in this metric (Pilat et al. 2003, 61).

The U.S.'s relative success in GPT diffusion stemmed from its capacity to cultivate software engineering skills and establish a computer science discipline, which systematized knowledge necessary to spread computerization. Benefiting from a decentralized, flexible education system as well as openness to tapping foreign talent, the U.S. quickly developed bachelor's degree programs in software engineering (Hislop et al. 2003). Compared to Japan, the U.S. could tap into a broader pool of "programmers undertaking more routine and standardized kinds of software engineering" (Arora et al. 2013, 772). By 2001, according to one estimate, the U.S. ICT talent pool was increasing by nearly three times as much as Japan's per year (Arora et al. 2013).

Japanese universities were slower in adapting to emerging trends in computer science. Centralized control of universities, exercised through the Japanese Ministry of Education, Sport and Culture, hampered cooperative networks between universities and industry (Drezner 2001, 20-22). Bureaucratic rivalries prevented universities from finding alternative sources of funding, limiting partnerships between new computer science departments and corporate labs where much of the computing talent was concentrated. Government funding concentrated in independent centers of excellence, which traded off with Japan's ability to broaden the pool of training institutions in software engineering (Anderson and Myers 1992, 565, 569). In sum, evidence from this case points toward GPT diffusion as the preferred explanation.

IV. Conclusion

This article has presented a novel theory of how and when technological revolutions affect economic power transitions. 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. Scholars recognize that technological revolutions can disrupt the economic balance of power, but few have systematically investigated how this process occurs. GPT diffusion theory suggests modifications to the standard explanation based on leading sectors (Drezner 2019, 289; Kennedy 2018; Tellis et al. 2000). Since shifts in economic leadership often precede disruptions to the military balance of power and hegemonic conflict, this paper contributes to questions power transition scholars have long grappled with related to when and why hegemons come and go (Reuveny and Thompson 2001; Wohlforth 1999, 32).

Additionally, GPT diffusion theory challenges the conventional wisdom about how AI, as the "next GPT" (Brynjolfsson et al. 2021), and other revolutionary technologies could shape the current U.S.-China power balance. Drawing on the LS template, policymakers and scholars frame China's challenge to U.S. technological leadership in terms of which country will first pioneer radical advances in new leading sectors (Allison and Schmidt 2020; National Security Commission on Artificial Intelligence 2021). GPT diffusion theory suggests that 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 support for elite labs and universities or government capacity to support national champions but rather those that widen the skill base in AI and enmesh AI engineers in cross-cutting networks with entrepreneurs and scientists. Based on measures of engineering-oriented AI education and intensive adoption margins for related ICTs, like cloud computing, the U.S. is better positioned than China to implement AI at scale.[15]

It is necessary to acknowledge limitations in translating lessons from past industrial revolutions and power transitions to the present. Scholars have argued that the current era of U.S.-China competition differs from previous eras with respect to the size of the technological and military gap as well as the greater difficulty of translating economic capacity into military capabilities

[15] For GPT diffusion theory's implications for U.S.-China technological competition, see supplementary appendix.

(Brooks and Wohlforth 2016).[16] Future research should probe factors such as the globalization of innovation, qualities unique to digital technologies, and changes in the overall pace of technological change. Still, the historical cases covered in this article exert substantial influence in the minds of academics and policymakers. At the very least, this article submits different lessons to be learned from these guiding precedents.

[16] For an extension of GPT diffusion theory to military balances of power, see Ding and Dafoe 2023.

References

Acemoglu, Daron, Suresh Naidu, Pascual Restrepo, and James A. Robinson. "Democracy Does Cause Growth." *Journal of Political Economy* 127, no. 1 (September 27, 2018): 47–100. https://doi.org/10.1086/700936.

Akaev, Askar, and Vladimir Pantin. "Technological Innovations and Future Shifts in International Politics." *International Studies Quarterly* 58, no. 4 (December 1, 2014): 867–72. https://doi.org/10.1111/isqu.12124.

Anders, Therese, Christopher J Fariss, and Jonathan N Markowitz. "Bread Before Guns or Butter: Introducing Surplus Domestic Product (SDP)." *International Studies Quarterly* 64, no. 2 (June 1, 2020): 392–405. https://doi.org/10.1093/isq/sqaa013.

Anderson, Alun, and Fred Myers. "Japanese Academics Bemoan the Cost of Years of Neglect." *Science* 258, no. 5082 (October 23, 1992): 564–70.

Anderson, John. "Machines and Tools for Working Metals, Wood, and Stone." In *Reports on the Philadelphia International Exhibition of 1876, Volume 1*, 214–36, 1877.

Bairoch, P. "International Industrialization Levels from 1750 to 1980." *Journal of European Economic History* 11, no. 2 (Fall 1982): 269–333.

Bakker, Gerben, Nicholas Crafts, and Pieter Woltjer. "The Sources of Growth in a Technologically Progressive Economy: The United States, 1899–1941." *The Economic Journal* 129, no. 622 (August 1, 2019): 2267–94. https://doi.org/10.1093/ej/uez002.

Beach, Derek, and Rasmus Brun Pedersen. "Selecting Appropriate Cases When Tracing Causal Mechanisms." *Sociological Methods & Research* 47, no. 4 (November 1, 2018): 837–71. https://doi.org/10.1177/0049124115622510.

Beckley, Michael. "China's Century? Why America's Edge Will Endure." *International Security* 36, no. 3 (2011): 41–78.

———. "The Power of Nations: Measuring What Matters." *International Security* 43, no. 2 (November 1, 2018): 7–44. https://doi.org/10.1162/isec_a_00328.

Berg, Maxine. *The Age of Manufactures 1700 -1820*. London: Fontana, 1985.

Blatter, J., and M. Haverland. *Designing Case Studies: Explanatory Approaches in Small-N Research*. Springer, 2012.

Bolt, Jutta, and Jan Luiten van Zanden. "Maddison Style Estimates of the Evolution of the World Economy. A New 2020 Update." Maddison Project Working Paper, 2020.

Bresnahan, Timothy. "General Purpose Technologies." In *Handbook of the Economics of Innovation*, edited by Bronwyn H. Hall and Nathan Rosenberg, 2:761–91. Elsevier, 2010.

Breznitz, Dan. "National Institutions and the Globalized Political Economy of Technological Change: An Introduction." *Review of Policy Research* 26, no. 1–2 (2009): 1–11. https://doi.org/10.1111/j.1541-1338.2008.00388.x.

Broadberry, Stephen. *Market Services and the Productivity Race, 1850–2000: British Performance in International Perspective*. Cambridge Studies in Economic History - Second Series. Cambridge: Cambridge University Press, 2006. https://doi.org/10.1017/CBO9780511495748.

Bruland, Kristine, and David C. Mowery. "Innovation through Time." In *The Oxford Handbook of Innovation*, edited by Jan Fagerberg and David C. Mowery, 350–77, 2006. https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199286805.001.0001/oxfordhb-9780199286805-e-13.

Brynjolfsson, Erik, Daniel Rock, and Chad Syverson. "The Productivity J-Curve: How Intangibles Complement General Purpose Technologies." *American Economic Journal: Macroeconomics* 13, no. 1 (2021): 333–72.

Bureau of Education. "Report of the Commisioner of Education for the Year 1890-91." Washington: U.S. Govt. Print. Off., 1894. https://babel.hathitrust.org/cgi/pt?id=coo.31924067337554&view=1up&seq=5&skin=2021.

———. "Report of the Commisioner of Education for the Year 1892-93." Washington: U.S. Govt. Print. Off., 1895. https://catalog.hathitrust.org/Record/009164574.

Comin, Diego A, and Bart Hobijn. "The CHAT Dataset." Working Paper. National Bureau of Economic Research, September 2009. https://doi.org/10.3386/w15319.

Committee of the Institution of Electrical Engineers on Electrical Legislation. "Report of the Committee of the Institution of Electrical Engineers on Electrical Legislation." *The Electrician*, May 2, 1902.

Crafts, Nicholas. "Historical Perspectives on Development." In *Frontiers of Development Economics*, edited by Gerald M. Meier and Joseph E. Stiglitz, 301–34. World Bank Publications, 2001.

———. "The Solow Productivity Paradox in Historical Perspective." SSRN Scholarly Paper. Rochester, NY: Social Science Research Network, January 1, 2002. https://papers.ssrn.com/abstract=298444.

David, Paul A. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *The American Economic Review* 80, no. 2 (1990): 355–61.

Devine, Warren D. "From Shafts to Wires: Historical Perspective on Electrification." *The Journal of Economic History* 43, no. 2 (June 1983): 347–72. https://doi.org/10.1017/S0022050700029673.

Ding, Jeffrey. "The Diffusion Deficit in Scientific and Technological Power: Re-Assessing China's Rise." *Review of International Political Economy* 0, no. 0 (March 13, 2023): 1–26. https://doi.org/10.1080/09692290.2023.2173633.
Ding, Jeffrey, and Allan Dafoe. "Engines of Power: Electricity, AI, and General-Purpose, Military Transformations." *European Journal of International Security* 8, no. 3 (August 2023): 377–94. https://doi.org/10.1017/eis.2023.1.
———. "The Logic of Strategic Assets: From Oil to AI." *Security Studies* 30, no. 2 (March 15, 2021): 182–212. https://doi.org/10.1080/09636412.2021.1915583.
Doshi, Rush. *The Long Game: China's Grand Strategy to Displace American Order*. Bridging the Gap. New York, NY: Oxford University Press, 2021.
Drezner, Daniel. "State Structure, Technological Leadership and the Maintenance of Hegemony." *Review of International Studies* 27, no. 1 (January 2001): 003–025. https://doi.org/10.1017/S0260210501000031.
Drezner, Daniel W. "Technological Change and International Relations." *International Relations* 33, no. 2 (June 2019): 286–303. https://doi.org/10.1177/0047117819834629.
Floud, Roderick. *The British Machine Tool Industry, 1850-1914*. Cambridge University Press, 1976.
Freeman, Christopher, John Clark, and Luc Soete. *Unemployment and Technical Innovation: A Study of Long Waves and Economic Development*. London: Frances Pinter (Publs.), 1982.
Fukao, Kyoji, and Miyagawa Tsutomu. "Productivity in Japan, the US, and Major EU Economies: Is Japan Falling Behind?" RIETI Discussion Paper Series, 2007.
George, Alexander L., and Andrew Bennett. *Case Studies and Theory Development in the Social Sciences*. Cambridge, MA: MIT Press, 2005.
Gilpin, Robert. "Economic Evolution of National Systems." *International Studies Quarterly* 40, no. 3 (September 1, 1996): 411–31. https://doi.org/10.2307/2600718.
———. *The Political Economy of International Relations*. 1st ed. edition. Princeton, N.J: Princeton University Press, 1987.
———. *U.S. Power and the Multinational Corporation*. London: Palgrave Macmillan UK, 1975.
———. *War and Change in World Politics*. Cambridge University Press, 1981.
Goldin, Claudia, and Lawrence F. Katz. *The Race between Education and Technology*. First Edition. Cambridge, Mass: Belknap Press, 2008.
Goldstein, Joshua S. *Long Cycles: Prosperity and War in the Modern Age*. New Haven: Yale Univ. Press, 1988.
Greasley, David, and Les Oxley. "Comparing British and American Economic and Industrial Performance 1860–1993: A Time Series Perspective." *Explorations in Economic History* 35, no. 2 (April 1, 1998): 171–95. https://doi.org/10.1006/exeh.1997.0688.
Hall, Peter A., and David Soskice. "Introduction." In *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*, edited by Peter A. Hall and David Soskice, 1–68. New York: Oxford University Press, 2001.
Hart, Jeffrey A., and Sangbae Kim. "Explaining the Resurgence of U.S. Competitiveness: The Rise of Wintelism." *The Information Society* 18, no. 1 (January 1, 2002): 1–12. https://doi.org/10.1080/01972240252818180.
Helpman, Elhanan, and Manuel Trajtenberg. "A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies." Working Paper. National Bureau of Economic Research, September 1994. https://doi.org/10.3386/w4854.
Henderson, W. O. *The Rise of German Industrial Power, 1834-1914* /. London :, 1975. http://hdl.handle.net/2027/mdp.39015034645104.
Hobsbawm, E. J. *Industry and Empire: An Economic History of Britain since 1750*. First Edition. London: Pantheon Books, 1968.
Horowitz, Michael. "Artificial Intelligence, International Competition, and the Balance of Power." *Texas National Security Review* 1, no. 3 (2018). https://tnsr.org/2018/05/artificial-intelligence-international-competition-and-the-balance-of-power/.
Horrell, Sara, Jane Humphries, and Martin Weale. "An Input-Output Table for 1841." *The Economic History Review* 47, no. 3 (1994): 545–66. https://doi.org/10.2307/2597593.
Jacob, Margaret C. *Scientific Culture and the Making of the Industrial West*. Oxford University Press, 1997.
Jin, Keyu. "No, China Is Not the 'next Japan.'" World Economic Forum, October 13, 2016. https://www.weforum.org/agenda/2016/10/no-china-is-not-the-next-japan/.
Kendrick, John W. *Productivity Trends in the United States*. Princeton: Princeton University Press, 1961.
Kennedy, Andrew. *The Conflicted Superpower America's Collaboration with China and India in Global Innovation*. Columbia University Press, 2018.
Kennedy, Andrew B., and Darren J. Lim. "The Innovation Imperative: Technology and US–China Rivalry in the Twenty-First Century." *International Affairs* 94, no. 3 (May 1, 2018): 553–72. https://doi.org/10.1093/ia/iiy044.
Kennedy, Paul M. *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000*. New York: Random House, 1987.

Kim, Sangbae, and Jeffrey A. Hart. "Technological Capacity as Fitness An Evolutionary Model of Change in The." In *Evolutionary Interpretations of World Politics*, edited by William R. Thompson, 285–314. New York: Routledge, 2001.

Kitschelt, Herbert. "Industrial Governance Structures, Innovation Strategies, and the Case of Japan: Sectoral or Cross-National Comparative Analysis?" *International Organization* 45, no. 4 (ed 1991): 453–93. https://doi.org/10.1017/S002081830003318X.

Kurth, James R. "The Political Consequences of the Product Cycle: Industrial History and Political Outcomes." *International Organization* 33, no. 1 (1979): 1–34.

Landes, David S. *The Unbound Prometheus*. London: Cambridge University Press, 1969.

Little, Arthur D. *Twenty-Five Years of Chemical Engineering Progress*. Vol. silver anniversary volume. New York: American Institute of Chemical Engineers, 1933.

MacLeod, Christine, and Alessandro Nuvolari. "'Glorious Times': The Emergence of Mechanical Engineering in Early Industrial Britain, c. 1700-1850." *Brussels Economic Review* 52, no. 3/4 (2009): 215–37.

Meisenzahl, Ralf R., and Joel Mokyr. "The Rate and Direction of Invention in the British Industrial Revolution: Incentives and Institutions." National Bureau of Economic Research, April 1, 2011. https://www.nber.org/books-and-chapters/rate-and-direction-inventive-activity-revisited/rate-and-direction-invention-british-industrial-revolution-incentives-and-institutions.

Milner, Helen V., and Sondre Ulvund Solstad. "Technological Change and the International System." *World Politics* 73, no. 3 (July 2021): 545–89. https://doi.org/10.1017/S0043887121000010.

Modelski, George, and William R Thompson. *Leading Sectors and World Powers: The Coevolution of Global Politics and Economics*. Columbia S.C.: University of South Carolina Press, 1996.

Moe, Espen. *Governance, Growth and Global Leadership: The Role of the State in Technological Progress, 1750-2000*. Modern Economic and Social History. Burlington, VT: Ashgate, 2007.

———. "Mancur Olson and Structural Economic Change: Vested Interests and the Industrial Rise and Fall of the Great Powers." *Review of International Political Economy* 16, no. 2 (June 26, 2009): 202–30. https://doi.org/10.1080/09692290802408865.

Mokyr, Joel. *The Lever of Riches: Technological Creativity and Economic Progress.* New York: Oxford University Press, 1990.

———. "The Second Industrial Revolution, 1870-1914." In *Storia Dell'economia Mondiale*, 1998.

Mowery, David C., and Nathan Rosenberg. *Technology and the Pursuit of Economic Growth*. Cambridge: Cambridge University Press, 1991.

———. "The U.S. National Innovation System." In *National Innovation Systems: A Comparative Analysis*, edited by Richard R. Nelson. Oxford University Press, 1993.

Murmann, Peter. "Chemical Industries after 1850." In *Oxford Encyclopedia of Economic History*, 398–406. Oxford University Press, 2003.

Nelson, Richard R. *National Innovation Systems: A Comparative Analysis*. Oxford University Press, 1993.

Nelson, Richard R., and Gavin Wright. "The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective." *Journal of Economic Literature* 30, no. 4 (1992): 1931–64.

Noble, David F. *America by Design: Science, Technology, and the Rise of Corporate Capitalism*. Knopf, 1977.

North, Douglass C. *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, 1990.

Perez, Carlota. *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*. Illustrated edition. Cheltenham, UK ; Northampton, MA, USA: Edward Elgar Pub, 2002.

Piore, Michael J., and Charles F. Sabel. *The Second Industrial Divide: Possibilities for Prosperity*. Basic Books, 1984.

Prestowitz, Jr., Clyde. *Trading Places: How We Are Giving Our Future to Japan and How to Reclaim It*. New York: Basic Books, 1989.

Rasler, Karen A., and William R. Thompson. *The Great Powers and Global Struggle, 1490-1990*. University Press of Kentucky, 1994.

Reuveny, Rafael, and William R. Thompson. "Leading Sectors, Lead Economies, and Economic Growth." *Review of International Political Economy* 8, no. 4 (January 1, 2001): 689–719. https://doi.org/10.1080/09692290110077629.

Ristuccia, Cristiano Andrea, and Adam Tooze. "Machine Tools and Mass Production in the Armaments Boom: Germany and the United States, 1929-44." *The Economic History Review* 66, no. 4 (2013): 953–74.

Rosenberg, Nathan. "Chemical Engineering as a General Purpose Technology." In *Chemical Engineering as a General Purpose Technology*, edited by Elhanan Helpman, 167–92. Cambridge, MA: MIT Press, 1998.

———. "Technological Change in the Machine Tool Industry, 1840-1910." *The Journal of Economic History* 23, no. 4 (1963): 414–43.

———. *Technology and American Economic Growth*. M. E. Sharpe, 1972.

———, ed. *The American System of Manufactures*. Edinburgh University Press, 1969.

Rosenberg, Nathan, and W. Edward Steinmueller. "Engineering Knowledge." *Industrial and Corporate Change* 22, no. 5 (October 1, 2013): 1129–58. https://doi.org/10.1093/icc/dts053.

Rostow, Walt W. *The World Economy History & Prospect*. Austin: Univ. of Texas Press, 1978.
Sanderson, Michael. *The Universities and British Industry, 1850-1970*. First Edition. London: Routledge and Kegan Paul, 1972.
Saul, S. B. "The American Impact on British Industry 1895–1914." *Business History* 3, no. 1 (December 1, 1960): 19–38. https://doi.org/10.1080/00076796000000014.
Sprout, Harold. "Geopolitical Hypotheses in Technological Perspective." *World Politics* 15, no. 2 (1963): 187–212. https://doi.org/10.2307/2009373.
Taylor, Mark Zachary. "Empirical Evidence against Varieties of Capitalism's Theory of Technological Innovation." *International Organization* 58, no. 3 (2004): 601–31.
———. *The Politics of Innovation: Why Some Countries Are Better Than Others at Science and Technology*. 1st edition. New York, NY: Oxford University Press, 2016.
Tellis, Ashley J., Janice Bially, Christopher Layne, and Melissa McPherson. *Measuring National Power in the Postindustrial Age:* Santa Monica, CA: RAND Corporation, 2000. https://www.rand.org/pubs/monograph_reports/MR1110.html.
Thelen, Kathleen Ann. *How Institutions Evolve: The Political Economy of Skills in Germany, Britain, the United States, and Japan*. Cambridge Studies in Comparative Politics. Cambridge ; New York: Cambridge University Press, 2004.
Thompson, William R. "Long Waves, Technological Innovation, and Relative Decline." *International Organization* 44, no. 2 (1990): 201–33. https://doi.org/10.1017/S0020818300035256.
Thomson, Ross. "Eras of Technological Convergence: Machine Tools and Mechanization in the United States, 1820-1929," 2010.
Timmer, Marcel P., Joost Veenstra, and Pieter J. Woltjer. "The Yankees of Europe? A New View on Technology and Productivity in German Manufacturing in the Early Twentieth Century." *The Journal of Economic History* 76, no. 3 (September 2016): 874–908. https://doi.org/10.1017/S0022050716000760.
Tunzelmann, G. N. von. "Innovation and Industrialization: A Long-Term Comparison." *Technological Forecasting and Social Change* 56, no. 1 (September 1, 1997): 1–23. https://doi.org/10.1016/S0040-1625(97)00027-9.
———. *Steam Power and British Industrialization to 1860*. Oxford Eng. ; New York: Clarendon Press, 1978.
Vernon, Raymond. *Sovereignty At Bay*. Basic Books, 1971.
Vogel, Ezra F. *Japan as Number One: Lessons for America*. Cambridge: Harvard University Press, 1979.
Weiss, Linda. *States in the Global Economy: Bringing Domestic Institutions Back In*. Cambridge University Press, 2003.
Whitworth, Joseph. "Special Report of Joseph Whitworth." In *The American System of Manufactures*, edited by Nathan Rosenberg. Edinburgh: Edinburgh University Press, 1969.