The Rise and Fall of Great Technologies and Powers

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Abstract

How and when do technological changes affect the rise and fall of great powers? Scholars have long observed that rounds of technological revolution disrupt the economic balance of power, bringing about a power transition in the international system. However, there has been surprisingly limited investigation into how this process occurs. The standard explanation emphasizes a country's ability to dominate innovation in leading sectors, seizing monopoly profits in new, fast-growing industries centered around major technological breakthroughs. 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. This GPT trajectory shapes which institutions matter. Specifically, variation in institutional adaptations that widen the human capital base to enable the spread of GPTs explain why some industrial leaders separate themselves from the pack. To test this argument, I set the leading-sector mechanism against the GPT diffusion mechanism across three historical case studies: Britain's rise to preeminence in the Industrial Revolution; America and Germany's overtaking of Britain in the second industrial revolution; Japan's challenge to America's technological dominance in the information technology revolution. Evidence from these case studies supports the relative explanatory power of the GPT mechanism over the leading-sector mechanism. According to some categorizations, these cases correspond to history's three industrial revolutions. Given that many argue we are in a fourth industrial revolution, the findings of this dissertation should be particularly relevant for how emerging technologies like AI will affect a possible U.S.-China power transition.

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AI	.....	Artificial Intelligence
ASoM	.....	American System of Manufacturing
ASME	.....	American Society of Mechanical Engineers
ASTM	.....	American Section of the International Association for Testing Materials
CME	.....	Coordinated market economy
DRAM	.....	Dynamic random-access memory
E&E	.....	Electrical and electronic
ENIAC	.....	Electronic Numerical Integrator and Calculator
GPT	.....	General-purpose technology
HDTV	.....	High-definition television
ICT	.....	Information and communications technology
IFR	.....	International Federation of Robotics
IR-1	.....	First industrial revolution
IR-2	.....	Second industrial revolution
IR-3	.....	Third industrial revolution
IR-4	.....	Fourth industrial revolution
LME	.....	Liberal market economy
LS	.....	Leading sector
MPD	.....	Maddison Project Database
OECD	.....	Organisation for Economic Cooperation and Development
TFP	.....	Total factor productivity
VoC	.....	Varieties of Capitalism

Chapter 1 Introduction

In the summer of 2020, OpenAI, a San Francisco-based AI lab, released the ultimate autocomplete tool: GPT-3. Trained on a dataset of nearly all the text on the web, GPT-3 soon set the entire internet aflame. Early users demonstrated GPT-3's ability to produce human-like text, which produced amazing results in writing code, translating languages, and generating poetry, science fiction, and essays from scratch.[1] Six months after its launch, one compilation listed 66 unique use cases of GPT-3, which ranged from automatically updating spreadsheets to generating website landing pages.[2]

While the name GPT-3 derives from a class of language models called generative pre-trained transformers, the acronym, coincidentally, also speaks to the broader significance of recent breakthroughs in AI: the arrival of the next general-purpose technology (GPT). Foundational breakthroughs in the ability of computers to perform tasks that usually require human intelligence have the potential to transform countless industries. Hence, scholars and policymakers often compare advances in AI to electricity, the quintessential GPT.[3]

In this dissertation, I examine the implications of GPTs for the balance of economic power in the international system. I argue that the ability to adopt GPTs on a widespread scale is central to the rise and fall of great powers, a process that involves, as Yale historian Paul Kennedy has established, "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

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[1] To the best of my knowledge — and believe me, I have searched wide and far — GPT-3 has not yet figured out how to write dissertations.

[2] Dickson 2021.

[3] A Google search for the exact phrase "AI is the new electricity," conducted on January 15, 2020, returned about 37,000 hits. Ng, founder of Google Brain, first popularized this comparison in a 2017 speech at Stanford. In 2014, Kevin Kelly, the former editor of *Wired*, wrote, "Everything that we formerly electrified we will now cognitize…business plans of the next 10,000 startups are easy to forecast: Take X and add AI." Kelly 2014.

balances."[4] By investigating the role of GPTs in the first step of this process — the link between technological change and differentials in long-term growth rates among great powers — I develop a novel explanation for how and when technological changes affect power transitions.

International scholars have long recognized the effects of technological change on the rise and fall of great powers, so it may be surprising to suggest that a new approach is necessary. Yet, while most acknowledge the link between disruptive technological breakthroughs and disruptions to the balance of power, few study the specific mechanism that underlies this connection. Among those that do, the standard explanation stresses which country pioneers critical technological advances in new, fast-growing industries. Exploiting monopoly profits, the country that dominates innovation in these leading sectors rises to become the world's most productive economy. Prominent examples often cited in support of this explanation include Britain's early lead in textiles during the Industrial Revolution and Germany's mastery of the emerging chemical industry in the late 19th century.

Diverging from the received wisdom, I suggest that the historical relationship between GPTs and productivity growth points toward another explanation of technology-driven power transitions. Compared to other technologies, GPTs tend to have more potential for continuous improvement, pervasive applicability across the economy, and synergies with complementary advances in other technologies. Studies of the productivity effects of electricity and computers, two prototypical GPTs, have shown that the diffusion of GPTs across a broad range of applications is a prolonged process that demands significant institutional and technological adjustments. In fact, after the release of GPT-3, OpenAI CEO Sam Altman alluded to this extended trajectory, "The GPT-3 hype is way too much...it still has serious weaknesses and

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[4] Kennedy 1987, xx.

sometimes makes very silly mistakes. AI is going to change the world, but GPT-3 is just a very early glimpse. We have a lot still to figure out."[5]

Informed by historical patterns of GPT diffusion, I construct a mechanism that diverges from the leading-sector (LS) explanation of how technological changes influence power transitions. The ultimate economic impacts of GPTs materialize in a pathway that differs from those of other technologies, including notable leading sectors such as textiles in the Industrial Revolution. My explanation of economic power transitions places less priority on which country monopolizes innovations in leading sectors and more on which country leads in the diffusion of GPTs. These two diverging trajectories match onto different institutional competencies for national success in emerging technologies. Specifically, I posit that differences in institutional adjustments to widen the skill base for GPT diffusion determine which great powers rise and which ones fall.

To test this argument, I set the leading-sector mechanism against the GPT diffusion mechanism across three historical case studies: Britain's rise to preeminence in the Industrial Revolution; America and Germany's overtaking of Britain in the second industrial revolution; Japan's challenge to America's technological dominance in the information technology revolution. Evidence from these case studies supports the relative explanatory power of the GPT mechanism over the LS mechanism. In all three revolutions, technological changes affected the rise and fall of great powers in a gradual, decades-long impact pathway that advantaged those that effectively diffused GPTs across a broad range of sectors. In each of the cases, successful GPT diffusion was based on education and training systems that cultivated broad pools of engineering talent in the GPT.

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[5] Vincent 2020. Many also noted that some of the most impressive examples were cherry-picked, and that GPT-3 still requires a lot of fine-tuning from humans. For more background on GPT-3, see Dale 2020.

These three cases allow me to probe the mechanism that connects major technological breakthroughs with economic power transitions. The first and second industrial revolution function as typical cases where the cause and outcome are clearly present, which are ideal for developing and testing mechanism-based theories.[6] In the information technology revolution, revolutionary technological breakthroughs occurred, but Japan did not overtake the U.S. as the new economic leader. This deviant case helps trace where the LS mechanism breaks down and provides further validation of the GPT mechanism. Since the publication of the field-defining works on technology and power transitions, new sources of evidence, such as the Cross-country Historical Adoption of Technology dataset, and new studies, including the application of econometric methods to quantify the historical significance of technological innovations, have significantly improved our understanding of the time periods covered by the case studies. In addition to gathering a variety of primary and secondary sources, I draw on these materials to trace how GPTs catalyze major shifts in economic leadership.

The thesis makes several contributions to scholarship on the causes of power transitions and the effects of technological change on international politics. First, it puts forward a new mechanism for how and when significant technological breakthroughs generate a power transition in the international system. GPT diffusion theory challenges the LS explanation, which is the dominant account in the existing literature. Second, in explaining the technological causes of power transitions, my argument offers a more grounded way to study the implications of emerging technologies for international affairs. Existing scholarship on the causes of power transitions has either grossly underestimated the implications of technological advances or assigned technological advance an overly determining role. Different from both of these

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[6] Beach and Pedersen 2019, 97-98; Goertz 2017.

approaches, I show how the interaction between institutional factors and GPT diffusion decides which countries take advantage of technological revolutions to achieve productivity leadership.

Finally, the findings of this thesis bear directly on present-day technological competition between the U.S. and China. Emphasizing where fundamental breakthroughs are first seeded, the LS template strongly informs not only assessments of the U.S.-China competition for technological leadership but also how leading policymakers in both countries formulate technology strategies. The three cases in my study correspond to history's three industrial revolutions. Given that many claim major technological breakthroughs, like GPT-3 and other advances in AI, are driving a fourth industrial revolution, GPT diffusion theory should be particularly relevant for reframing the contours of a U.S.-China power transition.

This introduction is organized as follows. Section 1.1 describes the state of the question, briefly reviewing existing arguments about emerging technologies and shifts in economic leadership. I introduce my argument about GPT diffusion in Section 1.2, explaining how the fit between GPT trajectories and national institutional competencies decides the balance of economic power. Section 1.3 provides a roadmap for the thesis.

1.1 The international relations of technology-driven power transitions

1.1.1 Leading sectors and the new "Tech Cold War"

In recent years, U.S.-China technological competition has intensified, leading many to go as far as proclaiming a new "Tech Cold War."[7] U.S. policymakers fear that China's advances in a range of critical technologies, such as AI, pose an "existential threat" to U.S. technological leadership.[8] They are not alone in connecting emerging technologies with power shifts. "Artificial intelligence is the future, not only for Russia, but for all humankind," said Russian President

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[7] See, for example, Segal 2019; Zhong and Mozur 2018.

[8] Council on Foreign Relations 2018.

Vladimir Putin in 2017. "It comes with colossal opportunities, but also threats that are difficult to predict. Whoever becomes the leader in this sphere will become the ruler of the world."[9]

How and when do technological changes shape who rules the world? Contemporary discussions of China's challenge to U.S. technological leadership align neatly with an influential theory in international relations based on "leading sectors," which argues that a country gains productive leadership of the global economy by cornering the key technological innovations in new, high-growth industries.[10] Drezner summarizes, "Historically, a great power has acquired hegemon status through a near-monopoly on innovation in leading sectors."[11] An influential RAND report reiterates this view in terms similar to Putin's remarks about artificial intelligence, "[The nation that] dominates these leading sectors dominates the world."[12]

The leading-sector (LS) explanation essentially takes the product life cycle, a model for how firms should understand the progression of a product in the marketplace, and applies it to national economies.[13] Much like the product cycle's emphasis on how firms capture exclusive profits from product innovations, the LS account highlights the monopoly profits a country gains from dominating innovations in the leading sectors, which "tend to cluster in time and space."[14] In the product cycle, there is a very limited time window for firms to corner these gains from innovation before competitors imitate the product. Similarly, international relations scholars also posit that leading sectors provide the greatest relative economic advantage to pioneers early in the sector's development before the innovations spread to other countries. Lastly, the product cycle tracks the life cycle of a single innovation in one industry; likewise, the LS explanation focuses on

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[9] Vincent 2017.

[10] Each assuming prominence at various periods over the past two and a half centuries, the textile, steel, and automobile industries are often held up as classic leading sectors. Kurth 1979, 3.

[11] Drezner 2001, 7; Drezner (2019, 289) repeats this claim in an article marking the centenary of the international relations discipline.

[12] Tellis et al. 2000, 39.

[13] In fact, one prominent LS-based account makes this exact comparison. Kurth 1976, 5.

[14] McNeil, 1974, 37; cited in Gilpin 1981, 181; Modelski and Thompson 1996, 91; Schumpeter 1962, 81-87.

the contributions of a narrow range of new industries on shifts in economic leadership. Though specific accounts vary, these broad outlines of LS theory underpin the work of Gilpin, Kennedy, Modelski and Thompson, Rostow, and Schumpeter.[15]

Leading sector accounts typically point to a few, remarkable technical breakthroughs and their effects on propelling certain countries to global leadership. The classic case is Great Britain's rise to global preeminence, which they claim was driven by its control of the innovations of the First Industrial Revolution (steam power and textiles).[16] Britain's subsequent decline, according to leading sector accounts, was due to the U.S. and Germany taking global leadership through achieving leads in critical sectors such as chemicals, electricity, and steel.[17] Lastly, they believe that the leading sectors of the postwar period — automobiles, aviation, electronics, and information and communications technologies — have cemented U.S. hegemony.[18] Rarely questioned by international relations scholars, this account influences both scholarship on scientific and technological power as well as present-day narratives of a U.S.-China technology race.

Yet, while the leading sector template is frequently referenced, it has not been systematically investigated. Long-cycle theorists show correlation between output in leading sectors and the relative economic growth rates of system leaders.[19] For instance, William R. Thompson's study, published by *International Organization*, matched variation in the output of leading sectors, such as civilian jet airframe production (1950-1990), to changes in the aggregate growth rates of leading economies.[20] These studies are mainly focused on proving the existence

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[15] Gilpin 1981; Gilpin 1987; Kennedy 1987; Modelski and Thompson 1996; Rostow 1960; Schumpeter 1934; Schumpeter 1939; Thompson 1990.
[16] Kennedy 1983, 150-151.
[17] Drezner 2001; Thompson 1990.
[18] Kennedy 2018.
[19] For the best review of the long-cycle literature, see Goldstein 1988.
[20] Thompson 1990.

of cyclical fluctuations in technological change and international economic leadership, but they do not investigate how and why the two processes are connected.

Indeed, much of the international relations literature paints the mechanism of technology-driven power transitions in broad brush strokes. Another influential explanation, which also has cyclical components, holds that leading economies are victims of their past success, burdened by powerful vested interests that resist adaptation to disruptive technologies.[21] Gilpin writes, "A national system of political economy that was most 'fit' and efficient in one era of technology and market demand is very likely to be 'unfit' in a succeeding age of new technologies and new demands."[22] The "advantages of backwardness," therefore, enable rising challengers to inevitably overtake established powers.[23] Since there are many cases where poorer countries fall further behind, these explanations have been criticized for not specifying the conditions under which convergence occurs.[24]

1.1.2 The state of the question: Technological changes and power transitions

There is a wide swath of social science literature that investigates national differences in prosperity. Economists, geographers, and historians have offered a variety of explanations for why some nations grew rich and others stayed poor, probing factors such as climate, culture, geography, human capital, technology.[25] Most relevant for my purposes, recent work by Acemoglu and Robinson has argued that "inclusive" institutions, including broad-based property rights and contract enforcement, are the key determinants of the growth differentials among nations.[26] This approach has been helpful in explaining diverging economic trajectories between

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[21] Gilpin 1996; Gilpin 1981, 179; Moe 2009.
[22] Gilpin 1996, 413.
[23] Gerschenkron 1962.
[24] Beckley 2018a, 113-115; Taylor 2004, 604.
[25] For a summary of this rich literature, see Acemoglu et al. 2005, 397-402.
[26] Acemoglu and Robinson 2013.

advanced economies and less developed ones, most notably the "Great Divergence" in the 19th century between Western Europe and East Asia.

This literature is less useful in accounting for divergences among the advanced economies themselves, which all have basic institutional competencies like broad-based property rights. In other words, it can explain why Western Europe diverged from East Asia but not why Britain diverged from the rest of Western Europe after the Industrial Revolution. The nature of technological competition is different for advanced economies. Scholars have found that divergences in long-term economic growth among advanced economies, which have strong capacities to absorb technologies from abroad, are shaped more by imitation than innovation.[27] Another common view is that the role of the state must shrink in guiding industrial transformation as a country gets closer to the technological frontier. In fact, Drezner argues that the very institutions that are crucial for technological catch-up in developing countries may constrain innovation at the technological frontier.[28] Additionally, recent empirical research has found that certain factors, such as openness to trade level of higher education, are more growth-enhancing in countries closer to the technological frontier.[29]

Differences at the technological frontier suggest that explanations of the Great Divergence require modification when applied to the rise and fall of great powers. Developing a mechanism of technological change and economic growth differentials that is specific to leading economies does limit the external validity of theory. However, understanding the dynamics behind the outcome variable, hegemonic power transitions, is a significant undertaking in its own right. Shifts in industrial leadership could result in a hegemonic war that determines who governs

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[27] Fagerberg 1987; Pavitt and Soete 1982.

[28] Drezner 2001, 18. The post-developmental state literature, mostly centered on East Asia, also supports this argument. Hsueh 2011; Yeung 2016.

[29] Aghion et al. 2014.

the international system, which Gilpin calls the "ultimate test of change in the relative standings of the powers in the existing system."[30]

The extensive body of work on institutions and the international political economy of technological change does speak to differences among developed economies.[31] Two streams of this research are particularly relevant for my question. The first attributes varied rates of technological change across industrialized democracies to differences in their domestic economic and political institutions. The second emphasizes the international forces that influence whether states can sustain technological success. The presence of both international linkages and threats has been linked to variation in national innovation rates.

With respect to the institutional foundations of international competitiveness, the Varieties of Capitalism (VoC) framework stands out. It highlights differences in the ways that firms organize behavior in coordinated market economies (CMEs) and liberal market economies (LMEs). In CMEs, such as Germany and Japan, non-market coordination shapes economic activities, whereas in LMEs, which include the U.S. and UK, market institutions coordinate economic behavior. According to VoC theory, LMEs specialize in radical innovation, whereas CMEs are more adept at incremental innovation.[32] Related work compares national innovation systems, captured by the relationships among national institutions responsible for technological development.[33]

The other stream of research explores the international dimensions of technological development. Some scholars emphasize the role of international security threats in motivating

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[30] Gilpin 1981, 198.
[31] Two of the canonical works in this tradition: Katzenstein 1985; Olson 1982. See also Cerny 1990; Porter 1990; Rosecrance 1999; Weiss 2003. For overviews, see Breznitz 2009; Pedersen 2010.
[32] Hall and Soskice 2001.
[33] Lundvall 1992; Nelson 1993.

states to adopt the latest technologies.[34] Threat-based accounts of technological success posit that states leverage external security threats to invest in institutional changes that allow for technological progress. Additionally, the globalization of scientific and technological development is another international variable that impacts the long-term technological capabilities of states. This literature identifies institutional adjustments to globalizing forces as an important factor in the economic trajectories of nations.[35]

Though these explanations help inform our understanding of how technological advances could generate an economic power transition in different ways, they gloss over the specifics of technological development. That is, they treat all forms of technological change equally. By only considering the rate of technological growth in aggregate, these studies do not explore how various types of technologies interact with political systems in different ways. To paraphrase a former chairman of the U.S. Council of Economic Advisers, this approach makes no distinction between an innovation in potato chips and an innovation in microchips.[36]

A few scholars do pay attention to how the match between specific institutions and specific types of technological change affects economic power transitions. Inspired by evolutionary economics, these studies highlight the interactive relationship between technological change and institutional adjustment.[37] Drezner argues that a decentralized state structure is necessary for a state to maintain technological leadership because decentralization increases the likelihood that the state can "hit on the correct formula for fostering lead technologies."[38] In Kitschelt's analysis of international competition in emerging technologies over the past two

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[34] Doner et al. 2005; Milner and Solstad 2021; Ruttan 2006; Taylor 2016.
[35] Kenney and Florida 2004; Saxenian and Hsu 2001.
[36] Michael J. Boskin allegedly said, "It doesn't make any difference whether a country makes computer chips or potato chips." Thurow 1994.
[37] Katzenstein 1978; Kim and Hart 2001; Kitschelt 1991.
[38] Drezner 2001, 9.

centuries, the match between state structure and the optimal industrial organization of key technologies is crucial.[39] Kitschelt posits, in contrast to Drezner, that centralized structures are crucial to cultivating some technologies, such as nuclear technology or aircraft.

Though these more developed explanations provide a useful starting point for my argument, they still treat technological leadership as a function of a state's success in capturing market shares and monopoly profits in new industries. The focal institutional factors are those that enable a nation's firms to be competitive in these new industries — i.e., dominating product cycles in leading sectors. But a state's "technological fitness" is not just about being the first to enter into a new industry.[40] In fact, in key periods of industrial transformation, technological fitness is more about successfully adapting GPTs across a wide range of industries. We still lack a general mechanism for how GPTs interact with institutional changes to produce major shifts in economic power.

1.2 The central argument: GPT diffusion

I argue that the pathway by which GPTs impact economic productivity illuminates an alternative mechanism of how technological change affects power transitions. The emergence of GPTs, fundamental advances that can transform many industries, provides an opening for major shifts in economic leadership. Characterized by their scope for continuous improvement, pervasive applicability across the economy, and synergies with other technological advances, GPTs carry an immense potential for boosting productivity.[41] Carefully tracking how that productivity boost is realized, a process I refer to as GPT diffusion, is essential to understanding how technological revolutions disrupt economic power balances.

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[39] Kitschelt 1991.
[40] I borrow this term from Kim and Hart 2001.
[41] Bresnahan and Trajtenberg 1995.

The diffusion of GPTs is an especially demanding undertaking. Specifically, the full impact of a GPT manifests only after a "gradual and protracted process of diffusion into widespread use."[42] Take electricity, the prototypical GPT, as an example. The first electric dynamo practical for industrial use emerged in the 1870s, but the boost of electrification to overall manufacturing productivity did not materialize until about five decades later.[43] Electricity brought about structural changes in a wide range of technology systems only after complementary technological breakthroughs, including steam turbines that powered large utilities, and organizational adaptations, such as decentralized factory layouts to make full use of electric drive.

GPTs affect economic power balances in a pathway that differs significantly from the standard LS account. Specifically, I show how the two mechanisms differ along three key dimensions, which relate to the timeframe of impact, relative source of advantage, and breadth of growth. First, the LS mechanism emphasizes the impact of technological innovations in the early stages of their life cycle. Thompson argues, "The greatest marginal stimulation to growth may therefore come early in the (leading) sector's development at the time when the sector itself is expanding rapidly."[44] This clashes with the GPT trajectory. As the above passage demonstrated, the greatest effects on productivity come late in a GPT's development.

Regarding the key phase of relative advantage, the GPT and LS mechanisms diverge on the relative weight of innovation and diffusion. The LS mechanism is primarily concerned about which country is the first to introduce breakthroughs in leading sectors, capturing the accompanying monopoly profits. Modelski and Thompson write, "The extent of national

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[42] David 1990, 356.
[43] This was the timeline for the U.S. case. Devine 1982. The productivity benefits of electrification materialized even later in other industrialized nations.
[44] Thompson 1990, 211.

success...is of the fairly extreme sort. One national economy literally dominates the leading sector during its phase of high growth and is the primary beneficiary of the immediate profits."[45] Under the GPT mechanism, no one country dominates innovations in GPTs. National success is determined by a state's effectiveness in adopting GPTs across a wide range of economic sectors.

Third is the breadth of growth. The LS mechanism focuses on the contributions of a limited number of leading sectors and new industries to economic growth in a particular period. In contrast, GPT-fueled productivity growth is spread across a broad range of industries.[46] As Grübler notes, "Any dominant individual technology or infrastructure studied under the leading sector hypothesis can explain only a fraction of economic growth."[47] Dispersed productivity increases from many industries and sectors come from the extension and generalization of localized advances in GPTs.[48] Thus, the LS mechanism expects the breadth of growth in a particular period to be concentrated in leading sectors, whereas the GPT mechanism expects the technological complementarities to be dispersed across many sectors.

1.2.1 The cause and outcome

Before outlining the institutional complementarities for GPT trajectories in more detail, it is important to clarify the cause and outcome that bracket both the GPT and LS mechanisms. The hypothesized cause is a "technological revolution," or a period characterized by particularly disruptive technological advances.[49] Since the shape of technological change is uneven, not all improvements in useful knowledge are relevant for power transitions.[50] However, some extraordinary clusters of technological breakthroughs, often deemed industrial revolutions by

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[45] Modelski and Thompson 1996, 91.

[46] See Harberger 1988 for the original formulation of these two views of long-term economic growth.

[47] Grübler 2003, 118.

[48] Crafts 2001, 306; David and Wright 1999, 12.

[49] Other related terms include "technology waves" (Milner and Solstad 2021) and "long waves" (Goldstein 1988).

[50] Technology includes both physical manifestations of hardware and blueprints as well as improvements in organizational and managerial practices. Rosenberg 1982.

historians, do have ramifications for the rise and fall of great powers. I am primarily interested in the pathway by which these technological revolutions influence the global distribution of power.

My outcome variable of interest is a shift in economic leadership, as captured by differentials in economic growth rates. While the balance of power can shift in many ways, I focus on relative economic growth rates because they are catalysts for intensifying hegemonic rivalries. Unique in its fungibility with other forms of power, sustained economic growth is central to a state's ability to exert political and military influence. The outcomes of interstate conflicts between great powers have demonstrated the significance of economic and productive capacity to military power.[51] My primary measure of economic capacity is productivity growth because it determines economic growth in the long run.

I look at differential rates of productivity growth among a set of countries that could be great powers. In some measures of productivity, other countries may rank highly or even outrank the countries I study in my cases. In the current period, countries such as Switzerland boast higher GDP per capita than the United States; before World War I, Australia was the world leader in productivity as measured by GDP per labor-hour.[52] However, pre-WWI Australia and present-day Switzerland are not included in the set of countries with the baseline economic and population size required to contend for great power status.[53]

1.2.2 Institutional complementarities for GPT trajectories

A clearer understanding of contours of technological change in times of economic power transition — as outlined in the differences between the LS and GPT model — informs the

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[51] Kirshner 1998; Modelski and Thompson 1996; on WWI, see Kennedy 1984; on WWII, see Hanson 2017. Economic strength does not map perfectly onto military strengths. Some economic giants, such as Japan in the 1980s, limit their military capabilities.

[52] Wright 1990.

[53] For instance, the population of Australia in 1870 was 1.6 million, which was only four percent of the U.S. population at the time. Romer 1996, 202.

institutional variables that are most salient. If the LS trajectory holds, then the most important institutional endowments and responses are those that support a monopoly on innovation in leading sectors. In the context of skill formation, institutional competencies in science and basic research gain priority. Based on the LS model, Drezner's analysis of changes in technological leadership, for example, attributes Germany's late-19th century dominance in the chemical industry to its investments in scientific research and highly skilled chemists.[54] This skill advantage supported Germany's dominance in synthetic dyes, a particular segment of the chemical industry in which Germany controlled 90 percent of world production by 1914 — a LS that is taken to explain Germany's overall industrial dominance.[55]

An understanding of economic power transitions based on GPT diffusion brings another set of institutional complementarities to the fore. My theory highlights the importance of *GPT skill infrastructure*: education and training systems that foster the human capital critical to GPT diffusion. When widespread adoption of GPTs is the priority, it is ordinary engineers, not heroic inventors, that matter most. Widening the base of engineering skills associated with a GPT cultivates a more interconnected technological system, with ample cross-fertilizations between applied technology and fundamental breakthroughs.[56]

Applied to chemicals in the late-19th century, the lesson is to pay less attention to who has more chemists and more to who has more chemical engineers. In line with the GPT model, advances in chemicals did not diffuse to a sufficient extent to affect the balance of industrial power before World War I. After a period of gestation, the development of chemical engineering practices enabled the chemicalization of a broad range of processes in industries beyond synthetic

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[54] Drezner 2001, 13-18; This is a common view. For instance, Moe argues, "The chemical industry is an important reason why industrially, by World War I, Germany was Europe's number one power." Moe 2007, 125.

[55] Moe 2007, 253-255; Thompson 1990.

[56] Shapley and Roy 1985.

dyes. Despite its disadvantages in chemical innovation relative to Germany, the U.S. benefited the most from advances in chemicals because it first institutionalized the discipline of chemical engineering.

There is no theory of everything for the relationship between technological change and the rise and fall of great powers. Human capital is just one of many factors that affect technology adoption, and GPT skill infrastructure is only one of many institutions that enables the diffusion of GPTs. Many other institutions, such as industry standards bodies, help coordinate complementary development efforts and the flow of information between the GPT sector and application sectors.[57] Still, because human capital upgrading permeates every aspect of technological development, GPT skill infrastructure is essential to other institutions that standardize and spread best practices associated with GPTs.

1.3 Plan of the thesis

The thesis proceeds as follows. Chapter 2 presents the theoretical framework, outlining the key differences between GPT diffusion theory and the LS-based account. In Chapter 3, I describe the case analysis procedures and selection strategy that allow me to systematically evaluate these two causal mechanisms. The bulk of the evidence follows in three case studies that trace how technological changes affected economic power transitions in the first industrial revolution (IR-1), the second industrial revolution (IR-2), and the third industrial revolution (IR-3).

The first two case studies, the IR-1 and IR-2, show that a gap in the adoption of GPTs, as opposed to monopoly profits from dominating LS innovations, was the crucial driver of an economic power transition. In both cases, the country that outpaced its industrial rivals made

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[57] Bresnahan and Trajtenberg 1995 argue that these coordination mechanisms help unleash positive externalities associated with GPT trajectories. See also Rosenberg 1978; Rosenberg 1998; Vona and Consoli 2014.

institutional adjustments that widened the skill base in the key GPT of the period. The IR-1 case, in Chapter 4, reveals that Britain was the most successful in fostering a wide pool of machinists who enabled the widespread diffusion of advances in iron machinery. Chapter 5, the IR-2 case, highlights how the U.S. surpassed Britain as the preeminent economic power by cultivating a wide base of mechanical engineering talent to spread advances in machine tools.

The IR-3 case, presented in Chapter 5, demonstrates that technological revolutions do not necessarily always produce an economic power transition. If the components of the LS and GPT mechanism were present, the fact that Japan did not overtake the U.S. as the economic leader would provide disconfirmatory evidence. In line with the LS mechanism, Japan did dominate innovations in the IR-3's leading sectors, including consumer electronics and semiconductor components. In contrast, the IR-3 does not discredit the GPT mechanism because Japan did not lead the U.S. in the diffusion of information and communications technology across a wide variety of economic sectors.

Chapter 7 applies the GPT diffusion framework to the implications of modern technological breakthroughs for the U.S.-China power balance. Focusing on AI technology as the next GPT that could transform the international balance of power, I explore the extent to which my findings generalize to the contemporary U.S.-China case. Finally, I conclude in Chapter 8 by underscoring the broader ramifications of the thesis.

Chapter 2 GPT Diffusion Theory

How and when do technological changes affect the rise and fall of great powers? Specifically, how do significant technological breakthroughs result in differential rates of economic growth among great powers? International relations scholars have long observed that rounds of technological revolution often lead to upheaval in global economic leadership, bringing about a power transition in the international system. However, very few scholars have investigated how this process occurs. The standard explanation emphasizes a country's ability to dominate *innovation in leading sectors* (LSs), monopolizing profits in new industries whose growth outpaces the rest of the economy.

I propose an alternative explanation based on the *diffusion of general-purpose technologies* (GPTs). Characterized by their scope for continual improvement, broad applicability across many sectors, and synergies with other technological advances, GPTs carry an immense potential for boosting productivity. Realizing this potential necessitates major structural changes across the technology systems linked to the GPT, which involves complementary innovations, organizational changes, and upgrading of technical skills. Thus, GPTs produce a productivity boost only after a "gradual and protracted process of diffusion into widespread use."[1] This is why more than five decades passed before key innovations in electricity, the quintessential GPT, significantly transformed manufacturing productivity.[2]

The process of GPT diffusion illuminates a pathway by which technological change affects power transitions that diverges from the standard LS mechanism. Under the GPT mechanism, some great powers sustain economic growth at higher levels than their rivals because

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[1] David 1990, 356.

[2] Devine 1982.

they benefit from more widespread diffusion of GPTs — a decades-long marathon that involves technological advances across a broad range of industries. The LS mechanism, in contrast, specifies that one great power rises to economic leadership because it dominates innovations in leading sectors and captures the accompanying monopoly profits — a sprint in which technological advance is limited to a few new industries.

Why are some countries more successful at GPT diffusion? Many scholars have shown that a nation's success in adapting to emerging technologies is determined by the *fit* between its institutions and the demands of evolving technologies.[3] The institutions that matter for successfully adapting to GPTs, therefore, are those that enable the diffusion of GPTs by standardizing and spreading novel best practices between the GPT sector and application sectors. Essential to all these institutions is *GPT skill infrastructure*, the education and training systems that foster the human capital needed to spread a GPT.

The clash between the GPT and LS mechanism can be seen in their interpretations of how electricity affected the U.S. and Germany's economic rise in the late 19th century. According to the LS mechanism, Germany dominated innovations in the electrical industry, seizing the dominant share of exports in electrical products.[4] This success was backed by Germany's superior scientific research apparatus and system of industrial organization that facilitated the rise of large electrical equipment firms. If examined under the lens of GPT diffusion, the focus turns instead toward the U.S.'s advantage in adopting electrical advances across many industries. The U.S. had institutional advantages in training electrical engineers, thereby widening the base of talent necessary for wide-scale electrification. The ordinary tweakers and the implementers come to the fore, and the star scientists and inventors recede to the background.[5]

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[3] Gilpin 1996; Kim and Hart 2001; Kitschelt 1991; Perez 2002.

[4] Henderson 1975, 189-190.

[5] I adopt the terms "tweaker" and "implementer" from Meisenzahl and Mokyr 2011, 446.

This chapter proceeds as follows. Section 2.1 clarifies the outcome I seek to explain: an economic power transition in which one great power becomes the economic leader by sustaining productivity growth at higher levels than its rivals. The starting point of my argument is that the diffusion of GPTs is central to the relationship between technological change and productivity leadership. Section 2.2 explicates this argument by justifying the emphasis on both GPTs and diffusion, highlighting the differences between the GPT and LS mechanisms. Section 2.3 extends the analysis to the institutional competencies that synergize with GPT trajectories. From the rich set of technology-institution interactions identified by evolutionary economists and comparative institutionalists, I justify my focus on institutions that enable countries to widen the skill base required to spread GPTs across industries. Section 2.4 differentiates my argument from alternative explanations.

2.1 The outcome: Long-term economic growth differentials and power transitions

Power transitions are to the international system as earthquakes are to the geological landscape. Shifts in the relative power of leading nations send shockwaves throughout the international system. What often follows is conflict — the most devastating form of which is a war waged by coalitions of great powers for hegemony over the globe.[6] Beyond heightened risks of conflict, the aftershocks of power transitions reverberate in the architecture of the international order, as victorious powers remake international institutions to benefit their own interests.[7]

While the power transition literature largely tackles the consequences of power transitions, I treat the rise and fall of great powers as the outcome to be explained. This follows

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[6] Power transition theory expects that the risk of war major power is greatest when a rising challenger threatens the established power. Gilpin 1975; Organski 1958; Tammen 2008. For a critique, see Chan 2007.

[7] For other possible consequences of power shifts, such as discussions of hegemonic stability, see Keohane 1984; Snidal 1985.

Baldwin's call for students of international relations "to devote more attention to treating power as a dependent variable and less to treating it as an independent variable."[8] Specifically, I explore the causes of economic power transitions, a process in which one great power sustains growth rates at higher levels than its rivals and takes on the mantle of economic leadership.[9]

It might not be obvious, at first glance, why I focus on economic power. After all, power is a multidimensional, contested concept that comes in many other forms. The salience of certain power resources depends upon the context in which a country draws upon them to exert influence.[10] For my purposes, differentials in economic growth are the most relevant considerations for intensifying hegemonic rivalry. An extensive literature has demonstrated that changes in relative economic growth often precede hegemonic wars.[11]

Moreover, changes in global political and military leadership often follow shifts in economic leadership. A leading nation's economic power — "the most fundamental and the most fungible form of power" — rests on its ability to sustain economic growth at a level higher than its rivals.[12] The outcomes of interstate conflicts bear out that economic and productive capacity is the foundation of military power.[13] Kennedy concludes, "[A]ll of the major shifts in

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[8] Baldwin 2012, 288.

[9] Economic power transitions have been studied by many others. The surrounding literature references 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 I focus on while avoiding the associations of "industrial" with heavy industry.

[10] For instance, a large military may be an especially important component of a state's influence in fighting conventional wars but not as salient for a state's influence in defending against cyberattacks from non-state actors. D. Baldwin (2016) cautions against context-free estimates of power resources as well as the reduction of the multidimensional concept of power into a single measure. I avoid both of these pitfalls. The following sections clearly specify the type of power I assess (the sustained growth of an economy over the long run) as well as the context for which it is especially salient (among leading powers at the technological frontier).

[11] Kennedy 1987; Kim and Morrow 1992; Kugler and Lemke 1996; Väyrynen 1983.

[12] Huntington 1993, 81. See also Monteiro 2014, 34.

[13] Kirshner 1998; Modelski and Thompson 1996; on WWI, see: Kennedy 1984; on WWII, see: Hanson 2017. Economic strength does not map perfectly onto military strengths. Some economic giants, such as Japan in the 1980s, limit their military capabilities.

the world's military-power balances have followed alterations in the productive balances...the rising and falling of the various empires and states in the international system has been confirmed by the outcomes of the major Great Power wars, where victory has always gone to the side with the greatest material resources."[14]

Specifically, differences in productivity growth drive economic power transitions at the technological frontier. Productivity growth ensures that growth in total economic output is driven by efficient and sustainable processes. Additionally, it is the most important determinant of economic growth in the long run, which is the appropriate time horizon for understanding power transitions. In the words of the Nobel-Prize winning economist Paul Krugman, "Productivity isn't everything, but in the long run it is almost everything."[15] Most international political economy scholars regard productivity growth as the most telling measure of technological competitiveness.[16]

Alternative conceptualizations of economic power cannot capture how effectively a country translates technological advance into national economic growth. Theories of geo-economics, for instance, highlight a state's balance of trade in certain technologically advanced industries.[17] Other accounts emphasize a state's share of world-leading firms.[18] National rates of innovation, while more inclusive, measure the generation of novel technologies but not diffusion across commercial applications, thereby neglecting the ultimate impact of technological change.[19] Compared to these indicators, which only account for a small portion of the value-added

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[14] Kennedy 1987, 439.

[15] Krugman 1997,11.

[16] Hart 1992, 15; Porter 1990, 5.

[17] Kim 2020; Luttwak 1993.

[18] Starrs 2013 measures American economic power by the profit shares of U.S.-headquartered transnational corporations.

[19] Taylor 2012; Taylor 2016.

activities in the economy, productivity provides a more comprehensive measure of relative economic growth.[20]

Lastly, it is important to clarify that I limit my analysis of differential economic growth rates to great powers.[21] Scholars largely concur that great powers have economies that are both large and efficient.[22] First, economic size, often correlated with a large population, narrows down the population of great powers. In some measures of productivity, other countries may rank highly or even outrank the countries I study in my cases. In the current period, countries such as Switzerland boast higher GDP per capita than the United States; before World War I, Australia was the world leader in productivity, as measured by GDP per labor-hour.[23] However, pre-WWI Australia and present-day Switzerland lack the baseline economic and population size to be great powers.[24]

Great powers must produce large economic output with high productivity. As recent empirical work has shown, solely relying on measures of gross economic and industrial output provides a distorted view of the balance of power, particularly in cases when one side was populous but poor.[25] If national power was measured by GDP alone, China was the world's most powerful country during the first industrial revolution. However, it was not a great power under my conditions because its surplus economic resources were used to support a large, impoverished population.

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[20] Krugman 1994.

[21] I am indebted to Allan Dafoe, Max Daniel, and Duncan Snidal for helping me clarify the points that follow.

[22] Many also emphasize powerful military capabilities. Monteiro 2014, 44; Kennedy (1987, 224) writes that a great power is "by definition, a state capable of holding its own against any other nation." I do not make this a necessary criterion for great powers in my study because some rising powers become economic leaders before developing capabilities to project military power overseas. In work in progress, Jennifer Lind employs the term "latent great powers" to characterize these powers. I am grateful to her for sharing insights on this topic.

[23] Wright 1990, 653.

[24] For instance, the population of Australia in 1870 was 1.6 million, which was only 4 percent of that of the U.S. at the time. Romer 1996, 202.

[25] Anders et al. 2020; Beckley 2018.

There is no exact line that distinguishes great powers from other countries. Kennedy's seminal text *The Rise and Fall of the Great Powers*, for instance, has been challenged for not providing a precise definition of great power.[26] Fortunately, across all the case studies in this dissertation, there is substantial agreement on the great powers of the period. According to one measure of economic power, which spans 1816 to 2012 and incorporates both economic size and efficiency, all the countries I study rank among the top six at the beginning of the case.[27]

2.2 Diffusion of GPTs

Scholars often gravitate to technological changes as the source of a power transition in which the mantle of industrial preeminence changes hands. However, there is less clarity over the process by which technical breakthroughs translate into this power shift among countries at the technological frontier. I argue that the diffusion of GPTs is the key to this mechanism. In this section, I first outline why my theory prioritizes GPTs over other types of technology. I then expound on why I emphasize diffusion over other phases of technological change, especially innovation. Finally, I position GPT diffusion theory against the leading sector (LS) model, which is the standard theory in the international relations literature.

2.2.1 Why GPTs?

Not all technologies are created equal. When assessed on their potential to transform the productivity of nations, some technical advances, such as the electric dynamo, rank higher than others, such as an improved sleeping bag. My theory gives pride of place to GPTs, such as electricity or the steam engine, which have historically generated waves of economy-wide productivity growth.[28] Assessed on their own merits alone, even the most transformative technological changes do not tip the scale far enough to significantly affect aggregate economic

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[26] D. Baldwin 2016, 103; Kaiser 1989, 738.

[27] My calculations based on data from Anders et al. 2020.

[28] Brynjolfsson et al. 2017; David 1990; Ruttan 2006, 5.

productivity.[29] GPTs are different because their impact on productivity comes from accumulated improvements across a wide range of complementary sectors; that is, they cannot be judged on their own merits alone.

Recognized by economists and economic historians as "engines of growth,"[30] GPTs are defined by three characteristics.[31] First, they offer *great potential for continual improvement*. While all technologies offer some scope for improvement, a GPT "has implicit in it a major research program for improvements, adaptations, and modifications."[32] Second, GPTs acquire *pervasiveness*. As a GPT evolves, it finds a "wide variety of uses" and a "wide range of uses."[33] The former refers to the diversity of a GPT's use cases, while the latter alludes to the breadth of industries and individuals that use a GPT.[34] Third, GPTs have *strong technological complementarities*. In other words, the benefits from innovations in GPTs come from how other linked technologies are changed in response and cannot be modeled from a mere reduction in the costs of inputs to the existing production function. For example, the overall energy efficiency gains from merely replacing a steam engine with an electric motor were minimal; the major benefits from factory electrification came from electric "unit drive," which enabled machines to be driven individually by electric motors and a radical redesign of plants.[35]

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[29] For instance, Fogel's classic study of railroads concluded that "the railroad did not make an overwhelming contribution to the production potential of the economy." Fogel 1964, 235.

[30] Bresnahan and Trajtenberg 1995.

[31] The following discussion is mostly drawn from Bresnahan and Trajtenberg 1995 and Lipsey et al. 2005. Other accounts employ similar definitions, albeit with some modification: Bresnahan 2010; Jovanovic & Rousseau 2005. For a critical view of the GPT concept, see Field 2008.

[32] Lipsey et al. 1998, 39.

[33] For an analysis of how a GPT can be seen as an emergent property constituted by interactions between technological characteristics and institutions, see Cantner and Vannuccini 2012.

[34] One does not imply the other. For instance, a screw has a "wide range of use" since it is used to fasten things together across a large swathe of productivity activities in the economy, but it does not have a "wide variety of uses." Lipsey et al. 1998, 39.

[35] Previously, factories were powered by shaft and belt drive systems, which relied on a single, central steam engine. Devine 1982.

At the micro-foundation level, a GPT differs from other technologies because it possesses the capacity to feed into many economic processes and spur complementary innovations. From these elements, one can derive some, but not all, of the three established characteristics listed above.[36] The "scope for continual improvement" characteristic, for example, does not seem essential to the general-purpose nature of a technology. Theoretically, a GPT could emerge fully formed, without need for much further elaboration. Empirically, GPTs do exhibit substantial scope for improvement because they interact with so many diverse application sectors, which sparks additional innovations in the GPT sector.

Taken together, these characteristics suggest that the full impact of a GPT materializes via an "extended trajectory" that differs from those associated with other technologies. David explains,

> We can recognize the emergence of an extended trajectory of incremental technical improvements, the gradual and protracted process of diffusion into widespread use, and the confluence with other streams of technological innovation, all of which are interdependent features of the dynamic process through which a general purpose engine acquires a broad domain of specific applications.[37]

For example, the first dynamo for industrial application was introduced in the 1870s, but the major boost of electricity to overall manufacturing productivity did not occur until the 1920s. Like other GPT trajectories, electrification required a protracted process of upgrades to workforce skills, organizational adaptations, such as changes in factory layout, and complementary innovations like the steam turbine, which enabled central power generation in the form of utilities.[38] Therefore, if one is to track the full impact of these engines of growth, one must travel the long roads of their diffusion.

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[36] For his helpful insights on this section, I am indebted to Allan Dafoe.

[37] David 1990, 356.

[38] Brynjolfsson 2017; David 1990; Smil 2005, 33-97.

2.2.2 Why diffusion?

All technological trajectories can be divided into a phase where the technology is incubated and then first introduced as a viable commercial application (*innovation*) as well as a phase where the innovation spreads through a population of potential users, both nationally and internationally (*diffusion*). Recognizing this commonly accepted distinction, other studies of the scientific and technological capabilities of nations primarily focus on innovation.[39] I depart from other works by giving priority to diffusion, since that is the phase of technological change that is most significant for GPTs.[40]

Favoring diffusion checks against the primacy of innovation in understanding scientific and technological prowess. In his 2018 book-length treatment of the concept of innovation, Godin describes the current moment as one when "innovation becomes a value *per se*" and an "object of veneration and cult worship."[41] One historiography of technology argues that "innovation-centrism" has permeated the analysis of technology in the social sciences.[42] Others have noted that studies of technological change in military affairs are strongly biased toward military innovation.[43]

Undeniably, the activities and conditions that produce innovation can also spur diffusion.[44] Theoretically, a country's lead in GPT innovation could translate directly into a

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[39] Existing work on the scientific and technological power of nations makes the same distinction. Kennedy (2018, 16) writes, "In this book, I focus on transnational processes that support firms' and universities' efforts to engage in the first of these tasks: the creation of a product or process that is 'new to the world.'" Taylor (2016, 28) writes that the primary occupation of his book *The Politics of Innovation* is "more with *innovation* than *diffusion*...where possible, I focus more on why some countries are better at inventing new technologies...I am somewhat less concerned with the spread of new technology throughout society." Emphasis in original. See also: Taylor 2009b, 865.

[40] It is important to clarify two aspects of GPT diffusion. First, it indicates a country's ability to spread a GPT within its domestic economy, not across the international system. Second, it entails the successful use of technology, not just widespread adoption. For an analysis that emphasizes the importance of optimal assimilation of technologies, see Timmer et al. 2016.

[41] Godin 2015, 8.

[42] Edgerton 2010, 689.

[43] Goldman and Andres 1999, 80n4.

[44] Taylor 2016, 231.

relative advantage in GPT diffusion.[45] Scholarship on the agglomeration benefits of innovation hotspots, such as Silicon Valley, support this case to some extent. Empirical analyses of patent citations indicate that knowledge spillovers from GPTs tend to cluster within a geographic region.[46] In the case of electricity, Fox and Guagnini underscore that it was easier for countries with firms at the forefront of electrical innovation to embrace electric power at scale. The interconnections between the "learning by doing" gained on the job in these leading firms and academic labs separated the "fast lane" and "slow lane" nations in terms of electrification.[47]

Innovation-centered explanations do well at sorting how technological breakthroughs could differentially advantage countries at the technological frontier compared to those trying to catch-up. However, differentiating between how advanced economies adapt to revolutionary technologies requires a different approach. As supported by a wealth of econometric research, for countries at the technology frontier, divergences in long-term economic growth are shaped more by *imitation* than innovation.[48] These advanced countries have firms that can quickly copy or license innovations, which limits first mover advantages from innovations even in industries like pharmaceuticals where intellectual property rights are the most strictly enforced.[49] Nevertheless, advanced countries that are evenly matched in their capacity for radical technological innovation can still undertake vastly different trajectories in the wake of technological revolutions. I argue that differences in the diffusion pathways of GPTs explain this puzzle.

While most countries at the technological frontier will be able to compete in the production and innovation of GPTs, the hardest hurdles in the GPT trajectory are in the

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[45] Grübler 1998, for example, argues that the leading innovation center, the country where new technological changes originate, tends to also have the highest adoption levels of the technology.
[46] Feldman and Yoon 2001.
[47] Fox and Guagnini 2004, 170.
[48] Fagerberg 1987; Pavitt and Soete 1982.
[49] Hannah 1994, 90-91. I thank Daniel Raff for sharing this text with me.

diffusion phase. For instance, leadership in the innovation of electric power technologies was fiercely contested among the industrial powers. The United States, 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).[50] However, the three other industrial leaders could not keep pace with the U.S. in the diffusion of electric power technologies. In 1887, the spread of incandescent lighting in the U.S. nearly tripled the next closest competitor; by 1900, there were ten times as many miles of electric trams in the U.S. than in the next closest competitor; by 1913, U.S. generating capacity in AC power more than doubled that of the next closest competitor.[51]

For great powers competing at the technological frontier, optimizing for GPT diffusion versus GPT innovation represents a choice between two different grand strategies. The latter prioritizes ensuring one is the first to introduce novel technologies, whereas the former places more value on the dissemination and transformation of innovations after they are introduced. In sum, industrial competition among great powers is not a race over who can create the most Silicon Valleys; it is a race over who can cultivate the closest connections between its Silicon Valleys and Detroits or Iowa Citys.

2.2.3 GPT diffusion and LS product cycles

GPT diffusion challenges the LS-based account of how technological change drives power transitions, which is the dominant explanation in the IR literature. The conventional wisdom emphasizes a country's dominance in leading sectors, defined as new industries that rapidly expand in early stages of their evolution, fueling the overall momentum of the economy.[52] Developed initially by Rostow and later adapted by IR scholars, the "classic sequence" of "great

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[50] Taylor 2016, 189.

[51] Germany was the next closest competitor in all cases. Taylor 2016, 189.

[52] Kennedy 2018, 51; Rostow 1960; 14.

leading sectors" includes: cotton textiles; railroads and iron; steel, chemicals, and electricity; and the automobile industry.[53] Under the LS mechanism, a country's ability to maintain a monopoly on innovation in these emerging industries determines the rise and fall of lead economies.[54]

Both the GPT and LS mechanisms are based on the same 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 in a particular time window. The concept of leading sectors also bears some similarities to the concept of a GPTs. Though conflicting definitions exist, some scholars associate leading sectors with broad spillovers across economic sectors.[55] In addition, lists of leading sectors and lists of GPTs sometimes overlap, as evidenced by the fact that electricity is a consensus inclusion on both sets of lists.

Despite these similarities, the GPT and LS mechanism diverge in many respects. Many classic leading sectors do not have general-purpose applications. For instance, cotton textiles and automobiles both feature on Rostow's series of leading sectors, and they are studied as leading sectors because each has "been the largest industry for several major industrial nations in the West at one time or another."[56] Although these were certainly both fast-growing, large industries, they do not fulfill the characteristics of GPTs. In addition, many of the GPTs I examine do not qualify as leading sectors. The machine tool industry in the mid-19th century, for instance, was not a new industry, and it was never even close to being the largest industry in any of the major economies.[57]

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[53] Rostow 1978, 104-109. Thompson (1990) uses ten indicators proposed by Rostow as proxies for the rise and fall of critical leading sectors, adding two new indicators for semiconductor and jet airframe production starting in the 1950s.

[54] Thompson 1990, 217.

[55] Drezner 2001, 7; Thompson 1990, 211. Leading sector scholars have also called for more comparisons between leading sector arguments and GPT studies. Reuveny and Thompson 2001, 711n11.

[56] Kurth 1979, 3.

[57] I expand on these differences in the methods chapter.

Moreover, though the GPT and LS mechanisms sometimes draw from the same underlying technological advances, they present very different understandings of *how* revolutionary technologies bring about an economic power transition. Under the GPT trajectory, long-term changes in productivity leadership are caused by differential rates of GPT diffusion, which require a multi-sectoral spread of complementary innovations and long timeframes. Table 2.2 specifies how the GPT mechanism differs from the LS mechanism along three dimensions: the timeframe of impact, the key phase of relative advantage, and the breadth of growth. 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.

Table 2.1: Two mechanisms of technological change and power transitions

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

Why does the GPT mechanism diverge so sharply from the LS mechanism? The answer lies in understanding the parallels between the LS mechanism and 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.[58] Much of the scholarship about the LS mechanism explicitly references the product cycle.[59] In his description of Gilpin's *U.S. Power and the Multinational Corporation*, a particularly influential text for the LS mechanism, one scholar stated that Gilpin "has 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."[60]

To further illuminate how the two mechanisms differ along these three dimensions, it is helpful to unpack the connection between the LS mechanism and the product cycle. 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. This matches up with the *phase of relative advantage* in the LS mechanism: the clustering of LS innovations and the attendant monopoly profits in a single nation.[61] "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 (even though the innovation is globally significant and the benefits spread wider over the long run)."[62] 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.[63]

In the next stage of the product cycle, the product innovation spreads to foreign markets and the technology gradually diffuses to foreign competitors. Monopoly profits associated with a

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[58] Vernon 1971.
[59] Gilpin 1975, 78, 197; Gilpin 1987, 234-237; Moe 2009, 207; Tellis et al. 2000, 37.
[60] Kurth 1979, 4.
[61] Rasler and Thompson 1994, 7. The emphasis on monopoly profits persists in present-day assessments of national scientific and technological power. For instance, Brooks and Wohlforth (2016, 25) claim that the technological dominance of the U.S. is "arguably best captured by royalty and license fee data, which reveal that the U.S. is by far the leading source of innovative technologies."
[62] Modelski and Thompson 1996, 91.
[63] The "relative phase of advantage" dimension captures these differences.

product innovation dissipate, as production of the innovation becomes routinized and transfers fully to other countries. Similarly, along the *timeframe of impact* dimension, the LS mechanism highlights the 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."[64] 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."[65]

The GPT trajectory expects the opposite. The greatest marginal stimulation to growth from a GPT comes later in its development. It is precisely the process by which diffusion transforms radical innovations into routine components of the economy — the stage which Modelski and Thompson say the causal effect 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."[66] In contrast, GPT-based growth is more like *planting seeds in the ground*. The radically valuable possibilities only come 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."[67]

One last dimension to note 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

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[64] Modelski and Thompson 1996, 52.

[65] 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."

[66] Newman and Zysman 2006, 393-394. Emphasis mine.

[67] Helpman and Trajtenberg 1994.

contributions of a limited number of leading sectors and new industries to economic growth in a particular period. According to the LS mechanism, LS-fueled productivity growth is driven by a small fraction of industries. In contrast, GPT-fueled productivity growth is spread across a broad range of industries.[68] Dispersed productivity increases from many industries and sectors come from the extension and generalization of localized advances in GPTs.[69] Thus, the LS mechanism expects the breadth of growth in a particular period to be concentrated in leading sectors, whereas the GPT mechanism expects the technological complementarities to be dispersed across many sectors.

2.3 Institutions for GPT Trajectories: *GPT Skill Infrastructure*

Having established GPT diffusion as the preferred mechanism for technology-driven power transitions, I turn to institutional differences as the factor that explains why some countries are more successful at GPT diffusion. Institutions are one of three main categories of explanation for cross-country differences in economic performance over the long-term.[70] The other two emphasize the importance of geography and culture in shaping cross-country income differences.[71] I choose to focus on institutional explanations for two reasons. First, natural experiments from certain historical settings, in which institutional divergence occurs but geographical and cultural factors are held constant, provide empirical evidence that institutional differences, rather than geographical and cultural ones, cause long-term economic growth differentials.[72] Second, it is more manageable to probe how various technological trajectories of

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[68] See Harberger 1998 for a related formulation of two views of long-term economic growth, which differentiates between mushroom-like and yeast-like growth.

[69] Crafts 2001, 306; David and Wright 1999, 12.

[70] For a review of these "three fundamental causes" of international patterns of growth, see Acemoglu et al. 2005, 397-402.

[71] For geographical explanations, see Diamond 1997; Gallup et al. 1999; for cultural theories, see Harrison and Huntington 2000; Weber 1930.

[72] Acemoglu et al. 2005, 402-421.

interest interact with particular institutions, which allows me to explore the deeper causes of differences in GPT diffusion across great powers.[73]

A clarified understanding of the contours of technological change in times of economic power transition — as revealed by the differences in the LS and GPT model — helps pinpoint the key institutional variables. My approach draws from a rich tradition of work on the co-evolution of technology and institutions.[74] According to Gilpin, a nation's technological "fitness" is rooted in the "extent of the congruence" between its institutions and the demands of evolving technologies.[75] Employing insights from this co-evolutionary approach, I use the GPT trajectory described above as a filter for which institutional factors are the most salient. Thus, I argue that the institutions that facilitate GPT diffusion dictate which great powers rise and which ones fall after a technological revolution. My theory highlights the importance of *GPT skill infrastructure*, which refers to education and training systems that broaden the human capital base in a GPT — crucial for widespread adoption of a GPT.

2.3.1 Which institutions matter?

Institutions matter, but which ones? Many scholars have investigated how institutional factors could account for the international competitiveness of nations.[76] 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.[77] Crucially, since this dissertation is limited to the study of shifts in

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[73] Some scholarship does explore how certain geographical settings are more conducive to specific types of technological change, but these studies are limited to agricultural technologies. For example, see Diamond 1997, 358.

[74] Seminal studies include Freeman and Louca 2001; Nelson and Winter 1982; Perez 2002.

[75] Gilpin 1996, 413.

[76] Two of the canonical works in this tradition: Katzenstein 1985; Olson 1982. See also: Cerny 1990; Porter 1990; Rosecrance 1999; Weiss 2003. For reviews of the literature on institutions and the international political economy of technological change, see: Breznitz 2009; Pedersen 2010.

[77] Respectively, see Acemoglu et al. 2018; Drezner 2001; Kitschelt 1991; Nelson 1993; North 1990; Hall and Soskice 2001.

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, they do not differentiate between an innovation in potato chips and an innovation in microchips.[78] 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."[79] Unencumbered by the vested interests that resist disruptive technologies, rising challengers inevitably overtake established powers. Because these explanations are underspecified, they cannot account for cases where rich economies expand their lead or where poorer countries do not catch up.[80]

A few scholars do examine how the interactions between specific technologies and institutions influence economic power transitions. For example, Drezner argues that decentralized government structures are necessary for technological leaders to maintain innovation in leading sectors.[81] 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

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[78] Michael J. Boskin allegedly said, "It doesn't make any difference whether a country makes computer chips or potato chips." Thurow 1994.

[79] Rasler and Thompson 1994, 81; see also Gilpin 1996; Gilpin 1981, 179; Moe 2009.

[80] Taylor 2004, 604.

[81] Drezner 2001.

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.[82]

Though these studies operate at the same level of specificity as my argument, they still equate technological leadership with a state's success in capturing market shares and monopoly profits in new industries.[83] In short, they use leading sector product cycles as the filter for which institutional variables matter. Existing scholarship lacks an institutional explanation for why some great powers are more successful at GPT diffusion.

2.3.2 GPT skill infrastructure

To build a more specific explanation, I draw from human capital-centered accounts of international differences in technology adoption. A substantial body of literature supports the fact that human capital plays a key role in technology adoption.[84] Building on these arguments, I reason that the human resources most relevant for technology-driven power transitions are those most suited for the GPT trajectory. Therefore, I underscore the importance of *GPT skill infrastructure*: education and training systems that foster the human capital critical to GPT diffusion.

The condition of GPT skill infrastructure is one of many factors that could affect GPT diffusion, but it provides a useful indicator for other institutions that standardize and spread the novel best practices associated with GPTs.[85] This broader set includes other institutions, such as industry standards bodies, that help coordinate complementary development efforts and the flow

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[82] Kitschelt 1991; Kim and Hart 2001 expand on Kitschelt's framework.

[83] Another example of this is Moe's work on the industrial rise and fall of great powers, which takes a state's competitiveness in a particular period's "core industry" to be equivalent to a state's industrial leadership. His choice of core industries draws from leading sectors identified in Gilpin 1987 and Modelski and Thompson 1997. Moe 2009, 224fn3; Moe 2007.

[84] For a sampling, see Comin and Hobijn 2004; Goldin and Katz 2009; Nelson and Phelps 1966.

[85] Rosenberg 1998; Vona and Consoli 2014.

of information between the GPT sector and application sectors.[86] I focus on GPT skill infrastructure because, as scholars that study the historical development of GPTs have shown, human capital upgrading spills over to all these other institutions.[87]

Specifically, the development of an engineering discipline is a key element of GPT skill infrastructure because they systematize the new knowledge associated with GPTs and new organizational paradigms. Historically, completely new engineering disciplines, such as chemical engineering and electrical engineering, have played an essential role in *widening* the knowledge base in the wake of a new GPT.[88] In addition, during the First Industrial Revolution, British mechanical engineering talent was the key limiting factor that prevented France's ability to absorb innovations in machinery.[89] The impacts of new machines were not inevitably realized after they were bought or innovated; they needed to be maintained and continually updated in different contexts. Centuries later, spurred by the possibilities associated with the computer industry, the growth of computer science as an engineering discipline has played an integral role in the U.S.'s ability to adapt to the new information paradigm.[90]

The differences in the technological trajectories of change under the LS and GPT models shape the institutional variables that are the most important. If the LS trajectory holds, then the most important institutional endowments and responses are those that support a monopoly on innovation in leading sectors. In the context of skill formation, institutional competencies in science and basic research gain priority. Drezner's LS-based analysis of changes in technological

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[86] Bresnahan and Trajtenberg 1995 argue that these coordination mechanisms help unleash positive externalities associated with GPT trajectories.

[87] David and Wright (2003, 154) also highlight "the better match between the technologies advanced by electrification and the country's institutions of education and worker training in the country" as a key factor in the U.S.'s ability to translate electrification to productivity growth. The case studies also show that GPT skill infrastructure is essential to other institutions that standardize and spread best practices associated with a GPT trajectory.

[88] Rosenberg 1998, 169.

[89] Harris 1991.

[90] Vona and Consoli 2014, 1403-1405.

leadership, for example, attributes Germany's late-19th century dominance in the chemical industry to its investments in scientific research and highly skilled chemists.[91] This skill advantage supported Germany's dominance in synthetic dyes, a particular segment of the chemical industry in which Germany controlled 90 percent of world production by 1914 — a LS that is taken to explain Germany's overall industrial dominance.[92]

An understanding of economic power transitions based on GPT diffusion brings another set of institutional complementarities to the fore. Widening the base of engineering talent associated with a GPT cultivates a more interconnected technological system, cross-fertilizing applied technology and fundamental breakthroughs. Pay less attention to who has better chemists and more to who has more chemical engineers. Under the GPT model, advances in chemicals did not diffuse to a sufficient extent to affect the balance of industrial power before World War I. After a period of gestation, during which a broad range of industries outside synthetic dyes adapted chemical processes, institutions that supported the discipline of chemical engineering were crucial to the diffusion of chemicals. Despite its disadvantages in chemical innovation relative to Germany, the U.S. benefited the most from advances in chemicals because it first institutionalized the discipline of chemical engineering.[93]

The features of GPT skill infrastructure have clearly changed over time. Whereas informal engineering associations systematized the skills necessary for mechanization in the 18th century, formal higher education has become increasingly integral to computerization in the 21st century.[94] Still, all configurations of GPT skill infrastructure are defined by their role in widening

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[91] Drezner 2001, 13-18; Moe 2007, 125.

[92] Moe 2007, 253-255; Thompson 1990.

[93] Rosenberg and Steinmueller 2013. I expand on this further in the chapter on the second industrial revolution.

[94] Still, recent studies emphasize the continuing importance of informal education opportunities for computer science. Guzdial et al. 2014.

the engineering talent base associated with a GPT. The form may vary, but the function remains consistent.

2.4 Alternative explanations

While I primarily set GPT diffusion theory against the LS model, I also consider two other prominent explanations that make specific claims about how technological breakthroughs differentially advantage leading economies. This section outlines these in turn.

2.4.1 Threat-based arguments

I categorize one strand of related arguments about why some states adapt better to technological change as threat-based theories. These theories seek to probe beyond good institutions as the crucial factor that explains cross-national differences in technological competitiveness.[95] They argue that threats of various forms motivate states to build the institutions necessary for technological success.[96] Most closely related to my argument, Ruttan argues that war, or the threat of a major war, is necessary for the development of GPTs.[97] Weiss also emphasizes how the U.S. "national security state" feeds off geopolitical rivalries to spur innovation.[98] Other studies have attributed Japan's industrial rise to its "cult of vulnerability."[99]

Related explanations connect the balance of external threats and domestic roadblocks to technological progress. Taylor's "creative insecurity" theory argues that the difference between a nation's external threats ("security politics") and its internal rivalries ("distributional politics") determines its propensity for innovation.[100] The greater the difference the greater the national

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[95] Under Taylor's view, "there is no particular national innovation system, type of government, or variety of capitalism that strongly correlates with successful innovation." Taylor 2016, 224.

[96] More broadly, many important works in international relations posit that international competition spurs the diffusion of military technology. See Gilpin 1981; Waltz 1979. For a more recent account, see Milner and Solstad 2021.

[97] Ruttan 2006, 184; see also Coccia 2017.

[98] Weiss 2014.

[99] Samuels 1994, 48.

[100] Taylor 2016; see also Milner and Solstad 2021 for an application of Taylor's argument to global waves of technology adoption.

innovation rate: threats from economic or military pressures abroad allow governments to break from status quo interest groups. A related argument, the "systemic vulnerability" theory, emphasizes external security and domestic pressures, which affects leaders' will to invest in institutions conducive for innovation, as well as the number of "veto players," which affects leaders' ability to do so.[101]

Applied to periods of remarkable technological change and shifts in industrial leadership, threat-based theories assume that institutional changes follow from geopolitical pressures, such as an international crisis or war. The idea is that the threat of or the actuality of a shift in a country's geopolitical position will produce revolutionary learning in governance structures. I am more open to the possibility of institutional adjustments to GPTs motivated by factors other than threats. There are also many cases when institutions remained remarkably resilient even in the face of enormous threats. Thelen's research, for instance, has shown that there was institutional continuity in Germany's vocational training system across "several regime changes, the incorporation of the working class, defeat in not one but two world wars, occupation, and transitions both into and out of fascism."[102]

It is also unclear that threat-based theories constitute a deeper explanation of the origins of technological competitiveness than institutional ones. One could just as easily argue that threat-based theories only explain how nations build momentum for institutional changes but do

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[101] Doner et al. 2005; Tsebelis 2002. I thank Duncan Snidal for pointing me to this literature. Interestingly, while the "creative insecurity" and "systemic vulnerability" theories both identify the positive effect of external threats for national competitiveness, they differ on the role of domestic tensions. The "systemic vulnerability" account argues that domestic pressures positively incentivize the development of institutions conducive for innovation. Political leaders invest in these institutional arrangements when they face "the credible threat that any deterioration in the living standards of popular sectors could trigger unmanageable mass unrest." (Doner et al. 2005, 328). In contrast, the "creative insecurity" theory proposes that a nation's domestic tensions have a negative effect on scientific and technological progress. Part of this difference can be attributed to different conceptions of domestic tensions. For the "systemic vulnerability" theory, domestic tension characterizes a relationship between the masses and the political leadership; for the "creative insecurity" theory, domestic tension refers to a relationship between status quo interests and proponents of science and technology. Another possible reason for the divergence is that the systemic vulnerability theory is usually applied to developing states.

[102] Thelen 2004, 7.

not explain why those institutional changes were the right ones. And for the purposes of my project, threat-based theories do not account for which institutional changes are particularly suitable for GPT diffusion.

2.4.2 Varieties of Capitalism

The Varieties of Capitalism (VoC) explanation highlights differences among developed democracies with respect to labor markets, industrial organization, and inter-firm relations, separating them into coordinated market economies (CMEs) and liberal market economies (LMEs). VoC scholars argue that CMEs are more suited for incremental innovations because their thick inter-corporate networks and protected labor markets favor gradual adoption of new technological advances. LMEs, in contrast, are more fit for radical innovations because their fluid labor markets and corporate organization make it easier to reorganize firms to adapt to disruptive technologies. Most relevant to GPT diffusion theory, VoC scholars argue that firms in CMEs provide industry-specific training that is more favorable for incremental innovation, whereas LME firms provide training in more general skills, which proves more conducive for radical innovations.[103]

Since it focuses on innovation as the key outcome of interest, it is unclear whether CMEs or LMEs should be more successful at GPT diffusion, according to standard VoC theory. On the one hand, LMEs are more likely to generate innovations that have the potential to become GPTs, and workers in LMEs tend to possess more general skills that could spread GPTs across firms. On the other hand, the collaborative inter-firm relations and trade unions that characterize CMEs may favor the spread of a GPT across different sectors.

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[103] Hall and Soskice 2001; for a critical view, see Taylor 2004.

One expansion of the VoC argument makes claims that are more specific to my question. Jingjing Huo argues that LMEs specialize in product innovations, which take new technological knowledge and translates it into new job opportunities. In contrast, CMEs specialize in process innovations, translating new technological advances into new methods to improve productivity.[104] Thus, Huo adapts VoC theory but emphasizes the distinction between product and process innovations, as opposed to radical and incremental innovations. In the context of GPT diffusion, one could argue that Huo's theory would favor CMEs as best suited to translate GPT innovations into productivity gains.

However, when taking a macro-view of how technologies spread horizontally (between firms) and vertically (upstream to downstream), the distinction between product and process innovations is more ambiguous. As noted by von Tunzelmann, a *product* innovation by one industry, such as an electric motor made by an electrical engineering firm, could be viewed as a *process* innovation when adopted by a textiles factory using that motor to power equipment.[105] While VoC arguments are an improvement over technology-agnostic accounts, distinctions between radical and incremental, or product vs. process, do not account for the skills demanded by specific GPTs.[106] In that light, my formulation of two distinct trajectories — GPT vs. LS — provides a clearer delineation between the effects of two different types of technological change.

2.5 Summary

The technological fitness of nations is determined by how they adapt to the demands of new technical advances. I have developed a theory to explain how revolutionary technological breakthroughs affect the rise and fall of great powers. My approach is akin to that of an

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[104] Huo 2015.

[105] von Tunzelmann 1995, 12.

[106] For an example of how VoC scholars have had to adjust their views on skill provision to the particular demands information technology, a GPT, see Thelen 2004, 10; see also Crouch et al. 1999.

investigator figuring out why one ship sailed across the ocean faster than all the others. I first contrast the GPT and LS trajectories with regard to the timing, phase, and scope of technological change, which is like differentiating the winning ship's route from possible sea lanes in terms of trade wind conditions and course change timings. Once the superior route has been mapped, attention turns to the attributes of the winning ship, such as its navigation equipment and sailors' skills, that enabled it to take advantage of this fast lane across the ocean. Similarly, having set out GPT diffusion as the superior route from technological revolution to economic leadership, my argument then highlights a nation's ability to widen the engineering skill base in a GPT as the key institutional attribute that dictates which great power capitalizes best on this route. The following chapter introduces my methodology for testing the explanatory power of the GPT and LS explanations across historical case studies.

Chapter 3 Setting up the Case Studies

Historical case studies are the most appropriate method to investigate how major technological breakthroughs influence shifts in the balance of economic power. The case study method allows for the detailed exploration of causal processes that connect technological change to power transitions, addressing a significant gap in the existing literature.[1] To separate the effects of the GPT mechanism from those linked to the LS mechanism, rich familiarity with historical cases is needed to carefully trace how and when various technological and institutional changes affected economic differentials among great powers.[2] I select cases and implement the analysis in a way that ensures a fair and rigorous test of the relative explanatory power of the two mechanisms. The resulting "three-cornered fight" among a theory, a rival theory, and the set of empirical information is the basis of theory-oriented social science.[3]

My approach to comparing the GPT and LS mechanisms is clear-cut. 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. The aim is to structure the competing mechanisms "so that they are composed of the same number of diametrically opposite parts with observable implications that rule each other out."[4] To judge the explanatory strength of the LS

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[1] Modelski and Thompson (1996, 100) describe this gap, "Regrettably we are not in a position to currently measure the extent to which our choices for leading sectors were responsible for the consequent wealth of the respective lead economies."

[2] Beach and Pedersen 2019; Bennett and Checkel 2015.

[3] Van Evera 1997, 83.

[4] Beach and Pedersen 2013, 15.

and GPT mechanisms, I employ within-case congruence tests and process-tracing to evaluate the predictions of the two theoretical approaches against the empirical record."[5]

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 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.

To ensure that my findings from the case studies are unbiased and generalizable, I select the first industrial revolution (IR-1), the second industrial revolution (IR-2), and the third industrial revolution (IR-3) cases. The IR-1 and IR-2 are cases where the cause, a technological revolution, and outcome, a shift in economic leadership, are both present, so they are the most suitable for confirming the validity of the GPT or LS mechanism. The U.S.-Japan case, in contrast, can provide disconfirmatory evidence of the viability of these mechanisms, since the outcome of an economic power transition does not materialize, and both mechanisms were potentially operative in this case. Taken together, what the case studies reveal about the LS and GPT mechanisms can be generalized to modify existing theories of how technological change affects the rise and fall of great powers.

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[5] Blatter and Haverland 2012, 144; George and Bennett 2005, 181-204.

This chapter is organized as follows. First, I introduce the historical cases, explaining how the case selection strategy enables comparing the GPT and LS mechanisms in a way that avoids selection biases and meets certain scope conditions. Next, I describe the standard set of procedures used to assess the GPT and LS mechanisms across the case studies. Lastly, I report the sources of empirical evidence that support my evaluation of the two mechanisms.

3.1 Case selection strategy

In developing my case selection strategy, I considered three main factors. First and foremost, the case studies should facilitate the tracing of mechanisms that connect technological breakthroughs to the rise and fall of industrial powers. Second, I selected the most relevant and crucial cases in a way that avoided favoritism toward my proposed theory of GPT diffusion. Lastly, my case selection strategy allows for my findings about the LS and GPT causal mechanisms to be generalizable within certain bounds, directly bearing on the current case of China's challenge to American technological leadership. Considering these factors, I chose the following three case studies: the IR-1 (1780-1840), IR-2 (1870-1914), and the IR-3 (1960-2000).

3.1.1 Typical cases and deviant cases

To determine which cases will be most helpful for evaluating the LS and GPT mechanism, I first establish the population of potential cases. I sort this population into four types of cases based on whether they score positively or negatively on the cause and outcome (Table 3.1).[6] For example, the Dutch Republic surpassed Portugal as the dominant economic leader (outcome-present) in the early 17th century, but there were not many significant technological innovations during the period (cause-absent). I avoid selecting cases like the Dutch Republic-Portugal power transition because cases where the cause is absent are not helpful for

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[6] This terminology comes from Beach and Pedersen 2019, 96-97.

tracing mechanisms. Instead, I prioritize typical cases, where the cause and outcome are clearly present, for building and testing theories of mechanisms.[7]

Table 3.1: A Typology of Cases

	Outcome absent (-)	Outcome present (+)
Cause absent (-)	*irrelevant* Dutch Republic (mid-17th century)	*deviant coverage case* Portugal-Dutch Republic transition (early 17th century)
Cause present (+)	*deviant consistency case* Third industrial revolution	*typical case* First industrial revolution; second industrial revolution

Cause = technological revolution; outcome = economic power transition; shaded = selected.

Therefore, the IR-1 and IR-2 serve as the two foundational cases in my study. Both revolutions brought significant technological advances (cause-present) that were linked to the rise of new industrial powers (outcome-present). The IR-1 and IR-2 were the clear-cut choices among a limited number of typical cases, since a shift in the predominant economic power of the international system, my outcome of interest, is a relatively rare occurrence. Other who study the rise and fall of great powers reach back further in the past for possible cases. Based on Modelski and Thompson's scheme, I considered including shifts in economic leadership from Genoa (1290-1381) to Venice (1381-1494) to Portugal (1517-1580) and to the Dutch Republic (1609-1713).[8] Ultimately, I coded all these cases as ones where the cause of interest was not present, as these all occurred before the industrial revolution marked a fundamental shift in the extent to which technological changes affected the productive power of nations.[9]

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[7] Beach and Pedersen 2019, 97-98; Goertz 2017.

[8] Modelski and Thompson 1996, 69.

[9] The IR-1 was 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.

To supplement the typical cases, I also study the deviant case of Japan's challenge to American technological leadership in the IR-3. Useful for disconfirming causal mechanisms when the cause is present but the outcome is not, deviant case analysis can aid theory development by pointing to other variables that can explain why a mechanism breaks down.[10] Specifically, the U.S.-Japan case is an important deviant case with respect to the LS mechanism, in which all the components of the mechanism are present but the outcome does not materialize. Based on Japan's success in key leading sectors, such as semiconductors and electronics, many scholars predicted that Japan would overtake the U.S. during this period, yet an economic power transition never occurred.[11] In addition, the case also serves as a check on the GPT mechanism. If the empirical information shows that all the components of the GPT mechanism were also present in this case, it should weaken the credibility of the GPT mechanism.[12]

Another potential deviant case I considered was the Cold War competition between the U.S. and Soviet Union.[13] The Soviet Union, like Japan, was also considered a challenger to U.S. industrial dominance but never overtook the U.S. in economic leadership, as evidenced by its negative productivity growth in the 1970s and 1980s.[14] However, compared to U.S.-Japan competition in the IR-3, the U.S.-Soviet case provides less leverage to test GPT diffusion theory against the LS explanation, because the Soviet Union did not have an advantage in any of the

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[10] Beach and Pedersen 2018, 861-863. Goertz (2017, 66) labels cases where the causal mechanism is present, but the outcome is absent (X = 1, Y= 0) as "disconfirming" or "falsifying" cases.

[11] Gilpin (1996, 428) summarizes, "The appreciation of Japan's increasing strength in one high-tech industry after another has led many American and European observers to fear that Japan will acquire a monopoly of the commanding technologies of the third industrial revolution."

[12] With respect to the GPT mechanism, this case is less relevant, since the empirical analysis reveals that the causal mechanism and outcome are not present (X = 0, Y = 0). One could think that this case shows that if the GPT mechanism is not present, then a shift in productivity leadership is less likely. However, while we have a relatively clear notion of what causes economic power transitions, there are countless explanations for non-shifts in economic leadership, which makes these types of cases conceptually problematic. Mahoney and Goertz 2004.

[13] I thank Duncan Snidal for pointing out this possible case.

[14] Beckley 2018, 34.

candidate leading sectors or GPTs of this time period. This accords with the very limited discussion of this case in scholarship on transitions in technological leadership.[15]

3.1.2 Crucialness, relevance, and selection bias

The IR-1, IR-2, and IR-3 cases have a very strong degree of "crucialness," or theoretical relevance, for testing the LS and GPT mechanisms. To avoid bias toward the GPT theory in case selection, I choose cases that favor the LS theory in terms of background conditions and existing theoretical explanations. Early in each of the cases, significant technological breakthroughs sparked the growth of new leading sectors. The LS mechanism is the dominant lens through which scholars analyze how technological change affected economic power balances in all three periods. The existing literature holds up the IR-1 and IR-2 as the classic cases of power transitions driven by LS product cycles.[16] Many scholars also point to the IR-3 case as evidence of the LS mechanism.[17] Thus, these are all "most-likely cases" for the LS mechanism.[18]

I take a cautious approach in characterizing the likeliness of the cases for GPT diffusion theory. The normal expectations of GPT diffusion theory for each case are more unsettled, as it is not as established as the LS interpretation. One could argue that the conditions were ripe for the GPT mechanism in the IR-1 and IR-2 cases because two prototypical GPTs, the steam engine and electricity, gained traction in the two eventual leaders of the IR-1 and IR-2. At the same time, the predictions of the GPT diffusion mechanism regarding the steam engine and electricity, derived from the background factors within the cases, are that they diffused too slowly to meaningfully affect the economic power transitions associated with the IR-1 and IR-2.

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[15] The Thucydides's Trap Case File, a project at the Harvard Belfer Center that tracks power transitions, is another source for possible cases. Available at: https://www.belfercenter.org/thucydides-trap/case-file. Some of these power shifts are closely linked to technological changes. For instance, after undergoing technological modernization following the Meiji Restoration in the late 19th century, Japan surpassed China and Russia in terms of industrial power. Since neither China nor Russia were the leading economic power in that period, this case does not qualify.

[16] Gilpin 1981; Gilpin 1987; Kennedy 2018, 51; Modelski and Thompson 1996.

[17] Freeman et al. 1982; Kim and Hart 2001.

[18] George and Bennett 2005, 91.

Ultimately, I categorize these as "likeliness unclear" cases for the GPT mechanism. In the IR-3 case, which differs from the other two cases in that an economic power transition does not occur, evidence that Japan did not have an advantage in GPT diffusion provides confirmation of the GPT mechanism. Since the U.S.'s success with adopting computers, another representative GPT, during the IR-3 is well-established in the surrounding literature and predicted by other contextual factors, I label it as a "most likely" case for the GPT mechanism.

This case selection strategy ensures that the cases are highly crucial and relevant for testing the GPT mechanism against the LS mechanism (Table 3.2). According to one scheme that grades case designs according to "theoretical relevance," defined by the possible impact on undermining dominant theories and strengthening new theories, the IR-1 and IR-2 cases rank as the second-best of 16 different possible case designs.[19] Of course, this potential for modifying existing theories is only realized if the empirical results confirm the GPT mechanism and disconfirm the LS mechanism across all three cases.

One natural source of concern with my case selection strategy is selection on both the explanatory and dependent variable, which has been described as the "most egregious error" of case selection.[20] This criticism only applies if my intention is to calculate the average treatment effect of one unit of technological change on the likelihood of an economic power transition. In variance-based interpretations of causality, the mean effect of causes is derived from evidence of covariation between values of the explanatory and dependent variable across a range of cases. Since representativeness is the key criterion for case selection, selecting cases that vary on both

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[19] Blatter and Haverland 2012, 198.

[20] King et al. 1994, 142. For a critique of selection on the dependent variable, see Achen and Snidal 1989.

the independent and dependent variable is encouraged.[21] Some scholars advocate for random selection.[22]

Table 3.2: The Theoretical Relevance of the Cases

	LS Mechanism (Dominant Theory)		**GPT Mechanism (Alternative Theory)**		**Theoretical Relevance ("Crucialness")**
	Context Conditions	*Empirical Result*	*Context Conditions*	*Empirical Result*	
IR-1	Most-likely	Disconfirmation	Likeliness unclear	Confirmation	Very strong/strong
IR-2	Most-likely	Disconfirmation	Likeliness unclear	Confirmation	Very strong/strong
IR-3	Most-likely	Disconfirmation	Most-likely	Confirmation	Strong

Categorization based on Blatter and Haverland 2012, 199.

I am not studying the average treatment effect of one unit of technological change on the likelihood of an economic power transition. My interest is in the causal mechanisms that link major technological revolutions with the rise and fall of great powers. Since this is a rare outcome, there are not many (1,1) cases. Random selection would lead to studying many cases without a technological revolution and hegemonic transition. Rooted in a mechanism-based approach to causality, I choose instead to prioritize typical cases where the cause and outcome are present.[23] This approach is consistent with recent discussions of case selection for studying causal mechanisms in small-N research, which have moved toward favoring the selection of cases that are positive on the main independent variable of interest and the dependent variable.[24]

Additionally, the plethora of possible confounding factors may also provoke concerns about the case selection. The standard guidance for researchers "to focus on a case where the

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[21] For a critique of representativeness as a criterion for case selection, see Goertz 2017, 247-252.

[22] Fearon and Laitin 2008; Herron and Quinn 2016.

[23] Beach and Pedersen 2019, 97-98; Mahoney 2010.

[24] Goertz and Mahoney 2012, 177-191; Schneider and Rohlfing 2013.

causal effect of one factor can be isolated from other potentially confounding factors"[25] cannot be followed for my cases, which involve long-timeframes and macro-level processes that cannot be reduced solely to technological drivers. Fortunately, since my endeavor is to assess the empirical evidence for the operation of a causal mechanism, controlling for other causes does not happen at the case selection process but instead at the level of mechanistic evidence within the case itself.[26]

3.1.3 Scope conditions and generalizability

How generalizable are the findings from these case studies? Addressing this question demands clarifying the scope conditions of the causal mechanisms. First, there are spatial bounds. Empirical information from these case studies is restricted to dynamics that affect great powers at the technological frontier because the GPT and LS mechanisms may operate differently in this context. Causal pathways that facilitate "catching-up" may be very different from the ones that enable "forging ahead."[27] Drezner's analysis, for instance, shows that the very institutions crucial for technological catch-up in developing countries may constrain innovation at the technological frontier.[28] Additionally, recent empirical research has found that variables such as openness to trade and higher education are more growth-enhancing in countries closer to the technological frontier.[29] Lastly, the contextual differences between great powers and minor powers — even technologically-advanced small states — could confound the GPT and LS mechanisms, since a nation with a larger overall economy and population may be better equipped to diversify its industrial specializations.[30]

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[25] Gerring 2006, 122.

[26] Beach and Pedersen 2013, 100. I further discuss my approach to dealing with alternative causes later in this chapter.

[27] Abramovitz 1986.

[28] Drezner 2001, 18.

[29] Aghion et al. 2013.

[30] Kitschelt 1991, 469.

Second, temporal bounds should also be specified. It is not a coincidence that the three periods I study correspond to what some scholars have deemed the "three great industrial revolutions," with Britain as the archetypal leader of the first in the late 18th century, the United States taking on that role in the second from the late 19th century, and Japan as the leader of the third in the latter part of the 20th century.[31] Although not without qualifications, this reflects a consensus that certain periods feature particularly significant technological changes, which serves as an initial condition for both the GPT and LS mechanisms. Therefore, care should be exercised when applying the findings of this study to periods that do not feature a technological revolution. Nevertheless, if those who claim we are in the midst of a fourth industrial revolution today are to be taken seriously, then it would be a mistake to undervalue the relevance of my results.[32]

The scope conditions establish the external validity of my conclusions. The findings clearly do apply to all contexts in which great powers grapple with a technological revolution. While these scenarios are limited, they are substantively significant due to the potential consequences of hegemonic power transitions.[33] Moreover, limiting the spatial scope conditions to great powers was a conservative approach. Some scholars, writing in the LS tradition, have argued that causal mechanisms related to shifts in industrial leadership among great powers can be extended to smaller powers.[34] Viewed in this light, studying the extreme cases of technological revolutions and the competitiveness of great powers could function as a building block for more general theories about technological change and the power of nations. As exemplified by how studies of the European Union have shaped broader thinking about supra-national political

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[31] von Tunzelmann 1997, 2. In the case study of the third industrial revolution I challenge the notion that Japan was the technological leader in that period.

[32] See, for example, Schwab 2017. I discuss the possibility of a fourth industrial revolution in Chapter 7.

[33] Tellis et al. 2000, 36.

[34] See, for example, Moe 2009, 223.

institutions, the in-depth investigation of extreme examples can be foundational for further research.[35]

3.2 Case analysis procedures

Each of the case studies follows a very similar structure to assess whether the expected implications of the LS and GPT mechanisms are present. I first describe the shift in industrial leadership and the major technological changes that occurred in the period. Clearly identifying the major industrial rivals at the technological frontier helps limit the geographical scope of the empirical analysis. Similarly, I also narrow the range of technologies I trace by sorting the significant technological breakthroughs associated with the period into candidate sources of LS and GPT trajectories.

Next, the bulk of each case study is focused on testing three pairs of competing propositions, derived from how the LS and GPT mechanisms differ across three dimensions, regarding how significant technological advances translate into a transition in industrial power. After tracing whether the LS or GPT trajectory prevails in a particular case, I analyze the match between the institutional competencies of leading industrial powers and the prevailing trajectory. If GPT diffusion is the key pathway by which technological revolutions impact economic power transitions, then cross-national differences in GPT skill infrastructure should explain which powers rise and fall. Finally, I consider prominent alternative theories, such as the "varieties of capitalism" and threat-based approaches, as well as explanations unique to the specific case.

In sum, each case study is structured around investigating a set of four standardized questions that correspond to the three dimensions of the LS and GPT causal mechanisms (*timeframe of impact*, *key phase of advantage*, *breadth of growth*) as well as the degree of institutional

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[35] Blatter and Haverland 2012, 84

match with the relevant technological trajectory. The format of structured, focused comparison allows for the case studies to provide data that can be compared across cases, so that the findings of each case cumulatively contribute to theoretical development. A focused comparison also offers practical benefits by limiting the exploration of the case to evidence that is theoretically relevant.[36]

3.2.1 Tracing the cause and outcome

For each historical case, I first map the outcome of interest — a shift in the leading economic power of the international system. As outlined in the theory chapter, an economic power transition occurs when a rising power surpasses the leading power in absolute productivity levels. Naturally, this requires that the rising power is able to sustain higher rates of productivity growth than the leading power. In each of the cases, I examine a range of measures to determine whether and when relative shifts in productivity leadership transpire. These standard proxies for productivity include total factor productivity (TFP), labor productivity, industrialization indicators, and GDP per capita.[37]

The use of a broad set of productivity indicators provides a number of advantages. Practically, alternative options are needed when limited data exists for some measures of productivity, such as the lack of labor and total factor productivity figures for Britain, France, and the Netherlands in the early 1800s. I track the general productivity trends from the balance of many measures, recognizing that each of the indicators captures one aspect of productivity. For instance, the U.S. led Britain in labor productivity within the manufacturing sector in the early

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[36] George 1979.

[37] Labor productivity and TFP are the standard indicators of national productivity. GDP per capita, often held up as a crucial indicator of relative economic power, is also closely tied to productivity. See: Fagerberg 1994, 1665; Rapkin and Thompson 2003, 324-325. Industrialization indicators provide additional insight into the productive activities of a country. For instance, Kennedy's (1987) study of the rise and fall of great powers relies on Bairoch's (1982) industrialization indicators.

1800s, but Britain was the clear leader on all other productivity metrics.[38] Even TFP, which incorporates both labor and capital productivity, has been criticized for not capturing the effects of technological advances that expand a country's resource base.[39] My approach avoids privileging one productivity measure, which could paint a distorted picture of the productivity landscape.

Establishing the cause — the key technological changes to trace — for each case is a much harder task. The LS and GPT mechanisms both call attention to the outsized import of particular technologies, but they differ on which ones are more important. A deep and wide understanding of the technological advances in each historical period is required to properly sort them by their potential to spark LS or GPT trajectories.

This task is complicated by the substantial disagreements over which technologies are leading sectors and GPTs. Proposed lists of GPTs often conflict, which raises questions about the criteria used for GPT selection.[40] Reacting to the length of such lists, other scholars fear that "the [GPT] concept may be getting out of hand."[41] According to one review of eleven studies that identified past GPTs, there were 26 different innovations that appeared on at least one list but only three that appeared in all eleven.[42]

The LS concept is even more vulnerable to these criticisms because the characteristics that define leading sectors are inconsistent across existing studies. Though most scholars agree that leading sectors are new industries that grow faster than the rest of the economy, there is marked disagreement on other criteria. Some scholars select leading sectors based on the fact that

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[38] Broadberry 1994.
[39] Wright 1997. For other critiques of TFP, see Lipsey and Carlaw 2000.
[40] Field 2008; Mokyr 2006; Ristuccia and Solomou 2014.
[41] David and Wright 2003, 145.
[42] Field 2008. These three were steam, electricity, and information technology.

they have been the largest industry in several major industrial nations for a period of time.[43] Others emphasize that leading sectors attract significant investments in R&D.[44] To better comprehend the extent to which the determination of leading sectors varies, I reviewed five key texts that analyze the effect of leading sectors on economic power transitions. Limiting the lists of proposed leading sectors to those that emerged during the three case study periods, I find that 15 leading sectors appeared on at least one list and only two appeared in all five (Table 3.3).

My process for selecting leading sectors and GPTs to trace helps alleviate concerns that I cherry-pick the technologies that best fit my preferred explanation. In each historical case, most studies that explicitly identify leading sectors or GPTs agree on a few obvious GPTs and leading sectors. Following classification schemes that differentiate GPTs from "near-GPTs"[45] and "multi-purpose technologies,"[46] I resolve many of the conflicts over what counts as a GPT or leading sector by referring back to a set of defining criteria. For instance, some accounts include the automobile as a GPT, but I exclude it because it lacks a variety of uses.[47] I support my choices with empirical methods for LS and GPT identification. To confirm certain leading sectors, I examine the rate of growth across various industry sectors. I also leverage recent studies that identify GPTs with patent-based indicators.[48]

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[43] Kurth 1979, 3.

[44] Drezner 2001, 6-7. Despite being universally recognized as a leading sector, the cotton textile industry in the late 18th century would not qualify as a leading sector under this definition because it did not require significant investments in R&D activities.

[45] Lipsey et al. 1998, 46-47.

[46] These technologies have multiple economically relevant application sectors but lack the pervasive technological complementarities of GPTs. X-ray and lasers, for example, fall under this category. Battke and Schmidt 2015, 336.

[47] Mokyr 2006, 1073. A "variety of uses" is a key characteristic of GPTs. Lipsey et al. 1998, 39.

[48] For efforts to empirically verify GPTs, see Gross 2014, 32; Petralia 2020, 1-2.

Table 3.3: Conflicting lists of leading sectors

Proposed leading sectors	Gilpin 1987, 98	Modelski and Thompson 1996, 69	Kim and Hart 2001, 304	Moe 2009, 210	Akaev and Pantin 2014, 868
First industrial revolution (1780-1840)					
Cotton textiles	x	x	x	x	x
Iron	x	x		x	
Steam power	x				x
Consumer goods			x		
Light machine tools			x		
Second industrial revolution (1870-1914)					
Chemicals	x	x	x	x	x
Electricity	x	x	x		x
Steel	x	x			
Automobiles			x		
Consumer durables			x		
Third industrial revolution (1960-2000)					
Information and communications technology (ICT)	x	x		x	
Computer	x		x		x
Electronics	x		x		
Internet					x
Semiconductors					x

A related issue is that the focus on GPTs excludes other types of technological trajectories that have a profound impact on economic growth. The focus on GPTs, for instance, may neglect many single-purpose innovations, such as the cotton gin and the Haber-Bosch process for synthesizing ammonia,[49] which produced transformative effects despite not qualifying as a GPT.[50] Since I trace leading sectors, in addition to GPTs, I also consider other non-GPT innovations for each period that scholars identify as particularly transformative. In fact, many of these single-purpose technologies (e.g., supercomputers in the U.S.-Japan case and cotton textiles in the First Industrial Revolution case) feature heavily in leading sector accounts of shifts in industrial power among great powers. Therefore, testing my mechanism against the leading sector mechanism across all cases should go a long way toward alleviating concerns related to excluding important technological trajectories in my selection of GPTs.

Two other practical considerations affect LS and GPT selection. First, some technologies are characterized as candidates for both trajectories. For instance, GPT and LS scholars both list electricity as a key technology.[51] In these instances, I categorize these technologies as both candidate GPTs and leading sectors, leaving it for the empirical analysis to reveal whether the GPT or LS trajectory more accurately captures that technology's development.

Second, there may be multiple leading sectors and GPTs that overlap in a time period. When it comes to GPTs, Ristuccia and Solomou rightly note that various GPTs at different stages of their life cycles could affect the economic growth rate.[52] I take care, therefore, to track when GPTs made their key contributions to economic growth differentials. For instance, in the IR-2 case, I find that electricity and chemicals — two of the period's consensus GPTs — were still in the early stages of their diffusion at the turn of the 20th century, so they could not account

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[49] The Haber-Bosch process revolutionized agriculture by making nitrogen fertilizer more accessible.

[50] Field 2008. These criticisms are also mitigated to an extent by my focus on the process of interaction between GPTs and surrounding institutions. The most productive effects of single-purpose innovations do not need two or three decades and large complementary investments because they offer "relatively complete, immediately usable solutions to a readily apparent problem" (Field 2008, 13). The ease of adoption suggests that countries at the technological frontier will achieve similar gains from single-purpose innovations. This reduces the risk that these types of technical advances constitute omitted variables for my analysis.

[51] Reuveny and Thompson (2001, 771n13) include GPTs in a list of concepts related to leading sectors.

[52] Ristuccia and Solomou 2014, 229.

for the bulk of the U.S.'s industrial rise.[53] These practical considerations underscore that taking stock of the key technological drivers is only the first step in the case analysis. To judge whether these breakthroughs actually brought about the impacts that are often claimed for them, it is important to carefully trace the GPT and LS mechanisms.

3.2.2 Tracing the mechanism

My approach adapts the methodology of process-tracing, which is often conducted at the individual- or micro-level, to macro-level mechanisms composed of structural factors and evolutionary interactions, which generally cannot be modeled by the aggregate beliefs and behaviors of individuals.[54] For instance, existing scholarship on diffusion mechanisms, which the GPT mechanism builds from, emphasizes the influence of population-level structural features. In these accounts the diffusion trajectory depends not just on the overall distribution of individual-level receptivity but also on structural and institutional features, such as the degree of interconnectedness in the population.[55] This approach aligns with a view of mechanistic thinking that allows for mechanisms to be set at different levels of abstraction.[56] As Falleti and Lynch write, "micro-level mechanisms are no more fundamental than macro-level ones."[57]

While tracing micro-level mechanisms often involves inspecting the particular decisions that link cause and effect, tracing macro-level mechanisms requires mapping broader causal patterns. LS product cycles and GPT diffusion both spell out macro-level patterns that connect technological revolutions to economic power transitions, but these mechanisms diverge on three

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[53] Instead, the IR-2 case analysis reveals that the effects of a GPT trajectory linked to machine were central to the outcome of the case.

[54] Mayntz 2004, 255.

[55] Mayntz 2004, 251.

[56] Falleti and Lynch 2009; Mahoney 2003, 5; George and Bennett 2005,142; Tilly 2001. While there is still much disagreement over the defining criteria of causal mechanisms, most scholars agree that they outline causal patterns that occur if certain initial conditions are present. For a systematic review of 24 different definitions of causal mechanisms, see Mahoney 2001. See also Mayntz 2004, 241.

[57] Falleti and Lynch 2009, 1149.

key dimensions related to the timeframe of impact, the key phase of relative advantage, and the breadth of growth. This enables the comparison of the two competing mechanisms according to diverging propositions about how technologies and institutions will interact in a particular period to generate an industrial power transition (Table 3.4).

First, the LS and GPT mechanisms support diverging explanations about the timing of when key technological changes translate into tangible productivity shifts. According to the LS mechanism, leading sectors make their greatest marginal impact on the distribution of industrial power early on in their development. Under the GPT mechanism, GPTs make their greatest marginal impact on the distribution of industrial power after a prolonged period of gestation. Assessing whether the historical timeline matches up with what mechanisms postulate is a crucial endeavor. Theda Skocpol's classic study on social revolutions, for instance, found that ideologically motivated vanguard movements cannot be important causes of social revolutions because these movements only emerged *after* major revolts had occurred.[58]

Second, the LS and GPT mechanisms emphasize different phases of technological change that drive transitions in productivity leadership. Calling attention to the location where major technological innovations take place, the LS mechanism posits that the nation that rises to industrial preeminence gains its edge due to monopoly profits from innovation in leading sectors. In contrast, in line with its focus on diffusion, the GPT mechanism posits that the nation that rises to industrial preeminence gains its edge due to more successful adoption of GPTs.

Third, the LS and GPT mechanisms embody different perspectives on the breadth of economic growth in a particular period. A limited number of key sectors or technologies, according to the LS mechanism, contribute to shifts in industrial power. According to the GPT

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[58] Skocpol 1979.

mechanism, a broad range of sectors, linked by complementary innovations to GPTs, contribute to shifts in industrial power.

Table 3.4: Testable Predictions of the LS and GPT Mechanisms

Dimensions	**Key questions**	**Examples of case-specific predictions (LS)**	**Examples of case-specific predictions (GPT)**
Timeframe of impact	When do revolutionary technologies make their greatest marginal impact on the economic balance of power?	The steam engine producing industry contributed significantly to Britain's industrial rise before 1815 (IR-1).	The steam engine did not contribute significantly to Britain's industrial rise before 1815 (IR-1).
Key phase of relative advantage	Do monopoly profits from innovation or benefits from more successful diffusion drive growth differentials ?	Germany dominated innovations in steel in the late 19th century. This monopoly on innovation propelled it to economic leadership (IR-2).	No one country monopolized innovations in machine tools in the late 19th century. U.S. success in widespread adoption of machine tool advances propelled it to economic leadership (IR-2).
Breadth of growth	Is technological advance concentrated in a few leading sectors, or is it spread across many GPT-linked industries?	The consumer electronics and semiconductor industries drove growth differentials between the U.S. and Japan in the late 20th century (IR-3).	A broad range of industries connected to information communications technologies drove growth differentials between the U.S. and Japan in the late 20th century (IR-3).
Institutional complementarities	Which types of institutions are most advantageous for national success in technological revolutions?	Institutions that deepen the pool of AI experts are most critical to current U.S.-China technological competition (IR-4).	Institutions that widen the pool of AI engineers are most critical to current U.S.-China technological competition (IR-4).

After establishing whether the LS or GPT trajectory applies in a particular period, I scrutinize the fit between the prevailing trajectory and the institutional arrangements of the leading industrial powers. If the GPT diffusion theory holds, the empirical evidence should reveal that institutional adaptations that enable the spread of GPTs can explain why some nations take better advantage of GPT trajectories. If the LS trajectory prevails in a certain period, then the case study evidence should show that differences in countries' institutional competencies that support monopolies in LS innovation can explain the variation in their abilities to take advantage of LS trajectories.

I limit the potential for overly subjective judgements by grounding the assessments of the diverging propositions in a consistent set of measures. The impact timeframe for each candidate GPT and LS is quantitatively measured using industry growth rates, diffusion curves, and output trends. Qualitative accounts help contextualize when certain technological trajectories were most influential. The growth trajectory of each candidate GPT and LS is then set against a detailed timeline of when a major shift in productivity leadership occurs.

I evaluate the key phase of relative advantage by compiling export statistics, cross-national technology adoption rates, and sectoral contributions to overall industrial production. Additionally, assessments of relative industrial advantages by contemporary observers inform the evaluation of this hypothesis. Lists of historically significant innovations also enable a specific test of whether the principal source of innovation in leading sectors is concentrated in a single economy, which is one of the key implications of the LS mechanism.[59]

Tracking the success of GPT diffusion across different countries is a more difficult process because it is more difficult to gauge the successful utilization of technology than to identify the introduction of a new technological breakthrough. Most diffusion studies present information on how single technology spreads through one or a limited number of countries.[60] These have led to important findings, such as the existence of S-shaped curves, or logistic curves, that characterize the slow initial pace of technological adoption, but they do not speak to cross-

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[59] Reuveny and Thompson 2001, 696.

[60] Griliches 1957; Skinner and Staiger 2007.

national differences in diffusion rates. Fortunately, datasets on historical technology adoption provide useful indicators of GPT diffusion.[61]

Lastly, I measure the breadth of economic growth in a particular case by using data on the backward and forward linkages associated with various technologies, the distribution of patents, and estimated contributions to productivity growth by sector. Given the differences in data availability, the specific evidence presented will vary in each case.

It is difficult to operationalize and measure institutional complementarities for GPT diffusion and those that support monopolies in LS innovation. Of a rich set of institutional arrangements that could stand in for these two types of institutional competencies, I highlight the institutions that build human capital, a crucial factor in both technological innovation and diffusion. I measure cross-national differences in the institutions most conducive to GPT diffusion by the quality and quantity of education and training systems that foster engineering skills most relevant for the GPT trajectories at work in each case. For some periods, I can leverage quantitative data on engineering graduates in certain subjects; in other periods I rely on qualitative evaluations of engineering training and education systems. Cross-national differences in the institutional competencies that support monopolies in LS innovation are measured by the quality and quantity of education and training systems that foster radical breakthroughs and innovations in the LS trajectories present in each case. I operationalize this institutional measure with numbers of experts and top scientists in new industries.

Careful interpretation of the case study evidence is key to fairly evaluating these competing mechanisms. As is typical of evaluating mechanisms cast at higher levels of abstraction, some of my tests leave room for subjective interpretation and investigator bias. Assessing whether the historical evidence supports the LS or GPT mechanism's expectations

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[61] Comin and Hobijn 2009.

regarding the timeframe of impact, for instance, may require subjective interpretations of relatively fuzzy notions of whether leading sectors or GPTs stimulate an industrial power shift after a prolonged period as compared to early on in their development. Relatedly, the problem of selecting the "facts" that favor a particular theory is especially pressing given my aim of testing competing theories. My approach to historical research attends to these concerns by adopting rigorous standards of measurement and drawing on a wide variety of sources.[62]

3.2.3 Alternative explanations

Lastly, I also consider alternative theories of technology-driven power transitions. For each case study, I evaluate general alternative explanations and case-specific explanations. The varieties of capitalism theory and neorealist theories of threat outline alternative mechanisms for technology-driven power transitions. Across all the cases, I assess whether they provide a better explanation for the process-tracing evidence than the GPT and LS mechanisms. I also control for case-specific confounding factors. For instance, some scholars argue that the natural resource endowments of the U.S. led to its embrace of more machine-intensive technology in the IR-2, claiming that Britain's slower rate of mechanization was an efficient choice given its natural resource constraints.[63] For each case, I determine whether these types of explanations could nullify the validity of the GPT and LS mechanisms.

Macro-level mechanisms inevitably interact with many potential alternative causes. Take, for example, a standard causal mechanism for democratic peace based on shared democratic norms: more democracies in the international system → more democratic norms of nonviolent conflict resolution and negotiation → political elites are socialized to act on the basis of these norms → peaceful conflict resolution.[64] Though each of these steps emphasize the importance of

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[62] Thies 2002.

[63] Broadberry 1997.

[64] See Bell and Quek 2018 for review of mechanisms to explain the democratic peace.

the transmission of norms and ideas, this mechanism for democratic peace also leaves places at every step for other factors to play a role. The balance of power in the system may influence the degree to which the presence of more democratic governments translates into more democratic norms, the diffusion of communications and transportation technology may enhance the socialization effect for political elites, and economic stability may affect how socialized elites can implement conflict resolution.

Likewise, in investigating the mechanism that connects technological revolutions to economic power transitions, it is neither feasible nor necessary to specify every contextual condition. Instead, I closely scrutinize factors that could provide an alternative account for differences in the explanatory power of the GPT vs. LS mechanisms in each case.

3.3 Sources and Data

I benefit from a wealth of empirical evidence on past industrial revolutions, which have been the subject of many interdisciplinary inquiries. Since the cases I study are well-traversed terrain, my research is primarily based on secondary sources.[65] I rely on histories of technology and general economic histories to trace how and when technological breakthroughs affected economic power balances. In particular, my analysis has benefited from the application of formal statistical and econometric methods to assess the impact of significant technological advances, part of the "cliometric revolution" in economic history.[66] Some studies that adopt such a quantitative approach have challenged the dominant narrative of previous industrial revolutions. For instance, Nick von Tunzelmann found that the steam engine made minimal contributions to British productivity growth before 1830, raising the issue that earlier accounts of British

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[65] This is an acceptable practice for comparative historical research. See Skocpol 1984, 382; Thies 2002, 359.

[66] In one classic study, Robert Fogel (1964) assessed the contribution of the railroad to the production potential of the U.S. economy by conducting a counterfactual on the possible expansion of the canal system as the next best alternative. Along with Douglass North, a fellow pioneer in cliometrics, Fogel was awarded the Nobel Prize in Economic Science in 1993.

industrialization "tended to conflate the economic significance of the steam engine with its early diffusion."[67]

I supplement these historical perspectives with primary sources. These include statistical series on industrial production, Census statistics, discussions of engineers in contemporary trade journals, and firsthand accounts from commissions and study teams of cross-national differences in technology systems. My research also benefits greatly from new data on historical technological development. I take advantage of improved datasets, such as the Maddison Project Database,[68] and new ones, such as the Cross-country Historical Adoption of Technology dataset.[69] Sometimes, hype about exciting new technologies influences the perceptions of commentators and historians about the pace and extent of technology adoption. More granular data can help substantiate these narratives. Like the reassessments of the impact of previous technologies, these data were released after the publication of the field-defining works on technology and power transitions in international relations. Making extensive use of these sources, therefore, provides leverage to revise conventional understandings.

All historical case studies can be unduly influenced by particular sources and by investigator bias in source selection. Triangulating a variety of primary and secondary sources checks against these two risks. Since cultural and national context could shape histories about the rise and decline of nations, I ensure that each case draws on historical accounts from at least all the leading industrial powers. Historical scholarship on my research question is also contested by different schools of historiography. The decline of the British economy in the late 19th century,

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[67] Nuvolari et al. 2011, 292. See also von Tunzelmann 1978.

[68] This project aims to provide better data on relative cross-country income levels over time. Inklaar et al. 2018.

[69] Comin and Hobijn 2009. For an expansion of this dataset, which is now the most extensive dataset on technology adoption, see Milner and Solstad 2021.

for instance, has been the subject of many different rounds of revisionism.[70] I take pains to incorporate interpretations of historians from different historiographical schools to avoid unwarranted selectivity in gathering empirical materials.[71]

3.4 Summary

At its core, process tracing is a methodology that uncovers the internal workings of all kinds of black boxes. Scholars often employ this approach to study mechanisms that connect causes and outcomes through the decisions and behavior of individuals, such as elite decision-making in crisis scenarios.[72]

My approach, instead, is to study the internal workings of the mechanism that connects technological revolutions to economic power transitions. Like economists who "have long treated technological phenomena as events transpiring inside a black box,"[73] international relations scholars have long neglected the in-depth investigation of technological change. I trace how the specific characteristics of individual technologies shape which countries can benefit more from periods of industrial revolution. In his seminal work on technological change and long-term growth, titled *Inside the Black Box*, Rosenberg wrote:

> "One of the things that all knowledgeable people supposedly 'know' is that technological change has been the critical variable in accounting for the spectacular long-term growth of the American economy and our resulting present affluence. And yet, when scholars of a quantitative turn of mind have attempted to link the story of the growing productivity of the American economy to some of the better-known facts and landmarks of our technological history, that story has turned out to be a remarkably difficult one to tell."[74]

My approach offers a way to better tell that story.

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[70] For a review, see Tomlinson 1996. British "Declinism" is now viewed as a malleable ideology. For a similar take on American "Declinism," see Huntington 1998.

[71] This follows one of the approaches put forward by Lustick 1996.

[72] Levy 2008, 6; George and Bennett 2005, 200.

[73] Rosenberg 1982, vii.

[74] Rosenberg 1982, 55.

Chapter 4
The First Industrial Revolution and Britain's Rise

Few historical events have shaken the world like the First Industrial Revolution (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. While the following sections will adjudicate debates over the exact timeline of Britain's industrialization, there is no doubt that Britain, propelled by the IR-1, became the world's most advanced industrial power by the mid-19th century.

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, including cotton textiles, iron metallurgy, and steam power. 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. It reveals that general-purpose transformations linked to advances in iron metallurgy diffused widely enough to significantly affect economy-wide productivity only after 1815 — a timeline that aligns with when Britain's industrialization significantly outpaced its rivals. Other prominent advances, including the steam engine, only made limited contributions to Britain's rise to industrial prominence in this period due to the prolonged period of gestation before the widespread diffusion of GPTs. 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. Lastly, the historical data illustrates that Britain's productivity growth was a product of widespread, complementary innovations in many sectors linked to the diffusion of cheap iron. 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 the 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 other institutions for human capital formation, including higher technical education to train expert scientists and engineers, France and other British competitors were far ahead. 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.

My assessment of the validity of the GPT and LS mechanisms in the IR-1 case relies heavily on secondary source materials. The IR-1 is the subject of countless studies and historical accounts that relate to my investigation into the causal mechanisms of technology-driven power transitions. In order to trace these mechanisms, I gathered and sorted through a wealth of evidence. I endeavored to triangulate a variety of sources that brought evidence to bear on my research objective from different lenses. Historical accounts were the foundational materials, including: general economic histories of the IR-1, histories of influential technologies and industries like the steam engine and iron industry, country-specific histories, and comparative histories of developments in Britain, France, and the Netherlands. I also benefited from contemporary assessments of the developments of the IR-1 provided by international study teams, trade journals, and the correspondences between key figures, such as the inventor of the steam engine, James Watt, and his partner, Mathew Boulton.

I drew from additional materials to assess the institutional complementarities for GPT trajectories. This evidence stems from proceedings of engineering associations, recruitment adverts for engineering workers published in local newspapers, and essays by leading engineers of the time. Despite my efforts to back up all claims with statistical evidence, lack of data — especially for reliable, cross-country comparisons — presented a significant barrier. So far as possible, I made use of the data that does exist, including industrial output data, patent data, and revised estimates of growth indicators.

The assessment of the GPT and LS mechanisms against historical evidence from the IR-1 proceeds as follows. Section 4.1 reviews Britain's rise to industrial preeminence, which is the outcome of the case. Section 4.2 sorts the key technological breakthroughs of the period by their potential to drive two types of trajectories — LS product cycles and GPT diffusion. Section 4.3 assesses whether Britain's rise in this period is better explained by the GPT or LS mechanism, tracing the development of candidate leading sectors and GPTs in terms of the timeframe of impact, source of relative advantage, and breadth of growth. If the GPT trajectory holds for this period, there should be evidence that Britain was better equipped than its competitors in institutional competencies that favored the spread of GPTs. Section 4.4 evaluates whether the historical data supports these GPT-institutional complementarities. Section 4.5 addresses alternative factors and explanations. Section 4.6 concludes.

4.1 Power transition: Britain's rise

When did Britain ascend to industrial hegemony? The broad outlines of the story are well-known. Between the mid-18th century and the mid-19th century, the industrial revolution propelled Great Britain to global preeminence. 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."[1] Its main competitors during this period, France and the Netherlands, did not keep pace with British growth in economic efficiency.

While both the LS and GPT model agree that Britain established itself as the preeminent industrial power in this period, a clearer sense of when this shift occurred is essential for testing the explanatory power of the LS and GPT mechanism during this period. One common view of Britain's industrialization, brought to prominence by Rostow, depicts an accelerated take-off into sustained growth. Rostow's timeline dates this take-off to the last two decades of the 18th century.[2] In alignment with this timeline, some scholars writing in the LS tradition claim that Britain achieved its industrial ascent by the late 18th century.[3]

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[1] Kennedy 2018, 53.

[2] Rostow 1960; Rostow 1956, 31.

[3] Gilpin 1996, 413; Thompson 1990, 220.

A different perspective, which is better supported by the evidence that follows, favors a delayed timeline for Britain's ascent to industrial preeminence. Under this view, Britain did not sustain economic and productivity advances at levels substantially higher than its rivals until the 1820s and after. To clarify the timeline of Britain's industrial ascent, the following sections survey three proxies for productivity leadership: GDP per capita, industrialization, and total factor productivity.

GDP per capita indicators

Trendlines in GDP per capita, a standard proxy for productivity, confirm the broad outlines of Britain's rise. The Maddison Project Database (MPD), which updates Angus Maddison's data on GDP per capita across countries and over time, provides the most accurate information on historical patterns of economic growth and decline. The 2020 version of the MPD incorporates new annual estimates of GDP per capita in the IR-1 period for France, the Netherlands, and the United Kingdom.[4] Though GDP per capita information is sometimes unavailable or only partial in the early years of the IR-1, the MPD is the best source for cross-country comparisons of national income in this period.

While data scarcity makes it difficult to mark out exactly when Britain's GDP per capita surpassed that of the Netherlands, the MPD evidence points toward the decades after, not before, 1800 as the key transition period. In 1760 the Netherlands boasted the world's highest per capita income, approximately 35 percent higher than Britain's.[5] The Dutch held this lead for the rest of the 18th century through to 1808, when Britain first overtook the Netherlands in

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[4] Bolt and van Zanden 2020, 8-9.

[5] My calculations based on Maddison Project Database, version 2020. See also: Maddison 2007, 76. The Dutch lead in GDP per capita in the early 19th century is also referenced in Engerman and O'Brien 2004, 462.

GDP per capita. By 1840, Britain's GDP per capita was about 75 percent higher than that of France and about 10 percent ahead of that of the Netherlands.[6]

Industrialization indicators

Industrialization indicators provide a mixed picture of the economic power transition during the IR-1. Some metrics back an early arrival of British economic leadership, but the evidence is not definitive. Other measures of industrialization support the delayed timeline.

By one influential set of metrics on industrialization levels, from a position of near-equality with France and Belgium in 1750, Britain established a lead over other developed economies by 1800 (Table 4.1). Compiled by Bairoch, these estimates of industrialization have played a prominent role in shaping the timeline of British industrial ascendance. Many scholars rely on Bairoch's indicators to map the trajectories of great powers.[7] Kennedy, who frequently references Bairoch's estimates throughout *The Rise and Fall of the Great Powers,* concludes that the Industrial Revolution "transform[ed] [Britain] into a different sort of power," based on Bairoch's figures for industrial output and share of world manufacturing output.[8]

A detailed examination of Bairoch's estimates qualify their support for the accelerated timeline of Britain's industrial ascendance. Bairoch uses the output of the manufacturing industry as his indicator for industrial output, but he admits that this involves "making some rather arbitrary distinctions," since his classification of manufacturing industries excludes the contribution of notable sectors such as construction and mining.[9] In addition, Britain's lead over

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[6] My calculations based on Maddison Project Database 2020. From 1809-1814, the MPD provides no data on the Netherlands. Before 1807, the data for the Netherlands is based on a partial series for Holland. Bolt and van Zanden 2020, 9.

[7] Other texts that use Bairoch's industrialization indicators to highlight long-term changes in power include Acemoglu et al. 2002, 1237; Ikenberry 2001, 168; Moe 2004, 146.

[8] Kennedy 1987, 151.

[9] Bairoch 1982, 322.

France in terms of industrialization levels in 1800 was within the margin of error for Bairoch's data.[10]

Table 4.1: Leading Countries by Per-Capita Industrialization Levels, 1750-1860

1750		**1800**		**1830**		**1860**	
UK	10	UK	16	UK	25	UK	64
Belgium	9	Belgium	10	Switzerland	16	Belgium	28
France	9	Switzerland	10	Belgium	14	Switzerland	26
China	8	France	9	U.S.	14	U.S.	21
Germany*	8	U.S.	9	France	12	France	20

United Kingdom in 1900 = 100; 1913 boundaries; *Italy tied with China and Germany in 1750. Source: Bairoch 1982, 294.

Other industrialization statistics show that Britain did not solidify its lead until decades into the 19th century. In 1700 the Netherlands had a substantially higher proportion of its population employed in industry (33%) compared to the UK (22%). In 1820 the proportion of people employed in UK industry rose to 33%, rising above the corresponding ratio for the Netherlands 28%.[11] One expert on the pre-industrial revolution in Europe notes that Belgium and the Netherlands were at least as industrialized as England, if not more so, throughout the 18th century.[12] Furthermore, Greasley and Oxley's calculation of the trend growth in aggregate industrial production identifies the mid-1820s as the peak of British industrialization.[13] What they

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[10] According to Bairoch's own judgement, there is a 25-30 percent margin of error for 1800 estimates of European countries. Bairoch 1982, 327.

[11] Maddison 2007, 76. There is limited primary source data that allows for cross-national comparisons of industrialization rates in this period. Maddison does not have statistics on this ratio for the years between 1700 and 1820.

[12] Guttman 1988, 119-120.

[13] Greasley and Oxley 2000, 105.

label as "the post-1815 surge in British industrialization" matches up with the timeline of delayed ascent.[14]

Productivity indicators

Finally, British total factor productivity growth, which captures improvements in technology and increased efficiency in the conversion of factors of production into useful outputs, provides the most definitive evidence in favor of the delayed ascent story. British growth in TFP did not take off until the early decades of the 19th century. Its TFP growth was very modest throughout the 18th century, averaging less than 1 percent per year.[15] Between the years 1780 and 1801, technological change accounted for only about 8-10 percent of Britain's total GDP growth.[16]

In terms of absolute TFP, the Dutch were still competitive with Britain before Britain's TFP growth surged. The Dutch attained "Europe's highest overall level of total factor productivity for the better part of the seventeenth and eighteenth centuries."[17] As was the case with trends in aggregate industrial output, British TFP growth accelerated after 1820, growing an average of .30 percent per year between the years 1780 to 1831 and .75 percent per year between the years 1831-1873.[18]

Which periodization of Britain's industrial ascent better reflects the empirical evidence? On balance, the three proxies for cross-national comparisons of industrial power — per capita GDP, industrialization levels, and productivity — support the delayed view of Britain's industrial

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[14] Greasley and Oxley 2000, 101.

[15] Crafts 1998.

[16] Moe 2007, 30.

[17] de Vries and van der Woude 1997, 693. It is difficult to find reliable data on productivity growth for France, the other main competitor for industrial leadership in this period. Tentative estimates of French productivity in 1815 suggest that Britain had opened up a substantial lead. Moe 2007, 32-33.

[18] Crafts 1995, 752

rise. A clarified timeline of the shift in the outcome variable provides a stable target to test the competing LS and GPT mechanisms.

4.2 Key technological changes in the IR-1

Before evaluating the LS and GPT mechanisms in more detail, the cause — a cluster of major technological breakthroughs — must be specified in more depth. Hargreaves' spinning jenny (1764), Arkwright's water frame (1769), Watt's steam engine (1769), and Cort's puddling process (1784), and many other significant technical advances emerged amidst the first Industrial Revolution. The criteria that define GPTs and leading sectors as well as existing work that call attention to key technologies help guide my process for identifying the possible technological drivers in this period. Tracing how these advances translated into Britain's rise to industrial hegemony will test the explanatory power of the GPT mechanism against the LS mechanism.

4.2.1 Candidate leading sectors: Cotton textiles, iron, and steam power

There is a strong degree of consensus on the leading sectors that powered Britain's rise in the IR-1, which makes it relatively easy to identify three candidate sectors: cotton textiles, iron, and steam power.[19] Among these, historians widely recognize the cotton textile industry as the original leading sector of the first Industrial Revolution.[20] New inventions propelled the industry's rapid growth, as its share of total value added to British industry rose from 2.6 percent in 1770 to 17 percent in 1801.[21] In characterizing the significance of the cotton industry, Schumpeter went as far as to claim, "English industrial history can, in the epoch 1787-1842...be almost resolved into the history of a single industry."[22]

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[19] Rostow 1990, 33, 52-57; Gilpin, 1975, 67; Tomory 2016, 155.

[20] Hobsbawm 1968, 40; Kurth 1979; Rostow 1960, 53-54.

[21] Freeman and Louca 2001, 154.

[22] Schumpeter 1939, 270-1.

If the cotton textile industry is placed first in the canon of the IR-1's leading sectors, then the iron industry follows right after. Modelski and Thompson single out these two major industries in their account of Britain's rise, employing pig iron production and cotton consumption as indicators for Britain's leading sector growth rates.[23] The choice of these two industries as leading sectors accords with historical studies that adopt a narrow view of technological change in the IR-1. Much of this scholarship is centered on developments in these two sectors.[24]

Lastly, I also evaluate the steam power industry as a third possible leading sector. A wide range of LS-based scholarship identifies steam power as one of the technological foundations of Britain's leadership in the 19th century.[25] Most of this literature only labels the steam engine as the leading sector, but since leading sectors are new industries, the steam engine producing industry is the more precise understanding of the leading sector related to major advances in steam engine technology. Compared to the iron and cotton textile industries, it is much more uncertain whether the steam engine producing industry, which experienced relatively slow growth in output and productivity, met the analytical criteria for a leading sector during the IR-1 case.[26] I still trace the impact of the steam engine producing industry as a potential leading sector, leaving it to the case analysis to dive deeper into the growth trajectory of this industry.

4.2.2 Candidate GPTs: Iron, steam engine, and the factory system

The possible sources of GPT trajectories in the IR-1 are less established. I draw candidate GPTs from previous studies that endeavor to map out the GPTs or technological paradigms that

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[23] Modelski and Thompson 1996, 85-87.

[24] Cameron 1989, 196; Temin 1997, 63.

[25] Rostow (1960, 54, 60), the pioneer of LS analysis, lists steam power as one of the key drivers of British takeoff. Long-cycle theorists consider steam power as the "emblematic" technology for the IR-1. Bruland and Smith, 2013, 1717. See also Reuveny and Thompson 2001, 689-719.

[26] Edquist and Henrekson 2006. They find that the steam engine producing industry's output never surpassed one percent of total industrial production in the UK from 1760-1860.

drove forward the IR-1.[27] I ultimately select three candidate GPTs based on advances in iron machinery and mechanization, the steam engine, and the factory system.

Of the two paradigmatic industries of the IR-1 — cotton and iron — the latter was a more plausible driver of GPT-style effects for Britain. As the demand for iron-made machinery grew, iron foundries developed new generations of machine tools such as cylinder-boring machines, contributing to the creation of a mechanical engineering industry.[28] This spurred the mechanization of production processes in a wide range of industries, including agriculture, food processing, printing, and textiles — which a number of scholars recognize as the key technological system during this period.[29] While both cotton textiles and iron were fast-growing industries, developments in iron better resembled a "motive branch," which drove pervasive effects across the economy.[30]

The steam engine is another possible source of GPT-style effects. Alongside electricity and information and communications technology, it has been described as one of the "Big Three" GPTs, appearing on nearly all the lists of GPTs.[31] Here, the emphasis is on the capacity for steam engines to transform a wide variety of industrial processes across many sectors, as opposed to the potential growth of the steam engine producing industry. Indeed, Deane's influential history of the IR-1 identifies the steam engine as one of two crucial advances that "ensured a continuous process of industrialization and technical change."[32]

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[27] Lipsey et al. (2005, 132) identify the factory system (an organizational GPT) and the steam engine as the GPTs of the late 18th to early 19th century. Von Tunzelmann (2000, 125) characterizes the first industrial revolution in Britain as one based on "the technological paradigm of mechanisation and use of iron in manufacturing." See also Freeman and Louca 2001.

[28] MacLeod and Nuvolari 2009, 229.

[29] MacLeod and Nuvolari 2009; Paulinyi 1986; von Tunzelmann 1995, 104-122.

[30] Freeman and Louca 2001, 155; Perez 1983, 363.

[31] Field 2008, 12.

[32] Deane 1965, 130. The other was Cort's puddling process, which facilitated the widespread availability of cheap malleable iron.

Finally, the late 18th century saw the emergence of centralized factories that significantly increased the scale of goods production. The factory system offered the potential to change the techniques of production across many industries. One widely cited classification scheme for GPTs picks out the factory system as an "organizational GPT," placing it alongside the steam engine as one of two GPTs in the late 18th to early 19th century period.[33] Other scholars describe the innovation of factory production systems as "one of the most fundamental changes of 'metabolism' in the Industrial Revolution."[34]

4.2.3 Sources of LS and GPT trajectories

Table 4.2 recaps the potential technological sources for both the GPT and LS mechanisms. Two points regarding this categorization scheme are particularly noteworthy. First, it is notable but not surprising that the candidate leading sectors and GPTs draw from similar technological wellsprings. Both mechanisms agree that some inventions, like Cort's puddling process for making wrought iron, mattered much more than others in terms of their impact on the economic balance of power. Where the mechanisms separate is in how this process actually transpired. Under the GPT model, Cort's puddling process and other innovations in ironmaking followed an impact pathway characterized by:

1. A longer timeline in terms of significant impacts upon shifts in productivity leadership (post-1815 surge) as opposed to a disproportionate impact in the early stages of its growth.
2. The diffusion of mechanization across the economy as opposed to monopoly profits from iron exports due to a national monopoly on innovation.

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[33] Lipsey et al. 2005, 132, 246.

[34] Freeman and Louca 2001, 174.

3. General-purpose applications that relied upon widespread complementary innovations in many machine-using industries as opposed to technological innovations concentrated the iron industry.

Table 4.2: Key Sources of Technological Trajectories in the IR-1

Candidate Leading Sectors	Candidate GPTs
Cotton textile industry	Factory system
Iron industry	Mechanization
Steam engine producing industry	Steam engine

Second, not all candidate leading sectors and GPTs necessarily played a causal role in the outcome of Britain's rise. They are labeled candidates for a reason. When subjected to more rigorous empirical analysis, developments in some technologies may not track well with the proposed LS and GPT trajectories for this period. For example, tracing the possible GPT-style impact of the steam engine shows that it generated economy-wide effects only after Britain had already established economic leadership.

4.3 GPT vs. LS mechanism in the IR-1

The candidate GPTs and leading sectors provide the raw materials for testing the validity of the GPT and LS mechanisms in the IR-1. By leveraging the differences between the two mechanisms with respect to the timeframe of impact, the key phase of relative advantage, and the breadth of growth, I derive three sets of opposing hypotheses for how technological changes translated into an industrial power transition in this period (Table 4.3). I then assess whether and to what extent the developments in the candidate GPTs and leading sectors support the GPT and LS mechanisms.

Table 4.3: Two Models of the IR-1

	Leading Sector Mechanism	GPT Mechanism
Key Technological Drivers	Cotton textiles, iron, steam engine producing industries	Factory system, mechanization, steam engine
Timeframe of Impact	Disproportionate in early stages (before 1815)	Disproportionate in later stages (after 1815)
Key Phase of Relative Advantage	Britain's monopoly on innovation	Britain's advantage in diffusion
Breadth of Growth	Concentrated in leading sectors	Dispersed across multiple sectors

Timeframe of impact hypotheses

When did the revolutionary technologies of the IR-1 disrupt the economic balance of power? If the impact timeframe of the LS mechanism holds, then radical technical advances in the cotton textile, iron, and/or steam engine producing industries should have substantially stimulated British economic growth in the early stages of their development. Scholars theorize that these leading sectors propelled Great Britain to industrial superiority in the late 18th century.[35] In line with this conception of a rapid timeline, Modelski and Thompson expect that the growth of two lead industries, cotton and iron, peaked in the 1780s.[36]

On the other hand, if the GPT mechanism was operational, the impact of major technological breakthroughs on Britain's industrial ascent should have arrived on a more gradual timeline. Key advances tied to mechanization, steam power, and the factory system emerged in the 1770s and 1780s. Given that GPTs require a long period of delay before they diffuse and achieve widespread adoption, the candidate GPTs of the IR-1 should not have had substantial

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[35] Cameron 1989; Modelski and Thompson 1996, 116. Rostow 1960.

[36] Modelski and Thompson 1996, 111. Using indicators on cotton consumption and wrought iron production, Modelski and Thompson designated a predicted "start-up" period (1740-1763) and "high growth" period (1763-1792) for the leading sectors of cotton and iron. The estimated peak is at the midpoint of the high growth period. They designate the years 1815-1850 as the high growth period for the steam engine (Modelski and Thompson 1996, 69), so evidence against H1.LS for the steam engine does not necessarily contradict LS predictions for the steam engine. I show that LS-accounts of the steam engine are still flawed in terms of timeline later in this chapter (4.3.1).

economy-wide repercussions until the early decades of the 19th century and after. The timeframe of impact dimension, therefore, gives the following hypotheses:

H1.LS: The cotton textile, iron, and/or the steam engine producing industries made a significant impact on Britain's rise to industrial preeminence before 1815.

H1.GPT: Mechanization, the steam engine, and/or the factory system only made a significant impact on Britain's rise to industrial preeminence after 1815.[37]

Key phase of relative advantage hypotheses

The LS mechanism places high value on the innovation phase of technological change. Where innovations arise is key. That Britain first generated the major innovations of the IR-1 explains the unevenness in industrial growth. Concretely, the LS mechanism proposes that Britain rose to industrial prominence because its dominance of innovation in leading sectors (cotton textiles, iron, and the steam engine) garnered monopoly rents from exports.[38]

The GPT mechanism emphasizes the diffusion phase of technological change. Where innovations diffuse is key. Differential rates of adoption of GPT-fueled changes across the economy generates the gap between an ascending industrial leader and other competitors. The GPT mechanism suggests that Britain's rise to industrial preeminence can be traced to its superior ability to diffuse generic technological changes across the economy. Therefore, I derive the following hypotheses:

H2a.LS: Innovations in cotton textiles, iron, and/or the steam engine were concentrated in Britain.

H2b.LS: British advantages in production and exports of textiles, iron, and/or steam engines were crucial to its industrial superiority.

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[37] The year 1815 functions as a rough cut-point to separate the accelerated impact timeframe of leading sectors from that of GPTs in this period.

[38] Monopoly rents refers to a condition wherein a producer lacks competition and can sell its goods and services at an above-market price. In line with my analysis of the parallels of the LS mechanism and the product cycle theory, monopoly rents can be captured by leads in production and exports.

H2a.GPT: Innovations in iron machinery, the steam engine, and/or the factory system were not concentrated in Britain.

H2b.GPT: British advantages in the diffusion of mechanization, steam engines, and/or the factory system were crucial to its industrial superiority.

Breadth of growth hypotheses

The last set of hypotheses relate to the breadth of growth during the IR-1 case. As illustrated in the above descriptions of the candidate leading sectors, many accounts attribute Britain's industrial ascent to a narrow set of critical advances.[39] In one of the first texts dedicated to the investigation of technology and international relations, for instance, Ogburn states, "The coming of the steam engine...is the variable which explains the increase of Britain as a power in the nineteenth century."[40] According to GPT diffusion theory, Britain's rise to industrial preeminence came from the advance of GPTs through many linked sectors. This difference gives rise to the following hypotheses:

H3.LS: Productivity growth in Britain was limited to the cotton textile, iron, and/or the steam engine producing industries.

H3.GPT: Productivity growth in Britain was spread across a broad range of industries linked to mechanization, the steam engine, and/or the factory system.

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[39] Bruland 2004; Kennedy 1983, 150-151.

[40] Ogburn 1949, 17.

Table 4.4: Specific, testable predictions for IR-1 case analysis	
H1.LS *(Timeframe of impact)*	The cotton textile, iron, and/or* the steam engine producing industries made a significant impact on Britain's rise to industrial preeminence before 1815.
H1.GPT	Mechanization, the steam engine, and/or the factory system only made a significant impact on Britain's rise to industrial preeminence after 1815.
H2.LS *(Relative advantage)*	Innovations in cotton textile, iron, and/or the steam engine producing industries were concentrated in Britain. British advantages in production and exports of textiles, iron, and/or steam engines were crucial to its industrial superiority.
H2.GPT	Innovations in iron, the steam engine, and/or the factory system were not concentrated in Britain. British advantages in the diffusion of mechanization, steam engines, and/or the factory system were crucial to its industrial superiority.
H3.LS *(Breadth of growth)*	Productivity growth in Britain was limited to the cotton textile, iron, and/or steam engine producing industries.
H3.GPT	Productivity growth in Britain was spread across a broad range of industries linked to mechanization, the steam engine, and/or the factory system.
***The operator "and/or" links all the candidate leading sectors and GPTs, because it could be the case that only some of these technologies drove the trajectories of the period.**	

As outlined in the methods chapter, I formulate predictions based on each set of hypotheses to guide the process-tracing of cases. I make the predictions specific to the IR-1 case by using the background information related to the timeline of the outcome as well as candidate leading sectors and GPTs. Table 4.4 lays out the set of specific, testable predictions that provide the framework of evaluation in the following sections.

4.3.1 Timeframe of impact: Delayed surge vs. fast rise of British industrialization

The painstaking reconstruction of temporal chronology is at the heart of process-tracing. Tremendous technological changes occurred during this period, but when did they actually make their mark on Britain's industrial superiority? The time period in which significant technological innovations emerge is often not the one in which they make their mark. Unfortunately, when drawing lessons from the IR-1 on the effect of technology on international politics, IR scholars have conflated the overall significance of certain technologies with near-immediate impact.[41] Establishing a clear chronology of when technological changes catalyzed a shift in productivity leadership during the IR-1, therefore, is an important first step in comparing the LS and GPT mechanisms.

A range of indicators, laid out earlier in the outcome section, support a delayed view of Britain's ascent to industrial superiority in the IR-1 period. This timeline establishes that Britain's relative surge in industrialization did not occur until the early decades of the 19th century, which makes it difficult for the LS hypothesis on timing (H1.LS) to hold up. If the LS account predicts that leading sectors had the greatest impact on Britain's industrial rise before 1815, and Britain's growth upswing accelerated after 1815, then the causal chronology of the LS mechanism is undermined. On the other hand, the GPT hypothesis on impact timeframe (H1.GPT) fits better with the delayed view of Britain's industrial ascent.

In addition to clarifying the timing of the outcome, tracking the timing of developments in the candidate leading sectors and GPTs is also important. This rest of this section tracks the development of all four sources of possible LS or GPT trajectories (cotton textiles, iron, steam engine, and factory system). The historical evidence bears out two main points. First, the trajectories of cotton and iron diverged, with the former following the expectations of the LS mechanism and the latter the GPT mechanism. Second, the effects of the steam engine and factory system on Britain's industrial rise were delayed and out-of-period. Analyzing the timing of

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[41] Nuvolari et al. 2011, 292. See Rostow (1990, 172-211) for a response to some of these criticisms.

technological changes in this period provides an initial filter on the technological trajectories I focus attention on in the later sections.

Diverging Timelines: Cotton vs. Iron

Time-series data on output growth of 26 industries, which accounted for around 60 percent of Britain's industrial production, helps differentiate the growth schedules of the cotton textiles and iron industries. According to this data, the major upswing in British industrialization took place after 1815, when the aggregate growth trend increased from 2 percent to a peak of 3.8 percent by 1825. In line with the expectations of the leading sector model, the cotton textile industry grew exceptionally fast following major technological innovations in the 1760s, but from the 1780s there was a deceleration in the output growth of cotton textiles. Based on the relatively early peak of the cotton industry's expansion, two scholars conclude that "it appears unlikely that cotton played the major role in the post-1815 upswing in British industrialization."[42]

Following a completely different trajectory, growth in iron goods was more in line with the GPT model. Starting in the 1780s, the growth rate of the British iron industry accelerated to a peak of about 5.3 percent in the 1840s.[43] "Compared to cotton textiles, change in iron was gradual, incremental, and spread out over a longer period of time," Moe writes.[44] With a limited role for cotton, the gradual expansion of the iron industry led Britain's post-1815 industrial surge, as its trend output tracked much more closely with that of the aggregate industry. In sum, the cotton industry followed the growth path of a leading sector, whereas developments in the iron industry reflected the impact timeline of a GPT.

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[42] Greasley and Oxley 2000, 114. There is general acceptance that the cotton industry's influence on British economic growth peaked relatively early. Farnie 2003, 734.

[43] Greasley and Oxley 2000. Trend growth for cotton stayed above that of the aggregate industrial economy in the period to 1860, so if following a strict definition of a leading sector, then cotton should be classified as a leading sector from the period of 1760 to 1860.

[44] Moe 2007, 81.

The timing of Britain's mechanization, linked to the expanded uses of iron in machine-making, also aligned with the GPT trajectory. The first metalworking tools for precision engineering, including Wilkinson's boring mill of 1774 and Maudslay's all-iron lathe, appeared in the late 18th century, but remained in a "comparatively rudimentary state" until about 1815.[45] According to accounts of qualified engineers and the 1841 Select Committee on Exportation of Machinery, over the course of the next two decades, improvements and standardization in such machine tools ushered in a "revolution" in machine-making.[46] The gradual evolution of the mechanical engineering industry provides additional support for a delayed impact timeframe for mechanization. According to British patent data from 1780 to 1849, the share of mechanical engineering patents among the total number of patents increased from an average of 18 percent in the decade starting in 1780 to a peak of 34 percent in the one starting in 1830.[47]

Delayed, Out-of-period Effects: Steam engine and Factory System

Analysis of the timing of technological diffusion in the IR-1 reveals the limited contributions of some candidate leading sectors and candidate GPTs — in particular the steam engine and the factory system — to Britain's industrial rise relative to its competitors. Specifically, this section assembles evidence to show that both the steam engine and factory system had not spread widely enough through Britain's economy by the mid-19th century to make a substantial impact on Britain's overall industrial productivity.

First, the steam engine contributed modestly to Britain's takeoff in the IR-1. Detailed investigations of the diffusion of steam engines have forced a re-assessment of commonly held assumptions about the rapid impact of steam power on British productivity growth.[48] According

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[45] Musson 1981, 34. Musson draws on over 20 years of research into British mechanical engineers

[46] Musson 1981, 34. See also Musson 1980, 90-93.

[47] MacLeod and Nuvolari 2009, 224.

[48] Greenberg 1982.

to Crafts's growth accounting analysis, which compares the impact of steam against water power as a close substitute source of power, steam power's contribution to British productivity growth was modest until at least the 1830s and most influential in the second half of the 19th century.[49] This revised impact timeframe conflicts with accounts that advance faster trajectories for steam's impact as a leading sector.[50]

Steam engine adoption was slow. In 1800, twenty-five years after the Watt steam engine was first introduced, there were only about 32 engines in Manchester, which was a booming center of industrialization.[51] Outside of the mining sector, the applications of steam power were very restricted through the first two decades of the 19th century. During the time period when LS accounts expect its peak growth, the steam engine could not claim generality of use. Even into the 1870s, many important sectors in the British economy, such as agriculture and services (excluding transport) were virtually unaffected by steam, as most of steam power's applications were concentrated in mining and in cotton textiles.[52]

The process by which the steam engine gained a broad variety and range of uses entailed many complementary innovations that followed many years after James Watt patented his steam engine in 1769. Sixty years later, the first maritime applications of steam engines arrived in the form of paddlewheel-propelled ships. Yet, wind and sail continued to power many merchant ships during this period, as sail-powered tea clippers set new speed records in the 1850s.[53] Steam eventually became the prime driver of maritime transport only after cumulative improvements in

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[49] Crafts 2004b; See also Mokyr, 2010, 124-125; von Tunzelmann 1978.

[50] Akaev and Pantin (2014, 868) dates "industries based on the steam engine" as key drivers of growth from the end of the 1780s to the beginning of the 1850s. Modelski and Thompson (1996, 69) posit that steam served as a "global lead industry" with a predicted "start-up" period from 1792-1815 and a "high-growth" period from 1815-1850..

[51] Bruland and Mowery 2006, 353. Much of the statistics used to measure the diffusion of steam engines focus on the usage of steam engines. Peralta 2020 criticizes this approach for not paying attention to how the diffusion of GPTs will enable the development of other technologies that complement it. Later in this section I show that the timeline of complementary innovations also supports the slow diffusion trajectory of the steam engine.

[52] Crafts 2004b, 341-342; von Tunzelmann 1978, 294.

[53] Smil 2010, 12.

the power of steam engines and the replacement of paddlewheels by screw propellers, which increased the speed of steam-powered ships.[54]

Later improvements to steam engines' energy efficiency also addressed bottlenecks to widespread adoption of Watt's original low-pressure design engines, which consumed large amounts of coal consumption. It was not until the early 1840s that reliable high pressure steam engines, enabled by the Lancashire boiler's invention, became economically viable in textile mills.[55] In the second half of the 19th century, scientific progress in thermodynamics unleashed efforts to develop steam engines that could handle higher pressures and temperatures.[56] In sum, steam power may be the quintessential example of the long delay between the introduction of a GPT and significant economy-side effects.

It is worth assessing whether steam's linkages with iron and cotton give grounds for an earlier impact trajectory.[57] Yet, both backward and forward linkages were limited in the early stages of the steam engine's evolution.[58] In terms of backward linkages, the steam engine producing industry did not substantially stimulate the iron industry's expansion. In the late 1790s, at a peak in sales, Boulton and Watt steam engines consumed less than .25 percent of Britain's annual iron output.[59] Forward linkages to textiles, the most likely sector to benefit from access to cheaper steam power, were delayed. According to von Tunzelmann's calculations, steam power's forward linkages to textiles did not materialize until the period 1847-1860.[60] Of course, over the long run, steam power was a critical technological breakthrough that changed the energy budget

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[54] Smil, 2010, 12-13

[55] von Tunzelmann 1978, 86-67.

[56] A host of inventors from throughout Europe and America worked on improving heat engines during this period. Bryant 1973.

[57] For those who make this argument, see Rostow 1960; Landes 1969.

[58] In this context, forward linkages allude to the effect of steam engine production on downstream activities; backward linkages refer to the upstream benefits from demand associated with steam engine production.

[59] von Tunzelmann, 1978, 285-286; Increased mechanization spurred the demand for technologies like the steam engine — not the other way around. Paulinyi 1986, 283.

[60] von Tunzelmann 1978, 289-292.

of the British economy.[61] However, for investigating the mechanisms that facilitated Britain's rise to become the clear productivity leader in the IR-1 case, the steam engine played a modest role and most of its effects were out-of-period.

A similar timeline characterizes the progression of the factory system, the final candidate GPT considered for this period. Described as a "revolution" in organization, the emergence of the factory system in the late 19th century is a central component of many accounts of the British industrial revolution.[62] Following a similar trajectory as the steam engine, the factory system diffused slowly and only took hold in a limited number of trades during the time that Britain established its industrial pre-eminence.

In Britain the transition to factories was spectacular but slow. The British textile industry, as the earliest adopter of this organizational innovation, established nearly 5,000 steam- or water-powered factories by the 1850s.[63] Other industries, however, were much slower to adopt the factory system. In the first decades of the nineteenth century, small workshops and domestic production still dominated the metal trades as well as other hardware and engineering trades.[64] Moreover, factories were still relatively small even into the mid-19th century, and some industries adopted a mixed factory system where many processes were still outsourced to household workers.[65] It was not until steam power overtook water power as a source of power in factories, a transition which took place in the 1830s and 1840s, that the subsequent redesigns of factory layouts led to large gains in the productivity of factories.[66]

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[61] Cipolla 1962; Wrigley 1988.
[62] Mantoux 2006, 25. See also Lipsey et al. 1998.
[63] Jones 1987, 71.
[64] Berg 1985; Mantoux 2006, 474-475; Mokyr 2001, 6
[65] von Tunzelmann 1997.
[66] Lipsey et al. 1998, 45.

What does this clarified chronology of technological impact mean for the explanatory power of the GPT and LS mechanisms for the IR-1 case? Because leading sectors should make their greatest impact on growth early in their development, the LS model predicts that major innovations in cotton textiles, iron, and the steam engine substantially affected Britain's economic momentum before 1815. Of the three candidate leading sectors, only cotton textiles followed the impact timeframe of a leading sector, expanding rapidly and peaking in terms of output growth in the 1780s. Yet, Britain only sustained productivity growth rates at higher levels than its rivals in the first decades of the 19th century. Thus, the period when cotton should have made its greatest impact on Britain's industrial ascent does not accord with the timeline of when Britain's industrialization surged.

In repudiating the more hurried timeline of the LS mechanism, this section's evidence validates the GPT mechanism's general expectations regarding the delayed impact of major technological breakthroughs. As predicted by the GPT mechanism, all three candidate GPTs — mechanization, the steam engine, and the factory system — did not make a substantial impact on Britain's industrial rise until after 1815. In fact, the diffusion timelines for the steam engine and factory system were so elongated that their impact on Britain's rise to industrial preeminence was limited in this period. Rather, the GPT trajectory most attune with the timing of Britain's rise to economic leadership was the gradual expansion of mechanization across industry in the 1820s and 1830s.

Thus far, the empirical evidence has presented a bird's-eye view of the overall timeline of technological change and industrialization in the IR-1, but this only assesses one dimension on which the GPT and LS mechanism diverge. A more up-close view of the IR-1 is needed to unpack the other dimensions of technological trajectories and institutional dynamics in this period.

4.3.2 Key phase of relative advantage: Diffusion of iron vs. monopoly profits from cotton

To comprehensively trace the contours of technological change in the IR-1, one must delineate between innovation and diffusion. The GPT and LS mechanisms differ in their emphasis on which phase of technological development was central to Britain's economic rise relative to its competitors in the IR-1. According to the expectations of the LS mechanism, the key driver was Britain's dominance of key innovations in cotton textiles, iron, or the steam engine. The GPT mechanism predicts, in contrast, that Britain's advantage in the diffusion of mechanization, the steam engine, or the factory system was the key driver.

The rest of this section tests two sets of predictions, derived from the diverging assumptions of the two mechanisms. First, regarding the geographic clustering of major technological breakthroughs in the IR-1, I assess whether innovations in candidate leading sectors and GPTs were concentrated in Britain. Next, regarding the comparative consequences of these technologies, I evaluate whether Britain's industrial superiority drew more from its advantages in the production and exports of the IR-1's leading sectors or its advantage in the diffusion of the IR-1's GPTs.

Innovation clustering in the IR-1's breakthroughs

Did Britain dominate innovations in the leading sectors and GPTs of the IR-1? At first glance, there is no question that radical advances in candidate leading sectors clustered in Britain. This list includes Watt's steam engine, Arkwright's water frame, Cort's puddling process, and many more. Per one analysis of 160 inventions introduced during the 19th and 20th centuries, Britain was home to 44 percent of major innovations from 1811-1849, which was double the rate of the second-leading country (the U.S. at 22 percent).[67]

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[67] Modelski and Thompson 1996, 117. Germany and France were first to innovate in 17 percent of the technological inventions. The list of major inventions comes from van Duijn 1983, 176-179.

Further investigation into British superiority in technological innovation paints a more mixed picture. Assessing which innovations count as "major" ones is a subjective endeavor, made more complicated because the timings and names of innovators are not as well documented for most early 19th century innovations.[68] Moreover, European competitors, France in particular, also competed for innovation leadership. The European continent was home to many significant innovations, including the Jacquard loom, mechanical flax spinning, chlorine bleaching, the Leblanc soda making process, and the Robert continuous paper-making machine.[69] In addition, France generated many of the major innovations in industries such as chemicals, clocks, glass, paper-making, and textiles.[70]

If innovation in leading sectors and GPTs also includes complementary innovations crucial to their development, Britain's innovation dominance is further qualified. An extended timeline of steam engine diffusion offers a much more dispersed picture of complementary innovations. In the 1820s the U.S. quickly transitioned to independent production of steam locomotives.[71] It was also the first to trial and incorporate practical screw propellers into steam-powered ships in the 1840s.[72] Plus, the U.S. produced innovative designs of steam engines, especially for large high-pressure versions.[73] During the mid-19th century British engineers spread across the European continent, helping French and Swiss engineering establishments innovate independently from British steam technology.[74]

Some scholars argue that Britain's comparative edge was in more incremental improvements. Reflecting on technological creativity in the IR-1, Mokyr argues, "Britain seems to

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[68] Van Duijn 1983, 174.
[69] Mokyr 1999, 36.
[70] Allen 2011, 358; Mathias 1975, 94.
[71] Buchanan 1986.
[72] Smil 2010, 12.
[73] The Corliss Steam Engine is the best example. Rosenberg and Trajtenberg 2004.
[74] Buchanan 1986, 510.

have no particular advantage in generating *macro*inventions . . . the key to British technological success was that it had a comparative advantage in *micro*inventions."[75] A proverb from the time captured this distinction: "(F)or a thing to be perfect it must be invented in France and worked out in England."[76] This suggests digging deeper into the different phases of technological development to uncover the roots of Britain's industrial leadership.

Monopoly profits vs. diffusion deficit

What was the key phase of relative advantage in Britain's rise? If innovation is the focal point, as the LS mechanism posits, then monopoly profits from being first to introduce new advances in cotton textiles, iron, or the steam engine should have driven Britain's rise. If diffusion is the focal point, as the GPT mechanism posits, then more effective adoption of mechanization, the steam engine, or the factory system should have driven Britain's rise.

First, as was the case with when they made their impact, developments in cotton and iron followed very different trajectories with respect to the key phase of relative advantage. Britain's cotton textile industry, which experienced a remarkable rise during the industrial revolution, is the most likely source of monopoly profits. Britain's cotton textile industry grew faster than other industries before 1800, and it sold most of its goods abroad. Technological innovations such as the spinning jenny and the water frame triggered exponential increases in the efficiency of producing cotton, and Britain's cotton output increased by 2,200 percent from 1770 to 1815.[77] From 1750 to 1801 cotton's share of Britain's major exports increased from 1 percent to 39.6 percent.[78]

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[75] Mokyr 1999, 36. Emphasis in original.
[76] Wadsworth and Mann 1931, 413
[77] Harley 1982, 268-269.
[78] Moe 2007, 38-39.

While the growth of British exports of cotton was certainly remarkable, monopoly rents associated with innovations in cotton textiles were not significant enough to produce the outcome of an industrial leadership transition. Supported by improved quantitative estimates of the cotton industry's impact on the British economy, historians generally accept that the cotton industry was much more significant for enhancing Britain's trade balance than for boosting economic productivity.[79] According to one estimate of the cotton industry's contribution to Britain's economy between 1800 and 1860, the industry accounted for 43 percent of the three-fold increase in the value of exports but only eight percent of the three-fold increase in national income.[80] Revised estimates, which incorporate a weighting scheme that indexes industry data to price and quantity trends from the 1841 Census, have also muted the role of the cotton industry in the earlier years of Britain's industrialization. Cotton represented only 1 percent of industrial production in 1770 and only 8 percent in 1815.[81]

Overall, exports constituted a small proportion of Britain's overall industrial activity during the IR-1. Some scholars calculate that in 1750 the size of Britain's domestic production was thirty-two times the size of Britain's export trade.[82] Another estimate of the relative importance of exports for industrial demand, for Britain in 1770, puts exports as accounting for 13 percent of overall industrial demand. In 1841, the relative proportion of exports in Britain's overall industrial demand only increased to 16 percent.[83]

The above contextualization of the monopoly rents from cotton solely assessed the LS mechanism. Evaluating the impact pathway of iron in the IR-1 allows a test of both mechanisms,

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[79] Farnie 2003, 734; Tomory 2016, 157.

[80] Farnie 2003, 735. The British cotton textile industry accounted for more than half of British exports by 1831 but never more than 7-8 percent of national income. Moe 2007, 37.

[81] Harley 1982, 269.

[82] Macpherson 1805, 340; cited in Hobson 1902, 12-13.

[83] Harley 1982, 282.

since iron is held up as both a candidate leading sector and candidate GPT. The LS mechanism posits that iron contributed to Britain's industrial ascent via monopoly profits from iron exports; the GPT mechanism proposes that it was the more widespread diffusion of iron usage across the economy that propelled Britain to the top. Which view does the historical data support?

Iron had less potential for LS-style effects than cotton textiles. It accounted for a much smaller proportion of Britain's exports and national income than cotton, whether measured in the total value of the industry (until as late as 1865) or in exports.[84] British iron manufacturers generated just 11 percent of Britain's manufacturing exports from 1794-1796 (compared to 18 percent for cotton). Iron's share of Britain's manufacturing exports actually declined to 2 percent in the 1814-1816 period and stayed at 2 percent in the years 1834-1836.[85]

It is also questionable whether Britain held a relative advantage in iron exports during the late 18th century, which is when LS accounts expect monopoly profits to drive British industrialization. Modelski and Thompson, for instance, cite figures that state British iron production led French production by 1780.[86] On the other hand, other reliable sources argue that the French were ahead at least until 1790.[87] Moreover, British imports of bar iron exceeded domestic production throughout nearly the entire 18th century.[88]

Clearly the impact pathway of major technological advances in the iron industry on Britain's economic rise did not run through monopoly profits from innovation. An alternative pathway, captured by the GPT trajectory, posits that Britain's advantage came from the diffusion

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[84] Moe 2007, 86.

[85] Both cotton and wool were each above 15 percent of manufacturing exports for these time periods. Davis 1979, 94-101.

[86] Modelski and Thompson 1996, 99.

[87] One account suggests that French iron output was greater than British output in 1780: Landes 1969, 95; another calculates that French pig iron output was 130-140,000 tons in 1790 compared to 60,000 tons for Britain: Crouzet 1990.

[88] In 1794 the share of imports in the bar iron supply in Britain dropped below 50 percent to 42.5 percent. Fremdling 2004, 148. The Sheffield cutlery and steel industries still relied on imports of high-grade iron from Sweden and Russia well into the nineteenth century. Berg 1985, 38-39

of iron machinery advances across a wide range of sectors. To trace this trajectory, it is necessary to pay more attention to what a prominent historian of the IR-1 calls one of the astonishing things about the phenomenon: the gap between "innovation as 'best practice' technique and the diffusion of innovation to become 'representative' technique."[89]

Britain was more successful than its industrial rivals in the diffusion of mechanization. Contemporary observers from the European continent often remarked upon Britain's ability to bridge this gap between best practice and representative.[90] Writing in 1786 in their *Voyages aux Montagnes,* French observers F. and A. de la Rochefoucauld-Liancourt commented on Britain's relative advantage in the widespread adaptation of the use of iron,

> The great advantage [their skill in working iron] gives them as regards the motion, lastingness and accuracy of machinery. All driving wheels and in fact almost all things are made of cast iron, of such a fine and hard quality that when rubbed up it polishes just like steel. There is no doubt but that the working of iron is one of the most essential of trades and the one in which we are most deficient.[91]

But France's deficiency in iron machinery was not a product of its lack of access to key innovations. In fact, France was the world's center of science from the late eighteenth century until the 1830s.[92] Rather, as the below quote illustrates, Britain's industrial rivals fell behind in "diffused average technology" and the "effective spread of technical change more widely." Mathias writes,

> It is remarkable how quickly formal knowledge of 'dramatic' instances of new technology, in particular steam engines, was diffused, and how quickly individual examples of "best-practice" technology in "show piece" innovations were exported. The blockage lay in the effective spread of technical change more widely — diffused average technology rather than single instances of best-practice technology in "dramatic" well-publicized machines.[93]

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[89] Mathias 1969, 127.
[90] Meisenzahl and Mokyr 2011, 448.
[91] Armytage 1961*,* 93.
[92] Moe 2007, 42.
[93] Mathias 1975, 102.

Advances in iron metallurgy played a crucial role in a GPT trajectory which spreads from a sector that improves the efficiency of producing capital goods. The GPT trajectory unfolds as the technology becomes more general-purpose through interactions between the upstream capital goods sector and the user industries that enlarge the range of applications. Rosenberg's depiction of this type of system highlights the 19th century American machine tool industry as the innovative capital goods sector.[94] In this case, Britain's metal-processing works were the crucial wellspring. Specifically, technical advances in iron fed into metal-working industries from which broadly similar production processes diffused over a large number of industries.[95] Berg pinpoints these industries as the "prime mechanism for technological diffusion."[96] Thus, these assessments support the proposition that iron's primary impact on Britain's rise to industrial preeminence materialized through a GPT trajectory.

Scholars also identify Watt's improved steam engine as a potential source of both LS- and GPT-based effects. Here, I focus on testing the LS prediction about the steam engine producing industry because the previous section showed that the steam engine and factory system, as candidate GPTs, diffused too slowly to make a meaningful impact on the economic power transition in the IR-1.

It is difficult to make the case that the growth of the steam engine producing industry generated a substantial source of monopoly profits for Britain. Equipped with an exclusive patent, Watt and Matthew Boulton set up a firm in 1775 to sell steam engines.[97] However, in the

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[94] Rosenberg 1963.
[95] Macleod and Nuvolari 2009; Rosenberg 1970.
[96] Berg 1985, 265.
[97] While Boulton and Watt faced competition from makers of "pirate" engines in the first 25 years of their exclusive patent (1775-1800), the sales of British "pirates" were relatively small and would not alter the overall trend of international sales of the Watt engine (Tann and Breckin 1978, 542).

period from 1775 to 1825, the firm only sold 110 steam engines to overseas customers.[98] By 1825 France and the U.S. were manufacturing the Watt engine and high pressure engines at more competitive prices and overseas demand declined sharply.[99] Thus, the international sales history of this firm severely weakens the significance of monopoly profits associated with the innovation of the steam engine.[100]

In sum, the evidence from this section supports two conclusions. British advantages in the *production* and *export* of iron, steam engines, and cotton textiles (the best representative of the LS trajectory) had muted effects on its overall industrialization and productivity advances. Second, the contributions of technological breakthroughs in iron metallurgy and steam power to Britain's industrial rise track better with the GPT mechanism based on relative advantages in widespread technological diffusion, as opposed to monopoly profits from innovation.

4.3.3 Breadth of growth: Complementarities of iron vs. spillovers from cotton textiles

The breadth of growth in the IR-1 is the last dimension on which the LS and GPT trajectories disagree. Was Britain's industrial rise driven by technological changes confined to a narrow range of leading sectors, or was it based on extensive, complementary innovations that enabled the spread of GPTs? Making use of data on industrial output, trade flows, and patents, I assess the LS and GPT mechanisms on their competing propositions about the breadth of technological change in the industrial revolution.

Widespread Technological Change

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[98] Tann and Breckin 1978, 544.

[99] By 1833 an estimated 946 steam engines were at work in France, 759 of which were of French manufacture. While the comparable U.S. figures are not as detailed, "there were, clearly, more U.S.A.-manufactured Watt engines at work than imported ones by 1810 and the total number of engines may have been in the region of 500 by 1825. Tann and Breckin 1978, 558-559.

[100] It could be the case that export growth in leading sectors caused growth in industrial output. One time series analysis of the period 1780-1851 finds that this was not the case. Greasley and Oxley 1998a.

To highlight the contrast between the narrow and broad view of technical change during the IR-1, consider two sets of estimates about the contribution of various industries to Britain's productivity growth. McCloskey's estimates show that technological changes were widespread in the British economy. Though cotton accounted for a remarkable 15 percent of Britain's total productivity growth, non-modernized sectors still contributed to the lion's share (56 percent) of productivity gains (Table 4.5). On the other hand, N.F.R.'s Crafts's estimates give much more weight to the role of leading sectors in British productivity growth. Modernized sectors, including cotton (25% of total productivity growth), accounted for 73 percent of total productivity growth, agriculture contributed 17 percent, and all other sectors only contributed 10 percent of total productivity growth.[101] This depiction of technological change stands in for the leading sector view, which sees the Industrial Revolution through the narrow lens of innovations in textiles, iron, and transportation. For Crafts the Industrial Revolution was decidedly concentrated in these leading sectors; all other manufactures and other services were technologically stagnant.[102]

As Table 4.5 illustrates, Craft's 1985 estimates revise downward the overall growth rate of British productivity over this period but keep McCloskey's estimates for the productivity gains of modernized sectors. This is akin to revising downward estimates of jobs created — but not adjusting estimates of jobs created by the manufacturing sector — and then concluding that the service sector accounted for a smaller share of jobs created. Following scrutiny, Crafts has revised his estimates.[103] In later work Crafts concedes that "the data may leave more possibility of productivity advance in the 'unmodernized sectors' than he allowed."[104]

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[101] McCloskey calculated the productivity gains of "all other sectors" by subtracting the total productivity gains of modernized sectors and agriculture from the rate of growth of production in the national economy. Reproducing McCloskey's calculations of the productivity gains of the modernized sectors and agriculture, Crafts substitutes his own estimate of total national productivity growth to come up with a revised figure for the contribution of non-modernized sectors. Crafts 1985, 86.

[102] Crafts 1985, 86.

[103] Berg and Hudson 1992; Crafts and Harley 1992.

[104] Crafts and Harley 1992, 719n67.

Table 4.5: Diverging estimates of sectoral contributions to total productivity growth, 1780-1860

	Widespread (McCloskey's estimates)	Localized (Crafts's estimates)
Cotton	15%	25%
Iron	2%	3%
Modernized sectors (inclusive of cotton, iron, and others)*	44%	73%
Agriculture	10%	17%
All other sectors	**46%**	**10%**

British productivity gains by sector in terms of percentage contribution to total productivity growth. *Modernized sectors include cotton, other textiles, iron, canals and railways, and coastal and foreign shipping.
Source: adapted from McCloskey 1981, 114; Crafts 1985, 86.

One test of these diverging depictions of the IR-1 leverages trade data on manufacturing exports. If other manufacturing industries outside of textiles and iron were technologically stagnant during the first fifty years of the 19th century, then British competitiveness in these industries should decline relative to textiles and iron. The implication is that Britain should have imported other manufactures. The GPT view expects the opposite — an increase in British competitiveness in other manufacturing industries — based on the assumption that mechanization enabled complementary advances across a broad range of sectors.

Temin's analysis of British trade data bolsters the GPT model. He finds that British manufacturing exports "kept pace" with cotton exports throughout the first half of the nineteenth century.[105] In a wide range of manufactures, such as arms and ammunition, carriages, glass, and machinery and metals, Britain held a clear comparative advantage. This pattern points to some general pattern of change that spanned industries. "The spirit that motivated cotton

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[105] Temin 1997, 76.

manufactures extended also to activities as varied as hardware and haberdashery, arms, and apparel," Temin concludes.[106]

The patent record also paints a broad landscape of technological change.[107] Certainly, the leading sectors were substantial sources of innovation. Per Christine MacLeod's data on British patents for capital goods from 1750-1799, textile machinery and power sources made up around 40 percent of all patents in capital goods.[108] In that same period, the textile industry contributed 13 percent of total patents, ranking the highest of six important industries to which patents were assigned.[109]

The thrust of the patent data, nevertheless, points to extensive technological change that cannot be contained in a few leading sectors. In the second half of the 18th century, 85 percent of all patented inventions came from outside the textiles and metals industries, and the majority of all capital goods patents still came from sectors outside of textile machinery and power sources.[110]

Widespread changes in core areas of economic activity such as agriculture, glass manufacture, and machine tools were occurring at the same time as the more visible innovations in textiles. MacLeod's data also shows a marked acceleration of patents in agricultural equipment, brewing equipment, building equipment, canals, metallurgical equipment, and shipbuilding in the last decade of the 18th century.[111] That these economic domains followed nearly the exact same trend as textile machinery and power sources is further evidence of a broad, general technological

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[106] Temin 1997, 79.

[107] There are some limitations to patent data. Many advances are not patentable. Patenting varies over time and across industries. The existence of a patent does not guarantee the technique had economic value, and patenting can also be affected by social factors. Still, the patent series "gives us a reasonable guide to the pace and direction of technological advance in industry." Bruland 2004, 123.

[108] Steam engines are included in textile machinery and power sources. MacLeod 1988, 148.

[109] The other five "strategic sectors" were metals, field agriculture, ocean shipping, heavy chemicals, and railroads. Sullivan 1990, 352.

[110] Sullivan 1990, 352; Macleod 1988, 148.

[111] Bruland 2004, 124.

trajectory. All of this affirms "the empirical fact that this was an economy with extensive technological change, change that was not confined to leading sectors or highly visible areas of activity."[112]

GPTs and Complementary Innovations

At this point, indicators of the multi-sectoral spread of innovation in the IR-1 should not be sufficient to convince a skeptical reader of the GPT mechanism's validity. While extensive technological change could reflect a GPT at work, it could also be a product of changes that produce economy-wide effects, such as reforms of financial institutions that increase investment.[113] Most famously, Max Weber argued that the Protestant ethic of individualism was crucial to modern economic development.[114]

Though the weight of evidence supports the view that technological change was widespread during the IR-1, it does not follow that technological change was *uniform*. Some British industries, such as clockmaking and watchmaking, declined in competitiveness due to stagnations in productivity and became import industries by the middle of the 19th century.[115] Yes, technological change was extensive, but if the GPT mechanism was operational, technological change should have also been unbalanced — in the sense that it was shaped by GPT trajectories. The section proceeds by evaluating whether mechanization served as the engine of this widespread growth.

Input-output analysis, which sheds light on the linkages between industries, suggests that improvements in the working of iron had broader economic significance. To better understand the interrelationships among industries during the industrial revolution, Horrell et al. constructed

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[112] Bruland 2004.
[113] The dispute between these two views is summarized in Hartwell 1965, 180-181.
[114] Weber 1930.
[115] For a history of clockmaking, see Landes 1983.

an input-output table for the British economy in 1841. Across the 17 industries included in the input-output analysis, the two industries most closely associated with mechanization — the metal manufacture and metal goods industries — scored the highest on combined backward and forward linkages.[116] These were "the lynchpins of linkage effects" during this period.[117]

Patent indicators confirm these results. Consider two ways of evaluating a dataset on patents issued in Britain between 1711-1850. Assigning patents to standard industry taxonomies reveals that the textile industry contributed to 15 percent of the patents issued over the period, making it the most inventive industry in aggregate terms. However, if patents are allocated to groups defined by general techniques as opposed to industry sectors, the same dataset underscores the underlying drive force of mechanical technology: It is linked to almost 50 percent of all British patents during this period.[118]

The effects of a plentiful supply of cheap iron had a profound impact on the rest of the economy. Advances in ironmaking were closely linked to the growth of machine technology, and Hyde claims a supply of cheap iron was "a prerequisite for the revolutions in building and transportation that were an integral part of the industrialization process."[119] Hyde is not overstating these spillover effects. The building industry, according to one estimate, accounted for 15 percent of British industrial production in 1815.[120]

Along all three dimensions of technological trajectories in the IR-1, the process-tracing evidence bolsters the validity of the GPT mechanism. First, the slower-moving developments in mechanization lined up with the delayed timeline of Britain's industrialization. Other candidate

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[116] Horrell et al. 1994, 555.

[117] Horrell et al. 1994, 557.

[118] Sullivan 1990, 354. Another analysis of British patents from 1780-1849 finds that the share of mechanical engineering patents grew from 17 percent at the start of the period to about 30 percent by the end. MacLeod and Nuvolari 2009, 223.

[119] Hyde 1977, 191. The falling price of iron contributed to the growing efficiency of water wheels, which increased in efficiency by about 20 or 30 percent from 1750 to 1780. Freeman and Louca 2001, 162.

[120] Harley 1982, 269.

leading sectors and GPTs either peaked too early (cotton) or got started too late (steam engine, factory system). Second, Britain gained its industrial dominance from a relative advantage in widespread adoption of iron metalworking and linked machinery. Third, the benefits from this GPT advantage did not stay concentrated in the iron industry but dispersed throughout the economy.

The standard explanation of how the IR-1 gave rise to a power transition, as captured in the LS mechanism, analyzes technological change at the level of industries that grow faster than others. The historical evidence from the IR-1 case reveals the limitations of industry taxonomies. Rather, advantages in the diffusion of production machinery, a general pattern of change that extended across a wide range of economic activities, propelled Britain to industrial dominance.[121]

4.4 Institutional complementarities: GPT skill infrastructure in the IR-1

Having mapped out the contours of the GPT trajectory in this period, there is still a need to explain why Britain was best positioned to exploit this trajectory. If other countries at the technological frontier can also cultivate GPT innovations at home and absorb them from abroad, why were Britain's competitors unable to benefit from the diffusion of metalworking processes to the same extent?[122] This section provides an explanation based on Britain's institutional competencies in widening the skill base to enable mechanization.

4.4.1 Skill gap for "diffused average technology" in iron-based GPT

Which types of institutions for skill provision were most conducive for national success in the IR-1? Answering this question requires first establishing which skills were most significant for Britain's rise. One common refrain is that Britain's leadership was rooted in the genius of

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[121] Sullivan 1990, 350; Temin 1997, 79.

[122] France was the leading Continental power at the time, so I focus on British-French comparative differences in this section. Crouzet 1967; Skocpol 1979, 54. For evidence that my explanation for Britain's comparative advantage over France also applies to the Netherlands, Britain's other rival for technological leadership, see Mokyr 2000.

individual innovators like James Watt, which did not transfer as quickly across borders during the IR-1.[123] Consistent with the assumptions of the LS mechanism, this explanation focuses on the institutions that could have helped Britain maintain a monopoly on innovations in new industries. However, under the GPT mechanism — which the previous section proved to be a superior explanation — Britain owed its relative success in the IR-1 to mechanical engineers. It is these "tweakers" and "implementers," rather than the heroic inventors, that take center stage in this account.[124]

First and foremost, it is necessary to differentiate between the types of knowledge that were easily absorbed by Britain's rivals and those that were stickier. In the eighteenth century, transmission belts for the diffusion of codified knowledge crisscrossed western Europe and North America. Formal knowledge was transferable via patent specifications, detailed correspondences and publications that facilitated global exchanges between scientific societies, and extensive visits by foreign observers to British workshops and industrial plants.[125] On the other hand, the continent faced more difficulties in acquiring tacit knowledge, embodied in practical engineering skills that were critical to a Britain's ability to diffuse follow-on innovations in metalworking and machine-building. The transfer of tacit knowledge in the fields of large-scale iron working and machine construction almost always necessitated the migration of British artisans, engineers, and entrepreneurs.[126]

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[123] For example, in his summary of the role of leading sectors in past industrial revolutions, Kennedy (2018, 54) claims, "British leadership in the first industrial revolution sprang from the genius of individual inventors."

[124] Meisenzahl and Mokyr 2011, 446. As Cookson (2018, 154) writes in her study of the engineers that built Britain's first modern textile machines, "here was a limit to how many James Watts could be accommodated in a business. The real need was for skilled workers on shop-floor duties."

[125] Mathias (1975, 100) even goes as far to write, "The republic of science was truly international at this time; possibly more so even than today...." He qualifies this with two caveats: there was much less specialization in scientific subjects and fewer people engaged in scientific institutions in the eighteenth century.

[126] Berg 1985, 188; Mathias 1975, 102-103.

British engineering talent, in particular engineers skilled in the precision metalworking of large-scale iron machinery, were in especially high demand.[127] Responsible for not just the first installation of a machine but also further refinement and maintenance, machine makers and mechanical engineers reduced the adoption costs for mechanization.[128] While Britain's industrial rivals could adopt the most high-profile, showpiece machines with relative ease, they struggled to adopt "diffused average technology."[129] "It was exactly in the skills associated with the strategic new industries of iron and engineering that [Britain's] lead over other countries was most marked," argues Mathias.[130] France suffered from a "human capital lag" in "engineers with skills in machinery," which hampered its adoption of mechanization.[131]

4.4.2 Britain's institutional advantages in widening the pool of skilled mechanics

Britain's advantage in GPT skill infrastructure did not materialize overnight. When demands for precision engineering escalated in the early phase of industrialization, Britain's pool of workers was insufficient in both quantity and quality.[132] This is consistent with the expected institutional lags in supplying skills for new GPT trajectories. The President of Britain's Institute of Civil Engineers reflected on the process in an 1848 address,

> [T]he rapid introduction of cast-iron together with the invention of new machines and new processes called for more workmen than the millwright class could supply...a new class of workmen was found and manufacturing establishments arose to which were attached iron and brass foundries with tools and machines for constructing machinery of every description.[133]

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[127] Berg 1985*,* 42; Mathias 1975, 107-108.
[128] MacLeod and Nuvolari 2009, 227.
[129] Mathias 1975, 102.
[130] Mathias 1969, 129.
[131] Moe 2007, 94.
[132] Buchanan 1841, 394-395. Cited in Jefferys 1945, 12; See also Pollard 1965, 167-168.
[133] Field 1848, 36. Cited in Jefferys 1946, 15n19.

Eventually, a wide talent pool of mechanically-skilled engineers essential to spreading best practices in the iron and machinery industries, which I call GPT skill infrastructure, emerged in Britain in the early decades of the 19th century.

Why did this repository of engineering skills develop more fruitfully in Britain than in its industrial rivals? A growing body of evidence suggests that Britain's institutions better adapted the distribution of skills to mechanization. First, institutes dedicated to training mechanical engineers helped diffuse ironmaking and machine-making skills. A flurry of trade associations that catered to a new class of mechanical and civil engineers sprung up in the 1820s.[134] Critical centers established in the first half of the 19th century included the Andersonian Institution in Glasgow, the Manchester College of Arts and Sciences, the School of Arts in Edinburgh, the Mechanical Institution in London, the Society for the Diffusion of Useful Knowledge, and hundreds of Mechanics' institutes.[135] These institutes helped to absorb knowledge from foreign publications on science and engineering, recruit and upskill new mechanical engineers from a variety of trades, and spread mechanical engineering knowledge more widely.[136]

Britain's institutional advantage was rooted in the system of knowledge diffusion that connected engineers with entrepreneurs, cities with the countryside, and one social class with another. The institutes that trained mechanical engineers were part of a broader "mushrooming of associations" that spread technical knowledge in early 19th century Britain.[137] By the mid-nineteenth century there were 1,020 such associations in Britain with a total membership of approximately 200,000, making these networks essential to any explanation that links human

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[134] Jefferys 1946, 17.

[135] Marsden 2004, 405; Pollard 1965, 180-181. By 1850 there were around 700 Mechanics' institutes across Great Britain. Birse 1983, 62.

[136] Musson and Robinson 1960; Musson 1969.

[137] Crafts 1996, 199.

capital to Britain's industrial ascent.[138] As a result, the British system of the early nineteenth-century had no match in its abundance of people with "technical literacy."[139] Compared to their peers on the continent, British mechanical engineers had superior access to scientific and technical journals.[140]

The French system, by way of comparison, lacked similar linkages and collaborations between highly educated engineers and local entrepreneurs.[141] Though France produced elite engineers at schools like the Ecole polytechnique, it trained too few practitioners to widen the base of mechanical engineering talent.[142] For instance, Napoleon's early 19th-century reform of France's higher education system emphasized the training of experts for narrow political and military ends, which limited the ability of trainees to build connections with industry.[143] Through the mid-1830s, only one third of École Polytechnique graduates entered the private sector.[144] "[T]he (British) system of knowledge diffusion was vastly superior to the French," summarizes Moe.[145]

It is only natural to question why Britain accumulated this advantage in GPT skill infrastructure.[146] While this chapter does not aim to explain the deeper causes for why Britain's institutions were responsive to the skill demands of mechanization, others have developed preliminary explanations. Zeev et al. argue, for example, that during the 18th century Britain's

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[138] Mokyr 2002, 66.
[139] Mokyr 2002, 73.
[140] Moe 2007, 94. Relatedly, the Netherlands and the UK far exceeded other countries in terms of book production per capita across Europe in the 18th century. Baten and van Zanden 2008.
[141] Jacob 1997, 184; Crouzet 1967, 239.
[142] This is the commonly held view. See, for example, Kindleberger 1976, 13. Others argue that middle-level technical schools like the Ecoles d'arts et metiers did implement reforms that widened access to mechanical engineering instruction. By the 1860s graduates of the Ecole d'arts et metiers "comprised about 40 percent of the trained engineers and middle-level technicians of France including almost all mechanical engineers" (Day 1978, 444). Lundgreen (1990, 39) also warns against "dubious retrospective extrapolations" that associate France's lack of technical education with its falling behind international competitors.
[143] Crouzet 1967, 239; Lundgreen 1990, 39; Moe 2007, 43.
[144] Ahlström 1982, 44.
[145] Moe 2007, 49.
[146] Landes regarded the source of Britain's superiority in mechanical skills as "mysterious." Landes 1969, 61-64.

system of apprenticeship was more flexible and responsive to train skilled mechanical labor, which proved essential in its later economic success.[147] Looking even further back, Sarid et al. examine the geographical origins of Britain's mechanical skills, tracing them to Britain's adoption of watermills in the early Middle Ages.[148]

It is important to distinguish between institutional competencies that enabled GPT diffusion, such as Britain's GPT skill infrastructure in mechanical engineering, and other institutions that were linked to human capital creation. Britain's advantage in skill provision did not extend to the population at large or the entire laboring class.[149] If measured by average literacy rates and school attendance, the average level of human capital in Britain was "surprisingly low for an industrial leader."[150]

Nor was England's advantage in GPT diffusion rooted in its higher education system, which lagged far behind that of France's during the IR-1 period. France had already established more than 20 universities before the French Revolution. The French system of higher technical education, from the late eighteenth century through the 1830s, had no rival. The *Grande Ecoles* system, including the elite École Polytechnique which was established in 1794, trained expert scientists and engineers to take on top-level positions as industrial managers and high-level political personnel.[151] Up until 1826, England had only set up two universities, Oxford and Cambridge. These institutions made limited contributions to training the workforce necessary for industrialization. One count of the 498 applied scientists and engineers born between 1700 and

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[147] Zeev et al. 2017.

[148] Sarid et al. 2019.

[149] Mitch 1999.

[150] Meisenzahl and Mokyr 2011, 475.

[151] Moe 2007, 42-43.

1850 found that only 50 were educated at Oxford or Cambridge; 329 were not university-educated.[152]

Finally, Britain's institutional advantage was not based on industrial policy. Britain did take some active measures to protect its technological lead. It attempted to implement legal prohibitions on the export of critical technologies and the emigration of skilled artisans. For instance, Britain prohibited the export of machinery, except for steam engines, from 1780 until 1825.[153] Compared to rival states, the British state played a relatively modest role in securing technological advantage. Aware that new technologies were progressing more quickly elsewhere, Continental governments, in particular France, undertook systematic efforts to support the absorption of these new industrial techniques.[154] In the late seventeenth and early eighteenth century, most continental governments were "deploying a whole range of economic policy weaponry," including tariff barriers, public procurement directed to state monopolies, and programs to attract skilled talent from other countries.[155]

Ultimately, British protectionist policies to maintain a monopoly on innovation largely failed, and Continental governments also made little progress with industrial policy to catch-up. In France, for instance, enterprises set up by skilled entrepreneurs helped facilitate some diffusion of new skills. However, heavy-handed industrial policy directed French engineers toward narrow objectives, lavishing resources to new technologies associated with luxury industries and specialized military purposes, which "tended to become locked away from the rest of the economy in special enclaves of high cost."[156] On the British end, its prohibitions on technology transfer were not effectively enforced, as machines were exported via component

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[152] Mokyr 2005, 311n90. The rest were educated at universities in Scotland.
[153] Berg 1985*,* 42.
[154] Moe 2007, 45.
[155] Mathias 1975, 99.
[156] Mathias 1975, 99.

parts, smuggling was commonplace, and artisans emigrated frequently, even to enemy countries in the midst of war.[157]

The core distinction between the LS and GPT mechanisms with regards to technology-institutional complementarities is in what aspect institutions need to adapt to technological change. The LS product cycle theory claims that it is the innovation that is hard: institutions to incentivize fundamental breakthroughs and prevent knowledge leakage are crucial, otherwise technology diffuses too quickly to rival nations. The GPT diffusion theory argues, instead, that it is the diffusion that is difficult: Britain's comparative advantage was rooted in its institutional adaptations and competencies to widen the base of mechanical engineering skills.

4.5 Alternative explanations of Britain's rise

The history of the IR-1 is certainly not a neglected topic. The literature features enthusiastic debates over a wide range of possible causes. Prominent explanations tie Britain's early industrialization to population growth,[158] demand and consumption standards,[159] access to raw materials in colonies,[160] slavery,[161] and trade,[162] etc. The obvious concern is that various contextual factors may confound the analysis of the LS and GPT mechanisms.

I am not rewriting the history of the IR-1. I am drawing from one particularly influential and widely-held view of the IR-1 — that technological advances drove Britain's industrial ascent — and investigating how technological change and institutional complementarities produced this outcome. The most relevant alternative factors, therefore, are those that provide a different interpretation of how technologies and institutions co-evolved to result in Britain's industrial

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[157] Mathias 1975, 104.
[158] Clark 2007.
[159] Gilboy 1932.
[160] Pomeranz 2000.
[161] Williams 1944.
[162] Habakkuk and Deane 1963.

hegemony. While I primarily focus on the LS mechanism as the most formidable alternative explanation to the GPT diffusion theory, other explanations based on varieties of capitalism as well as neorealist theories of threat are also worthy of investigation.

4.5.1 Threat-based explanation

Threat-based theories argue that external threats are necessary to incentivize states to innovate and diffuse new technologies. If this explanation applies to the IR-1 case, then the historical record should show that the Revolutionary and Napoleonic Wars (1793-1815) positively affected Britain's adoption of iron machinery and mechanization. There is some evidence in support of this argument. In fact, the British government's needs for iron in the war effort accounted for 17 percent of the total British iron output in 1805.[163] This wartime stimulus to iron production facilitated improvements in iron railways, iron ships, steam engines, and other civilian spin-offs.[164]

However, the wars also negatively impacted Britain's technological success in the IR-1. Aside from Wilkinson's cannon boring device and some incremental improvements, wartime pressures did not produce any major technological breakthroughs for the civilian economy.[165] In fact, the disruptive effects of war likely offset any stimulus effect. Military needs absorbed productive laborers from Britain's civilian economy, resulting in labor shortages.[166] War also limited the domestic demand for iron by halting investment in construction, agriculture, and other industries as well as the foreign demand for British iron by cutting off foreign trade. "In the

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[163] Hyde 1977, 115.

[164] O'Brien 2017, 51-53; Trebilock 1969.

[165] Mathias 1969, 124; O'Brien 2017, 47. Recent work has noted that the gun industry helped produce important spin-offs in other key industries such as textiles and machine tools. Satia 2019. While spin-offs from gunmaking played an important role in the initial development of the metal hardware trades, they do not explain why Britain progressed further and faster along the GPT trajectory after the initial incubation of these industries.

[166] Hueckel 1973, 371.

absence of fighting, overall demand for iron might have been higher than it was," concludes historian Charles Hyde.[167]

On a more basic level, the threat-based explanation cuts both ways in the IR-1 case, as France, Britain's main industrial rival, was fighting against Britain in the same war. Therefore, since France also faced a threatening external environment, the net effect of the war on the economic growth differential between Britain and France should have been minimal. In other words, any war stimulus mechanism for Britain should have also been present in France. Therefore, if enhanced trade protections during the Napoleonic Wars spurred faster diffusion of mechanization in countries facing this external threat, for example, then both Britain and France would have experienced this stimulus.[168]

4.5.2 VoC explanation

Some IR scholars posit that Britain's free market economy was central to explaining its technological rise in this period. Related to the VoC tradition, which argues that liberal market economies (LME) have a relative advantage over coordinated market economies in producing radical innovations, they emphasize the institutional complementarities of free markets with the development of new technologies such as consumer goods, light machine tools, and textiles.[169] As Kitschlet writes, "Britain, as a decentralized, market-oriented society with a weak state, could seize most energetically the opportunities offered by the new technological trajectory."[170]

The applicability of VoC theory to the IR-1 case is limited in two respects. First, to what extent Britain qualified as an LME in this period is much disputed. Britain did not establish many

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[167] Hyde 1977, 115-116.

[168] For evidence that the British iron industry benefited from British duties on Russia and Swedish iron imports during the war, see O'Brien 2017; for evidence that France's adoption of mechanized cotton spinning also benefited from wartime trade protections, see Juhász 2018.

[169] Kim and Hart 2001; Kitschlet 1991; Kurth 1979.

[170] Kitschelt 1991, 471.

of the key features of LMEs, including a high level of corporatization and decentralized collective bargaining, until the late 19th century.[171] Others have challenged the notion that Britain's free trade regime was more liberal than that of France in the early 19th century.[172]

Second, VoC-based explanations assume that producing radical innovations was the crucial driver of diverging technological trajectories. It is often used to explain why LMEs are more successful in pioneering product innovations in science-based industries. Yet, this model of technological fitness is not as useful for understanding why Britain was the leader in the diffusion of mechanization. Moreover, it is unable to differentiate between the performance of two LMEs. For example, Britain's other main rival for technological leadership, the Netherlands, was an open economy but was not able to adapt and diffuse significant technological changes.[173]

4.6 Summary

The industrial revolution is a typical case of the rise and fall of great technologies and powers. Britain effectively took advantage of general-purpose improvements in mechanization because its institutional milieu was conducive to widening the pool of mechanical engineering talent. According to GPT diffusion theory, countries like this will disproportionately benefit from technological revolutions, because they will be more successful in adapting to the GPT trajectories that transform productivity. In line with these expectations, Britain was more successful than its industrial rivals in sustaining long-term economic growth, which became the foundation of its unrivaled power in the early and mid-19th century.

The industrial revolution case analysis diverges from the interpretation of leading-sector accounts. Some of the proposed LS drivers either peaked too early (cotton) or got started too late (steam engine, factory system). It was the widespread adoption of iron metalworking and linked

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[171] Crafts 2014.
[172] Nye 1991.
[173] Davids 2008; Mokyr 2000, 514-515; Wrigley 2000.

production machinery, not monopoly profits from cotton textiles, that drove Britain's industrial ascent. Moreover, Britain's key advantage in human capital was not its supply of heroic inventors but rather its wide pool of mechanical engineering talent. Do these findings generalize to other periods of technological and geopolitical upheaval? After all, the industrial revolution, albeit a typical case in my research design, was one of the most extraordinary events in history. To further explore these dynamics, I turn to the case of the second industrial revolution.

Chapter 5
The Second Industrial Revolution and America's Ascent

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 a cluster of 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.[1] For many scholars, the international contest for supremacy in this technological revolution provides a key reference point for the effects of present-day technological advances on the balance of power.[2]

Often overshadowed by its predecessor, the IR-2 is equally important for investigating the causal mechanism that connects technological revolutions and economic power transitions. The IR-2 fulfills the characteristics of a typical case, since the cause and outcome are both present. 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.[3]

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.[4] In the words of Landes, this

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[1] 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.

[2] Allison 2017, xviii; Horowitz 2018, 51. Horowitz makes this point with respect to geopolitical competition in AI technology.

[3] Mowery and Rosenberg 1991, 22.

[4] Buzan and Lawson 2015, 43. Drezner 2001; Gilpin 2001,140.

was a "shift from monarchy to oligarchy, from a one-nation to a multi-nation industrial system."[5] The outcome of the IR-2 case had world-shaking implications. In the view of some scholars, British industrial decline in the IR-2 was the ultimate cause of World War I.[6]

The IR-2 provides a good test of the general-purpose technology (GPT) mechanism against the leading-sector (LS) mechanism. 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.[7] 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 chemical, electrical, and industrial dye industries of the IR-2.[8]

The Second Industrial Revolution (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.[9] Theoretically, this aligns well with the leading sector story: Groundbreaking clusters of technological innovations spurred the growth of new science-based 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.

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[5] Landes 1969, 247.

[6] Gilpin 1975, 77; Organski 1958, 291-292. Others criticize the explanations of power transition theorists regarding Germany overtaking the UK. in economic capabilities as the cause of World War I. For a summary, see Vazquez 1996, 41-42.

[7] Akaev and Pantin 2014, 869.

[8] For an argument about why China today compares unfavorably to Germany in the IR-2, see Beckley 2011, 63-72.

[9] Rostow 1960, 175.

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., which rose to industrial preeminence during the IR-2, was broadly distributed — not dominated by a few R&D based sectors. Moreover, the prominent technological changes featured in LS accounts, such as 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 economic power transition.

Instead, the IR-2 case study supports the GPT mechanism. The key GPT trajectory was embodied in the extension of interchangeable manufacture, or the "American System of Manufacture" (ASoM), characterized by the sequential operation of special-purpose machine tools that enabled mass production.[10] 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 extension 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.[11]

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

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[10] This definition is based on Ferguson 1968, 298. Scholars have questioned whether the developments in interchangeable manufacturing mapped neatly onto the standard concept of the "American system of manufacturing," citing inconsistencies such as the infeasibility of achieving perfect interchangeability of parts in the middle of the nineteenth century. Still, even if perfect interchangeability was not achieved in some industries during the IR-2, increased uniformity still played a significant role in enabling mass production. Hoke 1990; Hounshell 1985.

[11] David 1975; Rosenberg 1972, 87-90.

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 sector-specific educational institutes, specialized engineering programs at universities, technical high schools, and machine tool associations.

My evidence for the IR-2 case comes from a variety of sources. I trace the contours of the economic power transition with a combination of the same sources from the IR-1 case as well as revised versions of historical productivity measures available at this later date. To narrow down the range of major technical breakthroughs and link them to LS or GPT trajectories, I parsed through histories of technology, categorization schemes from the long-cycle literature, and general accounts of economic historians. I was able to test the two mechanisms with comparative histories of specific technologies, firsthand accounts from inspection teams commissioned to study related issues,[12] data on sectoral-level contributions to industrial productivity, and indicators of technological diffusion.

This chapter proceeds as follows. Section 5.1 describes the economic power transition that took place during the IR-2, which clarifies that the U.S., not Germany, ascended to industrial preeminence. Section 5.2 identifies the key technological breakthroughs, which are sorted according to their ties to GPT and LS trajectories. Section 5.3 demonstrates that the GPT trajectory aligns better with how the IR-2 developed, along dimensions such as the timeframe of impact, the key phase of relative advantage, and the breadth of growth. Section 5.4 shows that the institutional contexts that favored certain countries in the IR-2 differ depending on whether the GPT or LS trajectory holds up. Section 5.5 addresses alternative explanations. Section 5.6 concludes.

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[12] According to Piore and Sabel (1984, 46), "The most sober accounts of the consolidation of mass-production practice in the United States were written by the British engineers who toured American plants after 1850."

5.1 Power transition: America's ascent

As the IR-1 case demonstrated, tracing *when* an economic power transition takes place is critical. In 1860, Britain was still at the apogee of its industrial power.[13] Most historians agree that British industrial preeminence eroded in the late nineteenth century. By 1913, both the United States and Germany had emerged as formidable rivals to Britain with respect to the industrial and productive foundations of national power. According to Kennedy's influential account, before World War I Britain was "in third place," and "in terms of industrial muscle, both the United States and imperial Germany had moved ahead."[14] Aided with more data than was available for the IR-1 case, I map the timeline of this economic power transition with various measures on industrial output and efficiency.

In the IR-2 case, clarifying *who* surpassed Britain in economic efficiency takes on added gravity. Whereas in the IR-1 Britain separated itself from the rest, both the U.S. and Germany challenged British industrial power in the IR-2. But studies of this case often neglect the study of all three countries. In support of the proposition that World War I was sparked by Germany's overtaking of Britain in capabilities, the power transition literature has directed most of its attention to the Anglo-German rivalry and marginalized the rise of the United States.[15] Some LS-based accounts only explain Germany's rise in this period without investigating America's ascent.[16]

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[13] Its per capita level of industrialization was more than double that of the second-ranked power (Belgium). Bairoch 1982, 281.

[14] Kennedy 1987, 228.

[15] Chan 2008, 21; Vazquez 1996, 41. Kennedy (1987, 242) writes, "Of all the changes which were taking place in the global power balances during the late nineteenth and early twentieth centuries, there can be no doubt that the most decisive one for the future was the growth of the United States."

[16] Moe 2009, 215-218; Drezner 2001, 12n33. Drezner does acknowledge that the U.S. also surpassed Great Britain in this period. He justifies his choice to solely study Germany on two grounds. First, German science and technology were superior to the states. Second, since German military spending was greater than Great Britain's, the claim that Britain's military commitments detracted from its relative productivity can be tested.

As the assessment of industrial power shifts in the IR-2 will show, Germany and the U.S. both surpassed Britain on some measures of economic power, but it was the U.S. that emerged as the clear productivity leader. Therefore, any explanation of changes in technological leadership in this period must be centered on the U.S. experience. Moreover, this outcome sets up an even more rigorous way to test the competing mechanisms. The preferred mechanism should be able to explain why the U.S. was more successful than Germany in converting the technological changes of the IR-2 into productivity. The following sections track changes in industrial power in this period with a range of indicators for productivity leadership, including GDP per capita, industrialization, labor productivity, and total factor productivity.

GDP per capita indicators

Changes in total GDP over the course of the IR-2 provide a useful departure point to understanding changes in the balance of productive power. At the beginning of the period in 1871, Germany's economy was around three-quarters the size of the British economy; by the end of the period in 1913, Germany's economy was around 14 percent larger than Britain's. The growth trajectory of the American economy was even more stark. Over the same time period, the U.S. overall economic output increased from 1.2 times to around 3.4 times that of Britain's total GDP.[17] This trend is further confirmed by the growth rates of overall GDP for the three countries. In the period between 1870 and 1913, the U.S. GDP grew roughly 5.3 times compared to 3.3 for Germany and 2.2 for the UK.[18]

While gross economic size puts countries in contention for economic leadership, the most crucial outcome is sustained economic efficiency. Compared to total output, trendlines in real GDP per capita mark out a broadly similar picture of the IR-2 period, but they also differ in

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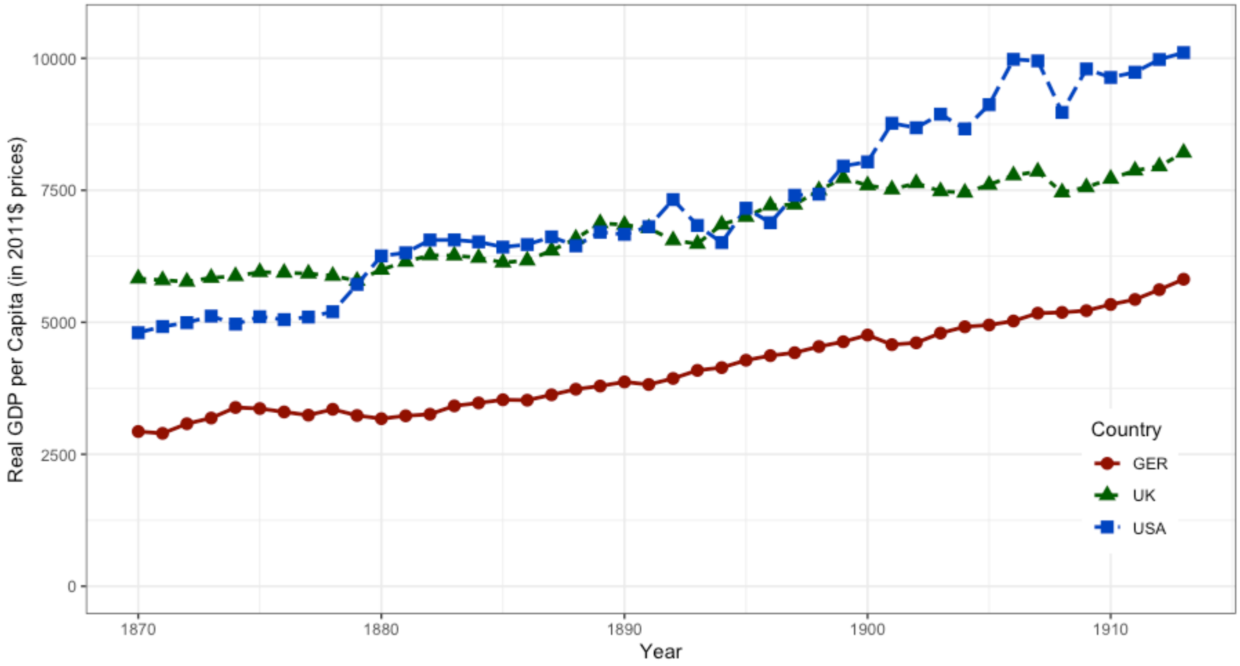
[17] Fouquin and Hugot 2016.

[18] Maddison 1995; cited in Smil 2005, 286.

two significant respects (Figure 5.1). First, whereas the U.S. was already the largest economy by total output in 1870, the UK maintained a slight lead in real GDP per capita over the U.S. in the 1870s. The UK's average GDP per capita over the decade was about 15 percent higher than the U.S. equivalent.[19] U.S. GDP per capita was roughly on par with that of Britain throughout the 1880s and 1890s, but the U.S. established a substantial lead starting around 1900.[20]

Figure 5.1: Economic Power Transition During the Second Industrial Revolution



Source: Maddison Project Database, version 2020 (Bolt and van Zanden 2020).

Second, in contrast to the trendlines in aggregate economic output, Germany did not surpass Britain in GDP per capita before World War I. Germany certainly closed the gap, as its GDP per capita increased from around 50 percent in 1870 to around 70 percent of British GDP per capita in the years before World War I. However, Germany never even came close to overtaking the UK in GDP per capita during this period.[21] This is an important distinction that

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[19] Calculations based on Maddison Project Database, version 2020. Bolt and van Zanden 2020.

[20] Nelson and Wright 1992, 1939.

[21] Maddison Project Database, version 2020. Bolt, Jutta and Jan Luiten van Zanden (2020), "Maddison style estimates of the evolution of the world economy. A new 2020 update."

justifies the focus on U.S. technological success in the IR-2, since surpassing at the technological frontier is a different challenge than merely catching up to the technological frontier.[22]

Industrialization indicators

Indicators of the relative industrialization of leading powers in the IR-2 tell a similar story. The U.S. emerges as the preeminent industrial power, boasting an aggregate industrial output in 1913 that equaled 36 percent of the global total — a figure that exceeded the combined share of both Great Britain and Germany.[23] More importantly, the U.S. became the leading country in terms of industrial efficiency, with a per-capita industrialization level about 10 percent higher than Britain's in 1913 (Table 5.1).

Table 5.1: Leading Countries by Per-Capita Industrialization Levels, 1860-1913

1860		**1880**		**1900**		**1913**	
United Kingdom	64	United Kingdom	87	United Kingdom	100	United States	126
Belgium	28	Belgium	43	United States	69	United Kingdom	115
Switzerland	26	Switzerland	39	Switzerland	67	Belgium	88
United States	21	United States	38	Belgium	56	Switzerland	87
France	20	France	28	Germany	52	Germany	85

United Kingdom in 1900 = 100; geographic boundaries at date given; triennial annual averages, except for 1913. Source: Bairoch 1982, 294.

Once again, the emphasis on productivity over aggregate output reveals that the economic gap between Germany and Britain narrowed but did not disappear. In aggregate terms, Germany's share of the world's industrial production rose from 13 percent in 1870 to 16 percent

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[22] I discussed these differences at length in the methods chapter (Section 3.1.3).

[23] Rostow 1978, 52-53.

in 1913, surpassing Britain by the end of the period, which declined from possessing 32 percent of the world's industrial production in 1870 to just 15 percent in 1913.[24] However, Germany did not overtake Britain in terms of industrial efficiency. In 1913, its per-capita industrialization level was about 75 percent of Britain's level.[25] This magnitude of this gap was approximately the same as the one between German per capita GDP and British per capita GDP.

Productivity indicators

Lastly, I consider various productivity statistics. Broadberry's work on the "productivity race" contains the most comprehensive and rigorous assessments of productivity levels in Britain, Germany, and the United States in this period.[26] Comparative statistics on labor productivity line up with findings from other indicators (Table 5.2). The U.S. surpassed Britain in aggregate labor productivity during the 1890s or 1900s, whereas Germany's aggregate labor productivity increased relative to but did not fully close the gap with Britain's over the IR-2 period — from about 60 percent of Britain's in 1871 to over 75 percent in 1911.[27]

Table 5.2: Comparative Labor Productivity Levels Across Rival Economies in IR-2

	US/UK Ratio (UK = 100)	Germany/UK Ratio (UK = 100)
1871	89.8	59.5
1891	94.1	60.5
1911	117.7	75.5

Source: Adapted from Broadberry 2006,110. Figures for US/UK comparisons are from 1869/1871; 1889/91; and 1909/11.

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[24] Rostow 1978, 52-53; for data that shows that industrial output growth was higher in the U.S. and Germany than it was in the United Kingdom from 1870-1913, see Bénétrix et al. 2015.

[25] Bairoch 1982, 292-302. The IR-1 case discussed Bairoch's methodology. See Section 4.1.

[26] Broadberry 2006.

[27] Broadberry 2006, 20-21, 150. In terms of labor productivity in the industrial sector, Germany did overtake Britain before 1911.

Another set of productivity indicators, Maddison's well-known and oft-cited historical data on comparative GDP per hour worked, support Broadberry's comparative measures of labor productivity levels.[28] According to Maddison's estimates of the average rate of productivity growth from 1870 to 1913, the American and German economies were both growing more productive relative to the British economy. The growth rate of America's GDP per hour worked was 1.9 percent compared to 1.8 percent for the corresponding German rate, and 1.2 percent for the UK rate.[29]

It should be noted that the UK may have retained a total factor productivity lead in this period. Per the last measurements available before World War I, 1909/1911, the U.S. aggregate TFP was a little over 90 percent of Britain's. By 1919/1920, U.S. aggregate TFP was nearly 10 percent larger than Britain's.[30] The U.S. could conceivably have surpassed Britain in overall TFP before World War I, but the data does not clearly demonstrate this outcome. Still, the TFP data track well with the general trends found in other measures of economic efficiency, including a marked increase in U.S. TFP in the 1890s and 1900s as well as a steady narrowing of the gap between UK and Germany TFP throughout the period. In addition, issues related to the availability, reliability, and comparability of capital stock estimates during this period caution against concluding too much from the TFP trends alone.[31]

Albeit with some caveats, the overall thrust of evidence clearly confirms the outcome in this case: the U.S. overtook Britain in productivity leadership near the 20th century, and Germany significantly narrowed the gap but did not surpass Britain in productive efficiency. A clarified picture of the outcome also helps structure the test of my theory for this case. In contrast to

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[28] Maddison 1995.

[29] Broadberry 1992; Smil 2005, 286.

[30] Broadberry 2006, 109.

[31] Broadberry 2006, 108.

work that focuses on Anglo-German rivalry in this period, I prioritize explaining why the U.S. became the preeminent industrial power. Moreover, if the *GPT diffusion* theory holds for this period, it should also be able to explain why the U.S. was more successful than Germany in overtaking Britain in productivity during this period.

5.2 Key technological changes 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).[32] Tracking down how every single technical advance could have affected the growth differentials among Britain, Germany, and the U.S. is an unmanageable task. I narrow the scope of analysis to the most likely sources of LS and GPT trajectories based on previous scholarship that calls attention to the significance of certain technological developments in the IR-2. Once confirmed to meet the established criteria for leading sectors and GPTs, these technological drivers serve as the fields of reference for assessing the validity of the GPT and LS mechanisms in this case.

5.2.1 Candidate leading sectors

I focus on the chemicals, electrical equipment, motor vehicles, and steel industries as the leading sectors of the IR-2. These choices are informed by scholars who study the implications of technological change during this period from a LS perspective. The first three sectors feature in the standard rendering of the IR-2 by prominent historical accounts, which centers major discoveries in chemistry and electricity, as well as the invention of the internal combustion.[33] Among those who study the effect of technological revolutions on the balance of power, there is

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[32] Indigo was the most important of natural dyes, so its synthesis marked a turning point in the organic chemical industry.

[33] Hull 1996, 192, 196; Landes 1969, 4; Schumpeter 1939, 167.

near-consensus on the chemicals and electrical industries as technologically progressive, fast-growing industries during this time.[34] Some scholars also identify the automobile industry as a key industry in this period,[35] though others reason that it only emerged as a leading sector in a later period.[36]

The automobile, chemicals, and electrical industries all experienced prodigious growth during the IR-2, meeting the primary qualification for leading sectors. According to statistics from the U.S. Census, the percent increase in value added by manufacture in each of the chemicals, electrical, and automobile industries was much higher than the average across all industries from 1899 through 1909. In fact, in terms of percent growth in value added by manufacture in this period, automobiles and electricity boasted the two highest growth rates among industries with products valued at more than $100 million.[37]

I also consider developments in steel as a possible source of leading sector product cycles. It is hard to ignore the explosive growth of the steel industry in both Germany, where it multiplied over 100-fold from 1870 to 1913, and America, where it multiplied around 450 times over the same period.[38] In addition, many scholars list steel as one of the leading sectors that affected the economic power balance in the IR-2.[39] Rostow identifies steel as part of "the classic sequence" of "great leading sectors."[40] In sum, I consider four candidate leading sectors in this period: the automobile, chemicals, electrical equipment, and steel industries.

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[34] Gilpin 1987, 309; Kim and Hart 2001, 304; Modelski and Thompson 1996, 87-88; Ostry and Nelson 1995, 43.
[35] Gilpin 1987, 309; Kim and Hart 2001, 304.
[36] Gilpin 1975; Kurth 1979, 26; Moe 2009, 218-219; Thompson 1990, 213. I further explore the automobile industry's timeframe of impact in Section 5.3.1.
[37] For statistics on automobiles and electricity (captured in the "electrical machinery, apparatus, and supplies" category), see Bureau of the Census 1913, 40; for statistics on the chemical industry ("chemicals and allied products"), see Bureau of the Census 1913, 53).
[38] Calculations based on crude steel output figures in Mitchell 1998, 466-467; Mitchell 1993, 356-358.
[39] Gilpin, 1975, 67; Kurth 1979; Modelski and Thompson 1996, 69; Rostow 1978, 105.
[40] Rostow 1978, 105.

5.2.2 Candidate GPTs

I focus on developments in electrification, chemicalization, the internal combustion engine, and interchangeable manufacture as the potential drivers of GPT-style transformations in the IR-2. Of these four, electricity is the prototypical GPT. It is "unanimously seen in the literature as a historical example of a GPT."[41] Electricity is one of three technologies, alongside the steam engine and ICT technology, that feature in nearly every article that seeks to identify GPTs throughout history.[42] Electrical technologies possessed an enormous scope for improvement, fed into a variety of products and processes, and synergized with many other streams of technological development. Empirical efforts to map patenting activity in certain technological domains to the features of GPTs provide further evidence of electricity as a GPT in this period.[43]

Like advances in electricity, clusters of innovations in chemicals and the internal combustion engine not only spurred the rapid growth of new industries but also served as a potential source of GPT trajectories. Historians of technology pick out chemicalization, alongside electrification, as one of two central processes that transformed production routines in the early 20th century.[44] Historical patent data confirms that chemical inventions could influence a wide variety of products and processes.[45] In line with GPT classification schemes by other scholars, I also evaluate the internal combustion engine as a candidate GPT, with the potential to replace the steam engine of a prime mover of many industrial processes.[46] After its introduction, many

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[41] Ristuccia and Solomou 2014.

[42] Field 2008, 10.

[43] Petralia 2020.

[44] Nelson and Winter 1982, 261; Noble 1975, 18; Landau and Rosenberg 1992, 76. Rosenberg (1993) highlights "chemical engineering" as the GPT of note this period. Departing slightly from Rosenberg's account, I take the principles of chemical transformations as the GPT, which spread across many industries. The profession of chemical engineering, in my analysis, is an institutional adaptation to systematize skills related to chemical production systems.

[45] Moser and Nichols 2004. Notably, Moser and Nichols (2004, 393) find that developments in chemicals "fulfill the criteria for GPTs at least as well as those in electricity." For further discussion of whether electrical technologies better fit the characteristics of a GPT than chemical technologies, see Petralia 2020.

[46] Jovanovic and Rousseau 2005; Lipsey et al. 2005, 133.

believed that the internal combustion engine would transform a range of manufacturing processes with smaller, divisible power units.[47]

Lastly, I examine the advance of interchangeable manufacture, spurred by innovations in machine tools, as a candidate GPT in this period. Though the machine tool industry was neither a new nor especially fast-growing sector, it did play a central role in further extending the mechanization of machine-making first incubated in the IR-1. The expansion of the ASoM owed much to advances in turret lathes, milling machines, and other machine tools that improved the precision of cutting and shaping metals. Rosenberg's seminal study of "technological convergence" between the American machine tool industry and metal-using sectors highlighted how innovations in metalworking machines transformed production processes across a wide range of industries.[48] Following Rosenberg's interpretation, historians recognize the nexus of machine tools and mechanization as one of the key technological trajectories during this period.[49]

5.2.3 Sources of LS and GPT trajectories

I aimed to include as many candidate technological drivers as possible, provided that the technological developments credibly met the criteria of a leading sector or GPT.[50] All candidate leading sectors and GPTs I study in this period were flagged in multiple articles or books that explicitly identified leading sectors or GPTs in the IR-2 period, which helped provide an initial filter for selection. This allows for a good test of GPT diffusion mechanism against the LS

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[47] Du Boff 1967, 514.

[48] Rosenberg 1963, 423.

[49] Mosk 2010, 22; Thomson 2010, 4. Nelson and Winter (1982, 261) identify a "natural trajectory," similar to a GPT trajectory, in mechanization. Note that Lipsey et al. (1998, 46-47) categorizes the 19th-century machine tool industry as a "near GPT" because the range of use of machine tools was restricted to manufacturing. The effect of machine tool advances on mechanization, however, affected many non-manufacturing sectors, including agriculture.

[50] I excluded two technologies from consideration as candidate GPTs. First, some also identify the Corliss steam engine as a GPT (Rosenberg and Trajtenberg 2004). They argue that this specific type of steam engine spurred urbanization in the United States. I view this innovation as an important advance within the general GPT trajectory of steam engines. Second, railway technology deserves attention, but empirical studies have found that the contributions of railroads to productivity growth were fairly modest in the mid-1800s. Fishlow 1966; Fogel 1964.

product cycles mechanism.[51] While a deeper excavation of the historical evidence is required to determine whether the candidates actually made the cut, this sorting process is an important initial step for evaluating the two mechanisms.

While there is substantial overlap between the candidate GPTs and leading sectors in the IR-2, as reflected in Table 5.3, two key distinctions are worth emphasizing. First, one difference between the candidate GPTs and leading sectors is the inclusion of machine tools in the former category. The international relations scholarship on leading sectors overlooks the impact of machine tools in this period, possibly because the industry's total output did not rank among the largest industries, and innovation in machine tools was relatively incremental.[52] One survey of technical development in machine in tools from 1850 to 1914 described the landscape as "essentially a series of minor adaptations and improvements."[53] Relatedly, the steel industry, commonly regarded as a LS, is not considered a candidate GPT. Under the GPT mechanism, innovations in steel are bound up in a GPT trajectory driven by advances in machine tools.

Table 5.3: Key Sources of Technological Trajectories in the IR-2

Candidate Leading Sectors	Candidate GPTs
Steel industry	Interchangeable manufacture
Electrical equipment industry	Electrification
Chemicals industry	Chemicalization
Automobile industry	Internal combustion engine

Second, even though some candidate leading sectors and GPTs connect to the same underlying technological advances, the two mechanisms emphasize different carriers of these

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[51] For example, Thompson 1990 (226) argues that Britain's lagging growth rates in the same four leading sectors as the ones I consider resulted in Britain's decline.

[52] According to one estimate of the U.S. machine tool industry's size in 1914, its total output only amounted to $31.5 million. Bureau of the Census 1918, 269.

[53] Floud 1976, 31.

breakthroughs. For the remarkable breakthroughs in electromagnetic waves, the electrical equipment industry serves as the key carrier under the LS mechanism, whereas the process of electrification takes on this role for the GPT mechanism. This distinction, which also applies to advances in chemicals and combustion, underscores the diverging interpretations of how the technological transformations of the IR-2 brought about an economic power transition. The rest of the chapter will show which explanation stands up to the case study evidence.

5.3 GPT vs. LS Mechanism in the IR-2

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: the timeframe of impact, the key phase of relative advantage, and the breadth of growth (Table 5.4).

Table 5.4: Two Models of the IR-2

	LS Mechanism	**GPT Mechanism**
Key Technological Drivers	Chemicals, electrical equipment, automobile, and steel industries	Chemicalization, electrification, internal combustion engine, and interchangeable manufacture
Timeframe of Impact	Disproportionate in early stages (before 1914)	Disproportionate in later stages (after 1914) — except interchangeable manufacture
Key Phase of Relative Advantage	Germany's monopoly on innovation	U.S. advantage in diffusion
Breadth of Growth	Concentrated in leading sectors	Dispersed across multiple sectors

Based on the differences between the LS and GPT mechanism across these dimensions, I test three sets of diverging propositions for how technological changes manifested in relative shifts in industrial power during this period. The specific, testable predictions, which follow from these propositions, are summarized in Table 5.5.

Timeframe of impact hypotheses

GPT diffusion and LS product cycles present two competing interpretations regarding IR-2's timeframe of impact. On this first dimension, the LS mechanism expects growth associated with radical technological breakthroughs to be explosive in the initial stages. 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 new industries stimulated substantial growth in the early stages of their development, bringing about a pre-WWI upheaval in the industrial balance of power.[54] This leads to the first hypothesis:

H1.LS: The electrical, 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, as was the case with the steam engine in the IR-1, the impacts of electrification, chemicalization, and the internal combustion engine should have materialized toward the end of the period.

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[54] Gilpin 1987, 98, 112; Thompson 1990, 226.

If the GPT mechanism was operational, the machine tool industry should have been the key source of transformational economic effects in this period. By the start of the IR-2, mechanization spurred by advances in machine tools was at a later stage of its life cycle 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-9th century saw many important innovations in machine tools, including the turret lathe (1845), the universal milling machine (1861), and the automatic lathe (1870).[55] In contrast to the other candidate GPTs of the IR-2, the full impact of advances in machine tools should have taken effect during the period. Therefore, I derive the following hypotheses:

H1a.GPT: Electrification, chemicalization, and/or the internal combustion engine only made a significant impact on the U.S.'s rise to productivity leadership after 1914.

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

Key phase of relative advantage hypotheses

The first dimension probes whether the impact pathways of leading sectors and GPTs accords with the timing of Britain's relative industrial decline and the rise of the U.S. and Germany. The second set of hypotheses unpacks the key phase of technological change that drove differences among the leading industrial powers in terms of how effectively they took advantage of leading sectors and GPTs. While the LS mechanism is primarily concerned with which country produced the initial breakthrough, the GPT mechanism gives more priority to the ensuing process through which an innovation is diffused. The different emphases of the two

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[55] Hobsbawm 1968, 147.

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. Instead, the U.S. and Germany benefited from the monopoly profits linked to being the lead innovators in electrical equipment, chemical production, automobiles, and steel. In particular, Germany's industrial rise in this period draws a disproportionate share of attention.[56] Many LS accounts attribute Germany's rise to its dominance of innovations in the chemical industry, "the first science-based industry."[57] 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.[58]

The GPT mechanism has different expectations regarding the key source of comparative advantage for productivity leadership. From the perspective of GPT diffusion theory, 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, chemicals, and/or automobile industries were concentrated in the U.S.

H2b.LS: German and American advantages in the production and exports of electrical equipment, chemical products, automobiles, and/or steel were crucial to their industrial superiority.

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[56] For an explanation of how the power transition scholarship's focus on Anglo-German rivalry shaped the emphasis on the German case, see the earlier section in this chapter on the outcome variable.

[57] Moe 2007, 125. See also Drezner 2001, 11-18.

[58] 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.

Breadth of growth hypotheses

Diverging expectations related to the breadth of growth constitute the final set of hypotheses used to decipher whether the LS or GPT mechanism best suits the dynamics of the IR-2 case. If the LS mechanism holds, new industries like chemicals should serve as the primary centers of productivity growth in the U.S. and Germany. The GPT mechanism views the rise and fall of industrial powers in the IR-2 through a wider lens. From this perspective, the U.S. and Germany should experience productivity growth spread across many GPT-linked industries. These differences, thus, produce the following testable hypotheses:

H3.LS: Productivity growth in the U.S. and Germany was limited to steel, electrical equipment, chemicals, and/or the automotive industries.

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

Table 5.5 collects all the predictions that structure the case analysis in the following sections.

Table 5.5: Specific, testable predictions for IR-2 case analysis

	IR-2 Case-Specific Predictions
H1.LS *(Timeframe of impact)*	The steel, electrical equipment, chemicals, and/or automobile industries made a significant impact on the U.S.'s rise to productivity leadership before 1914.
H1.GPT	Electrification, chemicalization, and/or the internal combustion engine only made a significant impact on the U.S.'s rise to productivity leadership after 1914. The extension of interchangeable manufacture made a significant impact on the U.S.'s rise to productivity leadership before 1914.
H2.LS *(Relative advantage)*	Innovations in the steel, electrical equipment, chemicals, and/or automobile industries were concentrated in the U.S. German and American advantages in the production and exports of electrical equipment, chemical products, automobiles, and/or steel were crucial to their industrial superiority.
H2.GPT	Innovations in machine tools, electricity, chemicals, and/or the internal combustion engine were not concentrated in the U.S. American advantages in the diffusion of interchangeable manufacture were crucial to its productivity leadership.
H3.LS *(Breadth of growth)*	Productivity growth in the U.S. was limited to steel, electrical, chemicals, and/or the automotive industries.
H3.GPT	Productivity growth in the U.S. was spread across a broad range of industries linked to interchangeable manufacture.

*****The operator "and/or" links all the candidate leading sectors and GPTs, because it could be the case that only some of these technologies drove the trajectories of the period.

5.3.1 Timeframe of impact: gradual gains vs. immediate effects from new breakthroughs

The opening move in assessing the LS and GPT mechanisms is to determine when the IR-2's eye-catching technological advances actually made their mark on leading economies. 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, advances in machine tools and steel — the remaining candidate GPT and leading sector, respectively — did substantially contribute to U.S. economic growth before World War I, which means their impact timeframes fit better with when the U.S. overtook Britain as the preeminent economic power.

Delayed Timelines: chemicals, electricity, and the internal combustion engine

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. Moe sums up the prevailing LS interpretation, "The chemical industry is an important reason why industrially, by World War I, Germany was Europe's number one power."[59] The competing hypothesis, aligned with the GPT mechanism, posits that developments in the chemical industry did not make a significant impact on relative industrial power before 1914. The weight of evidence that follows bears out the predictions of the GPT mechanism.

By the late 19th century there is no dispute that Germany was the clear leader in the chemicals sector, taking over a role previously held by Britain in the decades leading up to 1870. Germany was the first to incorporate scientific research into chemicals production, resulting in the synthesis of many artificial dyes before 1880.[60] The German chemicals sector drove much of the substantial increase in the global production of dyestuffs, which increased more than 4000 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.[61]

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[59] Moe 2007, 426. Modelski and Thompson (1996, 69) date the period 1874-1914 as the high-growth period of the chemical industry.

[60] Hull 1996, 195.

[61] Drezner 2001, 12; Murmann and Landau 1998, 30.

While growth in Germany's production of synthetic dyes was certainly impressive in the late 19th century, the chemical sector's greatest marginal impact on Germany's industrial strength came after 1914. A take-off in German plastics production, spurred by innovations such as polystyrene, did not occur until the late 1920s and 1930s.[62] The versatility of plastics widened the potential spillovers and linkages from the chemical sector to other industries, but plastics did not become ubiquitous in daily life until after World War II.[63] The LS mechanism expects that the growth rates of new industries, such as chemicals, are highest in their early development before eventually tapering off. The trajectory of the German chemical industry does not bear out this expectation. From 1935 to 1951 the German chemical industry grew faster than it did from 1895 to 1913.[64] This aligns with the timeline of complementary innovations in plastics and the expectations of the GPT mechanism.

It is even less likely that the chemical sector played a key role in stimulating the U.S. rise to industrial predominance. In 1905 U.S. chemicals production was valued at only $92.1 million.[65] For reference, the value of U.S. tobacco production about $330 million.[66] In 1914, there were only seven American dye makers due in part to the lack of scientifically trained researchers.[67] Major U.S. chemicals firms did not establish industrial research laboratories similar in function to German counterparts until the first decade of the 20th century. Du Pont, for instance, opened its first industrial research facility in 1902.[68] It is very difficult to argue that advances in chemicals made a meaningful difference in American relative power capabilities before WWI.

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[62] Freeman et al. 1982, 95. Meikle 1995, 89.

[63] Meikle 1995, 125.

[64] At the end of the IR-2 from 1895 to 1913 German production of chemicals grew by 2.4 times; from 1913 to 1935, the German chemical industry grew by 1.5 times; from 1935 to 1951, the German chemical industry grew by 2.6 times. My calculations based on statistics compiled in Murmann 2003, 400.

[65] Murmann 2003, 400.

[66] Bureau of the Census 1908, 554.

[67] Ilgen 1983. The small number of American dye makers meant that the WWI blockade of German shipping resulted in critical domestic shortages. The number of American dye makers grew to 118 by 1918.

[68] For further discussion, see Bruland and Mowery 2006, 358-366.

In the GPT trajectory, the priority is not on tracing the growth of the chemical sector in isolation but instead on the "chemicalization" of multiple industries — the spread of chemical processes across a variety of industries, such as ceramics, food-processing, glass, metallurgy, petroleum refining, etc.[69] 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 basic operations (e.g. condensing, crystallizing, electrolyzing, etc.) that were common in chemical processing across a number of industries.[70] 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 between the manufacture of different products.[71]

Therefore, LS accounts of Germany's dominance of the production of dyestuffs in the late nineteenth century miss the broader spillover effects that occurred with this chemicalization of industries.[72] Crucially, the effects of chemicalization on other industries followed a delayed trajectory compared to the growth of synthetic dyes. 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."[73] Crucially, this GPT trajectory required a

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[69] Noble (1974, 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.

[70] Little 1933, 7.

[71] Rosenberg 1993, 176.

[72] Drezner (2001, 12) does note that the chemical sector generated R&D spillovers across many industries, with chemical-related industries accounting for 40 percent of all research laboratories created from 1899 and 1946. One qualification for these estimates is the limited data on industrial research activity in the early 20th century. Mowery and Rosenberg 1993, 33. Additionally, given the evidence of the gradual process of chemicalization, it is likely that the chemicals industries spurred R&D in the period after 1914. Lastly, even if the chemicals sector drove the development of science-based industries in this period, the empirical evidence in this chapter argues that science-based industries did not play the crucial roles in America's rise to industrial dominance in the IR-2. See also Nelson and Wright 1992, 1941.

[73] Rosenberg 1998, 171.

longer period of gestation, which involved complementary innovations in unit operations and the training of chemical engineers, for the full effects to take fruit.

The timing of electrification mirrored that of chemicalization. Evidence from the American economy, the quickest to adopt electric power in manufacturing, shows that the transformative effects of the electrification of manufacturing on economic productivity only materialized after 1914. The first dynamo for industrial application was introduced in the 1870s but the transformative impact of electricity on manufacturing only gained momentum after 1914 — a four decade-long process of complementary innovations and organizational adaptations. Indeed, the scholarly consensus attributes the U.S.'s productivity upsurge after 1914 to the delayed impact of the electrification of manufacturing.[74]

The transition to electric "unit drive," which enabled the radical redesign of factories, gives substance to the delayed diffusion of electricity. From 1880 to 1930, the power production and distribution systems evolved from shaft and belt drive systems driven by steam and water power to the electric unit drive system, in which electric motors powered individual machines.[75] In the early 1880s power distribution in most factories relied on a system of belts and shafts that connected all machinery to "a single centrally located prime mover, such as a water wheel or steam engine."[76] When electric power was first used to drive machinery ("electric line shaft drive"), an electric motor replaced the steam engine or water wheel but kept in place the shaft and belt system — an inefficient system that required turning all the shafting regardless of the number of machines in actual use. Not until the late 1890s and early 1890s did new factories reorganize their method of power distribution to take advantage of electric motors that could

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[74] David 1990; Devine 1982, 46-47; Field 2003, 92; Rosenberg 1979, 48-49.
[75] This paragraph relies on the excellent overview in Devine 1983.
[76] Devine 1983, 350.

power a group of machines independently from other machines ("electric group drive"), thereby significantly reducing losses from the shaft and belt system.

More painful was the thirty-year transition to unit drive — only realized 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] Widespread use of unit drive did not culminate until the 1920s.[78] While group drive provided definite improvements in factory organization, these paled in comparison to the radical redesign of factories facilitated by unit drive. Unit drive smoothed the flow of production by allowing manufactures to arrange machinery according to the natural sequences of operations (rather than grouping them by shafts). Most crucial, by eliminating the need to rearrange and rehang shafts, unit drive enabled the relatively painless expansion of plants. All of these were benefits tied to structural changes, which cannot be captured by a mere reduction in the costs of inputs to the existing production function.

Does the quantitative evidence support this timeline? While the far-reaching impacts of the development of a system of electricity generation, transmission, and conversion are difficult to fully track, the progress of electricity in manufacturing industries can be quantitatively mapped.[79] 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.[80] Crafts's calculation of electricity's total contribution to American economic growth also aligns neatly with the timeline of unit drive adoption. From 1899 to 1929,

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[77] Devine 1982, 17-45; Devine 1983, 368-371.

[78] Devine states that the "unit drive did not become the predominant form of electric drive until after World War I." Devine 1983, 368.

[79] While other uses of electricity included lighting, heating, and communications, its chief significance was in powering many industrial practices. In addition, the evidence of electricity's effects in the service sector is much more fragmentary. It is possible that these effects came to fruition on an accelerated timeline, but the more likely scenario is that the timeline paralleled that in manufacturing. Crafts 2002, 13.

[80] Devine 1982, 46-47; Rosenberg 1979, 48.

electrification contributed to a .56 percent annual growth in GDP/person (28.2 percent of total GDP/person growth). Electricity's contributions in the last decade (1919-1929), when unit drive became widespread, were significantly higher than the earlier decades. It contributed to a .98 percent annual growth in GDP/person, which constituted 47 percent of all GDP/person growth.[81]

Though this analysis has focused on the electrification of the manufacturing sector because of the availability of detailed data for this sector, there is also evidence that a similar diffusion timeline transpired in the electrification of the overall economy. Petralia analyzes 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. Energy efficiency metrics tell a similar story.[82] Decreasing steadily from 1890 to 1920, the energy efficiency of the American economy dramatically increased after 1920.[83] These figures serve as a rough approximation of when electricity enabled the U.S. economy to achieve broader efficiencies in energy generation, distribution, and consumption.

Lastly, the impact timeframe of the internal combustion engine and automobiles fulfills the expectations derived from the GPT mechanism. The commercialization and diffusion of internal combustion engines across many application sectors was a lengthy process. Two main types of internal combustion engines emerged in this period. The Otto Engine, a gasoline-fueled,

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[81] As further evidence of the importance of the indirect savings from unit drive adoption, Crafts finds that the significant uptick after 1919 was "entirely due to the effect of the TFP spillovers kicking in. Absent this contribution, even in the 1920s, the total impact on growth would only have been about 0.3 per cent per year." (Crafts 2002, 12). Crafts calculates these TFP spillovers by estimating the capital savings and learning externalities that came from the widespread adoption of electric drive.

[82] Petralia 2020, 32.

[83] Devine 1982.

four-stroke engine produced in 1876, was the first instance of the internal combustion engine."[84] In the 1890s the development of the Diesel engine, which introduced the compression ignition engine, represented a significant advance in the design of internal combustion engines. Today, Otto engines power most cars, trucks, bikes, and diesel engines power most container ships, freight trains, and nearly half of all European passenger cars.[85] However, the path to ubiquitousness for these GPTs was slow, and there were few significant applications before 1914.

The ascent of diesel engines to become the prime mover of many sectors was a drawn-out process. One of the earliest application sectors of the diesel engine was submarines. In 1904, the French navy became the first to install a diesel engine on submarines, and most leading navies fielded diesel submarines fleets before World War I.[86] The diffusion of diesel engines to other early adopters did not occur until after World War I. The first demonstration of diesel engines in an ocean-going vessel was the maiden journey of the *Selandia* in 1912. A year later, the first tests of a large diesel-operated locomotive took place. Applications of diesel engines in shipping propulsion and railway services grew steadily in the 1920s and 1930s.[87] Diesel engines also found uses in trucks in the 1930s, but large-scale adoption of diesel engines in passenger cars did not occur until the 1970s. Overall, the transition to diesels in many industries was a "necessarily gradual process that took generations to accomplish and that proceeded at different paces in Europe, North America, and Asia."[88]

The Otto engine also spread slowly across major application sectors. One of the first use cases of Otto's four-stroke engine was to power stationary machines in factories. Despite its

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[84] Somerscales 1990, 307.

[85] For a penetrating history of the diesel engine, see chapter 3 of Smil 2010.

[86] Crisher and Souva 2013.

[87] One-quarter of the world's merchant marine ships were powered by diesel engines by 1939 (Smil 2005, 143); See also Smil 2010, 73.

[88] Smil 2010, 78.

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.[89] The aircraft industry, another important application sector of the internal combustion engine, was slow to take off. The internal combustion engine powered the Wright Brothers' first flights at Kitty Hawk in 1903, but the commercial aviation industry did not expand rapidly in the U.S. and Western European countries until the 1920s.[90]

What about developments in the automobile industry, the Otto engine's most prominent application sector? The evolution of the automobile industry is particularly relevant for testing the LS prediction regarding the timeframe of impact in this period. On a surface level appraisal, developments in automobiles lend credence to the notion that leading sectors could have significantly bolstered growth before 1914. Especially in America, the automobile industry registered genuinely astonishing growth in the IR-2. From 1899 to 1937, the automobile industry experienced a 181,000 percent increase in physical output, ranking first among individual manufacturing industries.[91] By 1914 the U.S. produced over 90 percent of the world's motor vehicles.[92]

However, further investigation of the empirical evidence exposes a more delayed impact timeframe for automobiles. First, early progress in the American automobile industry was unremarkable and very slow. In 1900, 24 years after the introduction of the Otto engine, there were 8000 cars in the entire United States.[93] Moreover, any American relative advantage over its rivals cannot be traced to automobiles until after 1904, which was when the U.S. motor vehicle

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[89] The electric motor eclipsed the internal combustion engine in this period. DuBoff 1967; Jovanovic and Rousseau 2005, 1188.
[90] Rae 1968.
[91] Fabricant 1940, 89. For reference, the cigarette industry ranked second with 4,226 percent growth over the same period.
[92] Thompson 1990, 226n34; Moe 2007, 168.
[93] This amounted to one for every 9,500 Americans. Smil 2005, 121.

industry overtook France as the world's largest.[94] Lastly, one of the most significant developments, the installation of a moving assembly line for the mass production of Model Ts by Henry Ford, did not occur until 1913.[95] One scholar, writing in the leading sector tradition, concludes that "the car did not have a major impact on the economy until the interwar years."[96]

Key timings: machine tools and steel

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. By conflating the revolutionary nature of these innovations with instantaneous impact, accounts that attribute the economic rise of the U.S. and Germany to the new electrical and chemical industries have made the same mistake of those that emphasize the role of the steam engine in Britain's ascent to industrial preeminence. In contrast, this section reveals the persevering impact of the older industries of machine tools and steel — the remaining candidate GPT and leading sector, respectively.[97]

First, the GPT trajectory linked to machine tools was incubated much earlier than other candidate GPT trajectories. In contrast to the breakthrough advances in chemicals and electricity in the early decades of the IR-2, the technological developments in the machine tool industry during the IR-2 were incremental, continuous improvements that helped disseminate

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[94] Smil 2005, 136. In 1912, France exported more automobiles than America. (footnote 18 in Locke 1984, 9)

[95] Hounshell 1985, 218; Moe 2007, 166-168. Other important industries, such as chemicals, did not adopt an assembly line or mass production before World War I. Stokes 2006, 22.

[96] Moe 2007, 167.

[97] Since the development of automobiles and the spread of the internal combustion engine took place so late in the IR-2, I do not specifically trace the effects of this candidate LS and candidate GPT in the two other dimensions. Although it is difficult to ignore the extraordinary growth of the American automobile industry in the last decade of this period, later sections of the case study assess inter-industry flows that connect the late-breaking surge in automobiles to earlier developments in this period.

transformative breakthroughs from an earlier period, such as the turret lathe (1845) and the universal milling machine (1861).[98] Accordingly, the GPT diffusion theory predicts that the machine-tool GPT, unlike other candidate GPTs, diffused widely enough to make a significant impact on U.S. industrial productivity before 1914.

Industry profiles and quantitative studies strongly validate this prediction regarding the impact timeframe of machine tool innovations. Marking 1880 as the date when "the proliferation of new machine tools in American industry had begun to reach torrential proportions," Rosenberg shows how three application sectors — sewing machines, bicycles, and automobiles — successively adopted improved metal-cutting techniques from 1880 to 1910.[99] The introduction of high-speed steel in machine-cutting tools, made possible by complementary innovations in the end of the 19th century, helped enlarge the number of application sectors for machine tools.[100] In addition to the machine-tool-using industries covered by Rosenberg's analysis, other application sectors also adopted mechanized production on a similar timeline. For instance, McCormick Harvesting Machine Company, the company that produced the McCormick reaper — a mechanical harvester that significantly improved agricultural productivity — only fully adopted interchangeable manufacture in the early 1880s.[101]

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

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[98] This is not to discount the importance of continuing technological innovations in machine tools. As Thomson notes, "For machine tools to gain usage, best practice methods had to spread but also to improve; the few, simple, inaccurate machines tools of 1820 could hardly manufacture the Corliss engines and sewing machines of 1860, much less the dynamos and automobiles of a half-century later." (Thomson 2010, 10).

[99] 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.

[100] Rosenberg 1969, 8.

[101] Hounshell 1985, 182.

million.[102] The number of potential machine tool users multiplied fifteen-fold from just 95,000 workers in 1850 to almost 1.5 million in 1910.[103] 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.[104] 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. Just as the 1780s were a period when the technological conditions for cotton production were transformed, 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.[105] Over the course of the IR-2 period, the U.S. and Germany quickly exploited these breakthroughs in steel-making to massively boost steel production.[106]

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.[107] By 1914, German steel output (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.[108] In 1910 U.S. production

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[102] Census of Manufactures (1914), II, "Reports for Selected Industries," 269. Cited in Rosenberg 1963, 421. 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.

[103] Thomson 2010, 9.

[104] Thomson 2010, 26.

[105] Kuznets 1930, 10. Other important breakthroughs: the Siemens-Martin open-hearth furnace (1867), which greatly increased productivity, and the Gilchrist-Thomas basic process (1877-78) which made it possible to use an entire range of new ores for steel manufacture. It should be noted that Schumpeter lumps steel in with steam and railroads (1840s-1875) as the key cluster of innovations for an earlier period (Schumpeter 1939).

[106] For a detailed study of this process in Germany's steel industry, see Wengenroth 1994.

[107] Sanderson 1972, 15.

[108] Kennedy 1987, 210.

of basic steel alone almost doubled that of Great Britain's total steel.[109] 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.[110] Given these impressive figures, the next section investigates the American and German advantages in steel production in further detail.

5.3.2 Key phase of relative advantage

The second test of the GPT and LS mechanisms relates to their account of the U.S.'s source of technological advantage over its industrial competitors in the IR-2. According to the LS interpretation, the rising technological leader's advantage is a "fairly extreme" national monopoly on leading sector innovation under which "one national economy literally dominates the leading sector during its phase of high growth and is the primary beneficiary of the immediate profits."[111] If this dimension of the LS trajectory characterizes developments in the IR-2, the U.S. should dominate fundamental innovations in steel, electricity, chemicals, and/or automobiles. As a result, the U.S.'s monopoly profits in these leading sectors should drive its relative productivity growth. Instead, the GPT mechanism predicts that the U.S. advantage in diffusing mechanization for production and interchangeable parts manufacture was the key source of its stronger growth compared to Britain and Germany.

Innovation clustering in steel, electricity, chemicals, and/or motor vehicles?

Contrary to the propositions of the LS mechanism, innovations in steel, electricity, chemicals, and motor vehicles were dispersed across the leading economies. No one country had a dominant edge in LS innovations. Take, for example, an influential list of major innovations throughout history which some scholars use to highlight that U.S. firms introduced 45 percent of

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[109] Hobsbawm 1968, 159.

[110] Calculations based on crude steel output figures in Mitchell 1998, 466-467; Mitchell 1993, 356-358.

[111] Modelski and Thompson 1991, 91.

the major innovations from 1850 to 1914.[112] If the list is limited to just innovations in leading sectors, a more dispersed geographic distribution emerges (Table 5.6). Across the four candidate leading sectors, American firms were first to introduce less than 30 percent of the innovations.

Table 5.6: Geographic Distribution of Innovations in Leading Sectors, 1850-1914

	Chemicals	Electricity	Motor Vehicles	Steel
France	2	1	1	1
Germany	3	3	3	0
Great Britain	1	3	1	1
U.S.	2	3	1	0
Various Countries	0	1	0	2
Sole U.S. Share	25%	27%	17%	0%

Tracking the technological trajectories of each LS illustrates that the U.S.'s true comparative advantages over other advanced economies, all of which generated many radical innovations, was rooted in its 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).[113] 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.

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[112] German firms produced 18 percent of the major innovations over the same period. Modelski and Thompson 1996, 117; data from van Duijn 1983, 176-179.

[113] Taylor 2016, 189.

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.[114]

Specifically, Britain contributed major innovations to the electrical equipment industry but fell behind in large-scale electrification.[115] 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.[116] While the steam turbine and many other electrical innovations were first introduced in Britain, other industrial rivals adopted these innovations across a wide range of applications.[117] 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."[118]

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 aniline dye industry, considered by most LS accounts to have played "a special role" in Germany's industrial

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[114] Germany was the next closest competitor in all cases. Taylor 2016, 189.

[115] According to calculations based on the CHAT dataset (Comin and Hobijn 2009), in 1912 Britain's electricity production per capita, an indicator for the penetration of electrification, was about 20 percent of the U.S. figure and 50 percent of the German figure.

[116] Field 2008 p. 23. The London Underground was also the first metro line to install an alternating current transformer of significance, but it was the U.S. that "forged far ahead of Britain in the number of alternating current stations." (Hughes 1962, 36).

[117] The Curtis impulse turbine, patented by the General Electric Company (an American firm) in 1914, broke Parsons' monopoly over steam turbines and most British-made turbines were of the impulse type by 1914. Saul 1960, 32.

[118] Hughes 1962, 38.

ascent, excelled not because it generated the initial innovations in aniline-violet dye processes, which were first introduced in Britain, but because it had perfected these processes for profitable exploitation.[119]

Through the first decades of the 20th century, the U.S. chemical industries' overtaking of Great Britain's was rooted in diffusion. Up until 1930, the U.S. cultivated its chemical industry "largely by importing European chemical technologies and adapting to the American context."[120] By 1913, the U.S. accounted for more of synthetic chemical production than Germany.[121] The United States also benefited from the adoption of foreign technologies. DuPont's Experimental Station, one of the most advanced chemical labs in the U.S. when founded in 1903, birthed many famous materials such as the world's first synthetic rubber, but one of its primary functions was to monitor and assess the potential of technological developments from external sources.[122] Just like German dyestuff firms, U.S. industrial laboratories advised their corporate arms on whether externally developed technologies were worth acquiring.[123]

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.[124] The U.S.'s economic rise in this period, in particular, was not based on exports. In 1913, Britain had almost double the share of the U.S. in chemical exports.[125] 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.[126] Even though the U.S. was

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[119] Drezner 2001, 12; Hull 1996, 195; Trebilcock 1981, 64.
[120] Murmann 2003, 399.
[121] Hobsbawm 1968, 158.
[122] Bruland and Mowery 2006, 362.
[123] Bruland and Mowery 2006, 363.
[124] 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.
[125] Murmann 2003, 401.
[126] Kennedy 1987, 244.

the leader in diffusing electrification across its economy, it was Germany that captured around half of the world's exports in electrical products.[127]

The myth of German technological superiority in steel

If monopoly profits from innovation clustering 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 their British counterpart in the 1890s and 1900s.[128] International relations 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.[129] Thus, having established the delayed impact of the electrical, chemical, and automobile industries in this period, the steel industry takes on an especially large burden for the LS mechanism's explanatory power in this period.

Inspecting the advanced economies' steel industries in further detail, however, raises questions about the significance of larger total steel production for sustained growth differentials. The prevailing wisdom takes total steel output figures to stand for superior American and German technological know-how and productivity.[130] These accounts have been particularly influential in entrenching 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."[131]

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[127] Henderson 1975, 189-190.

[128] 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).

[129] Kennedy 1987, 199-200; Modelski and Thompson 1996, 87-88; Thompson 1990, 213.

[130] Landes 1969 was a particularly influential account in highlighting Britain's failure to keep up with Germany in steel production. Wengenroth 1994, 393n29. For example, Kennedy's (1987) *The Rise and Fall of the Great Powers* cites Landes's work multiple times to argue that declining steel output explains Britain's productivity slowdown. Kennedy 198n16; 228n110.

[131] Wengenroth 1994, 390.

Relying on trade data and detailed accounts of different steelmaking processes, the following sections demystify this myth.

Germany and the U.S. did not rise to industrial preeminence on the back of dominating innovations in steel. Neither the U.S. nor Germany was the sole source for the four key innovations in the steel industry from 1850 to 1914.[132] In addition, the rising economic powers did not have a comparative advantage in steel exports. According to figures by the Iron and Steel Division of the U.S. Department of Commerce, in 1922 the United Kingdom exported over 715,000 long tons of steel, around forty percent more than Germany and the United States, which each exported around 500,000 long tons of steel.[133] An analysis of global trade data illuminates that the British and steel industries took up the second (1899) and third (1913) largest share of British exports among sixteen sectors. The German and American steel industries ranked much lower on the same metric for both 1899 and 1913.[134] In other words, the British iron and steel industries maintained a revealed comparative advantage over their rivals throughout the IR-2.

A closer examination suggests that aggregate measures of crude steel output do not adequately capture how technological innovations were affecting productivity growth.[135] The introduction of new steel-making processes in the 1860s and 1870s, commonly associated with the birth of a new steel industry, was actually creating two separate steel industries. The key

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[132] See Table 5.6. Referencing a similar list of advances in steelmaking, Hobsbawm (1968, 159) writes, "Every major innovation in the manufacture of steel came from Britain or was developed in Britain." Britain was also an early adopter of many major innovations in open-hearth technology, including the Talbot furnace, which George James Snelus, vice-president of the Iron and Steel institute, deemed "the greatest advance that had been made in the manufacture of steel for some years." Talbot 1900, 62; cited in McCloskey 1973, 71.
[133] Yearly Index of Forging and Heat Treating 1922, 357.
[134] Crafts 1989, 130.
[135] 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 Beckley 2018b; Wohlforth 1999, 13.

difference between the British and German steel industries was that Britain shifted toward producing open-hearth steel, which was higher in quality and price, whereas Germany produced cheap Thomas steel and exported a large amount at dumping prices. According to the British Iron Trade Association, Britain produced more than 1.5 million tons of open-hearth steel in 1890, about four times higher than Germany's production of open-hearth steel that year.[136] Germany even exported substantial amounts of cheap soft Thomas steel to Britain where it was processed into higher-quality steel and re-exported.[137]

Indeed, the difference between the two steel industries was not rooted in Britain failing to adopt the newest techniques. The two chose to specialize in different steelmaking processes but were "not very different in terms of productivity and know-how."[138] The historical evidence for steel — the candidate LS that best supported the LS mechanism's expectations regarding the impact timeframe of revolutionary technologies — does not track well with the LS mechanism's pathway of monopoly profits from dominance of innovation. The implication is not that steel was inconsequential in the IR-2. Rather, disaggregating the steel industry into various steel-making processes reveals the interconnections between steel and other industries. The next section, which evaluates the GPT mechanism's predictions regarding the relative phase of advantage in the IR-2, shows that improvements in steel such as the introduction of high-speed steel in machine-cutting tools, were crucial to the diffusion of mechanization.[139] The GPT diffusion lens offers a more multi-dimensional understanding of the steel industry's impact on industrial power shifts in the IR-2.

American Machine Tools -- GPT Diffusion Advantage

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[136] Wengenroth 1994, 384.
[137] Wengenroth 1994, 392.
[138] Wengenroth 1994, 375. McCloskey (1971, 296) has uncovered similar productivity trends in the U.S. and British steel industries before WWI.
[139] Rosenberg 1963.

The historical evidence largely discredits the predictions of the LS mechanism regarding monopoly profits from leading-sector innovation. Neither the U.S. nor Germany monopolized innovation in chemicals, electricity, motor vehicles, and steel. The GPT mechanism, on the other hand, is less concerned with innovation leadership. It predicts that the U.S. advantage in diffusing general-purpose transformations connected to machine tools was the key source of its economic gains relative to Britain and Germany.

Was the U.S.'s sustained growth advantage over its industrial rivals due to its relative success in adopting a mass production system supported by special purpose machinery? Although there is limited cross-national data on the pace of mass production, recent research has provided comparative estimates that depicts 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 more than doubled the British and German rate.[140] 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 a significantly wider gap in the tools most crucial for mass production, such as broaching machines (80 percent), honing and lapping machines (79 percent), gear-cutters (29 percent).[141]

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.[142] Exploiting research from its institutes of technology, Germany also built higher quality machinery in certain fields, including sophisticated

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[140] Calculations based on data in Timmer et al. 2016. Germany's machine intensity rate is based on data 1909. 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. 2016, 879-881. I thank Pieter Woltjer for sharing the link to this data.

[141] Ristuccia and Tooze 2013, 959-960.

[142] Great Britain Committee on the Machinery of the United States of America 1855, 32.; cited in Rosenberg 1963, 420n12. See also Litterer 1961, 467. British machine tools remained superior to those of other European countries in the IR-2 period (Floud 1976, 68).

power technology.[143] Rather, the distinguishing feature of the U.S. machine tool industry was excellence in diffusing innovations across industries.[144]

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.[145] 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.[146] 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"[147] and "the eagerness with which they [the Americans] call in the aid of machinery in almost every department of industry."[148]

From a position of uncontested superiority in the 1850s, Britain's machine tool trade gradually eroded over the next seventy years. Britain was slow to adopt American methods of machine-making, which only gained reluctant acceptance in Britain in the 1890s.[149] The British machine tool industry's competitiveness rebounded in the 1890s, but Britain was already too far behind in this GPT trajectory.[150] In 1913, half of British imports of American machinery were for

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[143] Braun 1984, 16.

[144] Rosenberg 1963, 417; Saul 1960, 22.

[145] Braun 1984; Nolan 1994; Timmer et al. 2016, 882-883.

[146] The travels of Wallis and Whitworth covered regions that employed 75 percent of the U.S.'s manufacturing workers (Rosenberg 1969, 24). John Anderson was a prominent British engineer.

[147] Great Britain Committee on the Machinery of the United States of America 1855, 32.

[148] Whitworth 1969 (originally published in 1854), 387.

[149] Whitston 1997; Saul 1960; Rosenberg (1969, 72-73) notes, for instance, the milling machine did not gain widespread adoption in England until the popularization of bicycles in the 1890s.

[150] Floud 1976.

industries using interchangeable methods.[151] Though Britain maintained pockets of excellence in machine-using industries, including shipbuilding and textiles, it fell behind on the wide front of mechanization.

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."[152] On the importance of the production system enabled by machine tool advances, Mokyr concludes,

> From a purely economic point of view, it 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.[153]

5.3.3 Breadth of growth: the wide reach of interchangeable manufacture

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

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[151] Saul 1960, 37.

[152] Hobsbawm 1968, 151. Machinery makers comprised nearly a quarter of the top two hundred largest industrial enterprises in the U.S. in 1917 (Chandler 1990, 194). As Saul (1960, 21) writes, "Possibly the sector of the (British) engineering industry to come most powerfully under American influence was the machine tool trade."

[153] Mokyr 1990, 136.

dispersed across a broad range of industries. Sector-level estimates of total factor productivity growth provide useful evidence to assess these diverging propositions.

Widespread Productivity Growth

The historical data support the GPT theory's expectation of pervasive U.S. productivity growth. Kendrick's estimates of growth contributions by sector, the seminal account of U.S. productivity growth in this period, endorsed a pattern of relatively balanced productivity growth. From 1899 to 1909, the last full decade before WWI, nearly 60 percent of Kendrick's sample of 80 manufacturing industries experienced steadily positive growth in productivity, averaging between one to three percent increases in output per labor-hour.[154] Updates to Kendrick's estimates also paint a picture of broadly distributed productivity growth in the states. Construction, wholesale and retail trade, transport equipment, and printing and publishing, and other non-leading sectors eclipsed the IR-2's leading sectors in terms of contribution to TFP growth during the first two decades of the 20th century. From 1899 to 1941, 33 of 38 sectors averaged at least 1 percent annual TFP growth.[155]

Concentrated TFP growth in special industries does not describe the IR-2. Bakker et al. found that "great-inventions," which roughly correspond to the candidate leading sectors, accounted for only 29 percent of American TFP growth from 1899-1909.[156] Based on their calculations of electricity-linked TFP spillovers across manufacturing sectors, which were only available for the period from 1919-1941, this broad picture of productivity growth in the IR-2

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[154] Kendrick 1961, 163. See also Broadberry 2006, which stresses the importance of the U.S. narrowing the gap with Britain in productivity performance within the service sector. Others also argue that "the development of organized innovation during the Second Industrial Revolution outside of the electrical equipment and chemical industries has received far too little attention" (Bruland and Mowery 2006, 376).

[155] Bakker et al. 2019, 2288.

[156] Bakker et al. 2019, 2285. This figure aggregates various industries' *intensive growth contributions* — a measure that is the product of an industry's value-added-share and TFP growth. The "great inventions" category includes sectors that correspond to chemicals and pharmaceuticals, electricity, the internal combustion engine, and modern communications technologies.

stands up even when accounting for TFP spillovers.[157] The chemical industry's share of U.S. TFP growth in the 1920s was only 7 percent — despite employing 40 percent of all research scientists at the decade's start.[158] That economic growth in the IR-2 was not dominated by a few R&D-based sectors rebuts another common variant of the LS account.[159]

Machine tools and broadly-distributed productivity growth

Though GPTs are often associated with productivity upsurges, just because American productivity growth was broadly dispersed does not necessarily mean that this pattern was generated by a GPT. A dispersed pattern of productivity growth could be explained by macroeconomic factors. Alternatively, the accumulation of many different, unconnected sources of TFP growth could result in widespread TFP growth. 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 manufacture 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.[160] Its influence covered "almost every branch of industry where articles have

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[157] Bakker et al. (2019, 2287) find that the contributions of the great inventions to TFP growth increases by about 10 percent in the 1920s when TFP spillovers are included. Since TFP spillovers from electricity and other "great inventions" did not gain momentum until the 1920s, it is reasonable to assume that these indirect spillovers would be more muted in the last decades before WWI.

[158] Bakker et al. 2019, 2290.

[159] See, for instance, Landau and Rosenberg 1992; Mowery 2009, 2.

[160] Anderson 1877; Hounshell 1985; Rosenberg 1963; Thomson 1989. Consider the possible spillover effects from sewing machines alone. The percent increase in value added by manufacture in women's clothing grew by approximately 135 percent in the U.S. from 1899-1909, which ranked third highest (only after automobiles and electricity) for industries valued at over $100 million. Bureau of the Census 1913, 40.

to be repeated."[161] Per a 1930 inventory of American machine tools, the earliest complete survey, nearly 1.4 million metalworking machines were used across 20 industrial sectors.[162] Based on his detailed study of American productivity growth during this period, Kendrick identifies progress in "certain types of new products developed by the machinery and other producer industries (that) have broad applications across industry lines" as a key source of the "broad, pervasive forces that promote efficiency throughout the economy."[163]

The degree to which specific kinds of machine tools proved useful to many industries provides another test of the breadth of this trajectory. If each industry purchased its own specialized type of machine tool, then broad technological convergence should be questioned. However, as sales records from leading machine tool firms show, many application sectors purchased the same type of machine. In 1867, Brown and Sharpe Manufacturing Company sold the universal milling machine, just five years after its invention, to 31 other machine tool producers and 27 other firms that made products ranging from ammunition to jewelry."[164] The share of generic patents among a population of lathe patents increased from one third of all patent types from 1816-1865 to 60 percent of all patent types in the period from 1900-1921.[165]

The breadth of productivity spillovers from machine tools was not boundless. Machine-using industries constituted a minority of the manufacturing industries, which themselves accounted for less than a quarter of national income.[166] However, the users of new machine tools extended beyond just manufacturing industries. Technologically-intensive services, such as railroads and steam transportation, also benefited significantly from improved metalworking

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[161] Anderson 1877, 235; cited in Rosenberg 1963, 420n12.
[162] This is a conservative estimate, as some sectors were omitted in the survey (Thomson 2010, 6).
[163] Kendrick 1961, 178, 181.
[164] Brown & Sharpe 1997, 20-23; cited in Thomson 2010, 29. As these figures show, other machine tool producers were the largest single group of buyers of the universal milling machine. Rosenberg, 1963, 433.
[165] Thomson 2010, 14.
[166] Harley 2003, 827.

techniques.[167] In agriculture, specialized machine tools helped advance development and widespread adoption of the reaper, which revolutionized agricultural productivity.[168]

In describing how machine tools served as a transmission center, Rosenberg describes the industry as a pool of skills and technical knowledge that replenishes the economy's machine-using sectors: an innovation that addresses one industry's problem gets added to the pool and becomes available (perhaps with a few modifications) for all technologically related industries.[169] This pool system is sustained by strong upstream-downstream relationships between machine tool firms and their users.[170] In this way, the machine tool industry functioned as "a center for the acquisition and diffusion of new skills and techniques in a machinofacture type of economy."[171]

5.4 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 this GPT trajectory. Why did Britain fail to take advantage of the GPT trajectory linked to machine tools? The explanation, according to GPT diffusion theory, rests on institutional complementarities. Specifically, the historical data should reveal that the U.S.'s leadership in mechanization was based on institutional adaptations that widened the base of mechanical engineering talent.

LS-based theories tend to emphasize Germany's edge in advanced scientific education as the reason behind its success in science-based industries such as electrical equipment and chemicals. Under the GPT model, technical and engineering education is more crucial to widening the talent base in technologies with pervasive economic effects such as electricity and

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[167] Rosenberg 1979, 34; Scranton 1997, 290.
[168] See chapter 4 of Hounshell 1985.
[169] Rosenberg 1963, 426.
[170] von Tunzelmann 2000, 132.
[171] Rosenberg 1963, 425.

chemicals. To supplement my analysis of mechanical engineering skills, I also investigate the skill gaps related to chemical innovations. Although the wide-scale diffusion of chemical advances 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.

5.4.1 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. It is less clear, however, which institutions and which forms of human capital were most crucial to U.S. technological fitness. 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 the 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 claim that the U.S. benefited from a general advantage over Britain in human capital.[172] In support of this argument, one 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.[173] Other empirical evidence, more tightly bound to the IR-2 period, 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

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[172] Crafts 1989, 35; Mankiw et al. 1992, 432.

[173] Greasley and Oxley 1998b. 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.

America (by a factor of 2.3) between 1870 and 1929.[174] 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."[175]

Other skill-based explanations are more sensitive to 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 new industries. Unlike Britain, these rising powers expanded scientific training in universities to prepare graduates for new, expanding industries such as chemicals.[176]

These interpretations suffer from a misplaced attention to both the German case and LS product cycles in 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, as the evidence from the first half of this chapter supports, then the significance of scientific infrastructure fades. In fact, the U.S. trailed both Britain and Germany in scientific achievements and talent.[177] 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.[178]

The U.S. machine tool trajectory relied, instead, on a broad pool of machinists and mechanical engineers. Machinists multiplied as mechanization advanced, as reflected in the growing ratio of machinists to blacksmiths, who typically employed craft methods. In 1870 there were less than half as many machinists as blacksmiths; by 1910 there were nearly two times as

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[174] 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 1998b, 185).
[175] Williamson 1996, 296.
[176] I further explore this line of thinking in section 5.4.3.
[177] Hughes 1994, 433; Kocka 1980, 95-96; Nelson and Wright 1992, 1940.
[178] Bruland and Mowery 2006, 359-360. In 1921, there were less than 7000 researchers employed in American industry, according to the first survey of American industrial laboratories Chandler 1990, 84.

many machinists as blacksmiths.[179] These engineers played a crucial role in expanding the possible applications of 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).[180] 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.[181]

Indeed, the key disparity between the U.S. and Britain in mechanical skills was in the breadth of engineering talent, rather than the quality of industrial scientists.[182] 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.[183] By 1906 the U.S. had approximately ten times as many engineering students as Britain.[184] Meanwhile in Britain, the University of Oxford "was probably the only first-rate university in the world without an engineering professorship."[185] 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.[186]

5.4.2 U.S.'s institutional advantages in widening the pool of mechanical engineers

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

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[179] Thomson 2010, 9.
[180] Thomson 2010, 11-12.
[181] Locke 1984, 61; Thomson 2010, 14, 15
[182] Rosenberg and Steinmueller 2013, 1129.
[183] Sanderson 1972, 24.
[184] Sanderson 1972, 24.
[185] Sanderson 1972, 39.
[186] Locke 1984, 34-88; Thomson 2010, 40.

U.S. was limited to informal apprenticeships.[187] 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, specialized educational institutes (e.g. Philadelphia's Franklin Institute and the Worcester County (MA) Free Institute of Industrial Science), professionalized engineering programs at universities (e.g. the University of Cincinnati's cooperative engineering course), technical high schools, machine tool associations, and higher education institutions that favored the mechanical arts.[188] 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.[189]

Beyond the increase numbers 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.[190] 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.[191] Coordinated to share best practices and address labor supply issues, many of these

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[187] Lundgreen 1990, 55; Scranton 1997, 60.

[188] Nelson and Wright 1992, 1942; Scranton 1997, 65-71.

[189] Noble 1977, 24; See also Maloney and Caicedo 2017, 12-13.

[190] Hounshell 1985; Noble 1977.

[191] Notably, Germany's standardization efforts took a different path. Rather than converging on machine interoperability standards, the main standards-setting body, the Verein Deutscher Ingenieure (VDI), initially prioritized safety standards. The VDI was slow to follow the U.S. example. American economist Robert Brady

national associations evolved from local institutions.[192] Consistent with this was a general trend of new associations and institutes dedicated to improving American skills in the mechanical arts.[193]

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.[194]

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 capture engineering 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.[195] 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.[196]

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concludes, "No national standards movement was inaugurated in [the German machine industry] until after the outbreak of the [World War I]" (Brady 1933, 150; cited in Yates and Murphy 2019, 68).

[192] 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.

[193] Rosenberg and Steinmueller 2013, 1130.

[194] Morris 1987, 5-6.

[195] Maloney and Caicedo 2017.

[196] Maloney and Caicedo 2017, 16.

5.4.3 LS-based theories and chemical engineering

While this chapter's account of the institutional factors behind technological leadership in the IR-2 concentrates on explaining the U.S.'s advantage in systematizing machine tool advances — the key GPT trajectory during this period — LS-based explanations focus on how Germany pioneered novel products in fast-growing industries, especially the chemical sector. These accounts emphasize Germany's advanced scientific education system and industrial research laboratories, which allowed German chemical firms to pursue breakthrough R&D projects.[197] 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.[198]

Based on a different model of how and when advances in chemicals registered substantial economic gains, this section highlights a different set of institutional competencies that explains why the U.S., not Germany, most effectively exploited new chemical advances. Advanced scientific education and cutting-edge R&D infrastructure were not the differentiating factors in diffusing chemical processes across a broad range of industries — beyond the production of synthetic dyes.[199] Despite trailing Germany in training highly skilled chemists, the U.S. was early to institutionalize chemical engineering as a discipline, which proved crucial in translating chemical research into industrial applications.

A preoccupation with Germany's dominance in dyestuffs and organic chemicals in the late 19th century misses the more significant expansion of chemical processing to a wide range of industries such as ceramics, food-processing, glass, metallurgy, petroleum refining, etc. A key

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[197] Beckley 2011, 63-64. Drezner 2001, 12n33, 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).

[198] Sanderson 1972, 23. See also Locke 1984, 61.

[199] For more on the pace and trajectory of chemicalization, see earlier sections of this chapter.

marker on this path was the emergence of "unit operations" concept, which broke down chemical processes into a sequence of basic operations that were common in chemical processing across a number of industries (e.g., condensing, crystallizing, electrolyzing, etc.).[200] Spurred by the central theme of unit operations, the development of chemical engineering broke down the siloed divisions of industrial chemistry, which had been organized around the production of a very large variety of chemical products with little concern for the unifying principles between the manufacture of different products.[201]

In line with how it adapted to innovations in machine tools, the U.S. benefited the most from chemicalization due to institutional advantages in widening the relevant engineering talent base. Despite lagging Germany in chemical breakthroughs and top chemists, the U.S. first institutionalized the discipline of chemical engineering.[202] American institutions of higher education, most notably MIT, embraced the unit operations model and helped cultivate a common language and professional community of chemical engineering.[203] 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."[204]

In contrast, Germany was slow to develop an infrastructure for supporting chemical engineers. Throughout the interwar period, the chemical engineering profession "failed to

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[200] Little 1933, 7; Rosenberg 1993, 176.

[201] Little 1933, 7; Rosenberg 1993, 176.

[202] 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.

[203] Guédon 1980, 45-76; Noble 1977, 26-27, 192-195; Rosenberg 1998a, 171; Trescott 1982.

[204] Rosenberg and Steinmueller 2013, 1145.

coalesce in Germany."[205] Chemical engineering did not become a distinct academic subject area in Germany until after the Second World War.[206] German universities did not equip chemists with engineering skills, thereby shifting the burden of training to firms.[207] For its part, 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.[208]

The U.S. reaped the spoils of technological convergence in chemicalization not just because it trained large quantities of chemical engineers but also because it strengthened university-industry linkages and standardized techniques in chemical engineering.[209] Without the connective tissue that promotes information flows between the chemical sector and application sectors, a large base of chemical engineers was insufficient. Britain, for instance, was relatively successful at training chemical engineers during the interwar period; however, the weak links between British educational institutions and industrial actors 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 U.S.[210] Additionally, professional engineering associations in the U.S., including the American Institute of Chemical Engineers, advanced standardization in the chemical industry — an initiative imitated in Britain over a decade later.[211] Unlike their American peers, it was not until after WWII that British chemical engineers saw themselves as "members of a professional

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[205] Divall and Johnston 1998, 204.

[206] In fact, there were no chemical engineering departments outside of the U.S. until the 1930s. Rosenberg 1998b, 195.

[207] Rosenberg 1993, 192; Rosenberg 1998b, 198-199.

[208] Guédon 1980.

[209] Rosenberg 1998b, 205.

[210] Divall and Johnston 1998, 212. In fact, controlling for the total population, there were more British accredited chemical engineers than American ones.

[211] Noble 1977, 38, 72; Reynolds 1983, 41-42.

group that shared a broad commonality cutting across the boundary lines of a large number of industries."[212]

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.[213] This section, therefore, provides a secondary test of which types of institutions were most apt for national success in the IR-2.

5.5 Alternative factors

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.[214] 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 the neorealist theories of threat and varieties of capitalism literature, deserve further examination.

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[212] Rosenberg and Steinmueller 2013, 1146.

[213] Relatedly, given that chemical engineering tapped into foundational practices from mechanical engineering, one could argue that chemical engineer was an extension of mechanical engineering into chemistry, or "the product of mechanical engineering and chemistry." Noble 1977, 38.

[214] Kennedy 1987, 228.

5.5.1 Threat-based explanation

What is the role of external threats in how leading countries adapted to the IR-2? Scholars have argued that U.S. military investment, mobilized against the threat of a major war, was crucial to driving forward the U.S.'s development of many GPTs.[215] Similarly, some studies stress that U.S. military procurement was crucial to spur advances in machine tools. The U.S. military subsidized the high costs needed to outfit factories with machinery to produce interchangeable parts in small arms manufacture.[216] First seeded in firearms manufacturing in national armories, this mechanized system of production diffused to other industries in the second half of the nineteenth century.[217]

Though firearms production was an important experimental ground for mechanized production, military support was not *necessary* to the development of the American system of manufacture. 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 public funding and subsidies were not vital to the American System.[218] 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 drastically increase sales and cut costs.[219] In his definitive study of the history of American interchangeable parts manufacture, Hounshell concludes, "the sewing machine and other

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[215] Ruttan 2006.

[216] Smith 1985; Ruttan 2006. A related point is that the first attempts to transfer the American system of manufacturing occurred in the 1850s because of national security concerns over the Crimean War (Rosenberg 1969, 72-73).

[217] The U.S. military had a much tighter relationship with its small arms manufacturers than the British firearms contracting system, which helps explain why the American firearms first developed large-scale interchangeable manufacture in the early decades of the 19th century (Deyrup 1948).

[218] Hoke 1990.

[219] Hounshell 1985, 50;-61; Clockmaking also inspired an earlier generation of machine tool builders in Britain. Musson and Robinson 1989.

industries of the second half of the 19th century that borrowed small arms production techniques owed more to the clock industry than to firearms."[220]

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 American system of manufacture, 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.[221]

Another threat-based argument, Taylor's "creative insecurity" theory, posits that countries that face more external threats than internal rivalries will achieve more technological success.[222] 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).[223] 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.[224] Creative insecurity, therefore, provides little leverage in the IR-2 case.

5.5.2 VoC explanation

A second alternative explanation 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

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[220] Hounshell 1985, 51.

[221] Deyrup 1948, 6.

[222] Taylor 2016.

[223] The Spanish-American War in 1898 is an exception, but this lasted one year and occurred late in the period.

[224] Civil wars are categorized as "extreme cases" of high domestic tensions under creative insecurity theory (Taylor 2016, 238).

that came from mass production.[225] This firm-centered approach contrasts with the 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.[226] From 1899 to 1909, sectors that relied on batch and custom production, including machine tools, accounted for a third of value added in manufacturing.[227] In fact, over this decade, the increase in value-add of batch and custom producers exceeded that for bulk and mass producers between 1899 and 1909.[228]

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.[229] "No single governance structure matched the requirements of production in all areas," notes Kitschelt.[230]

5.6 Summary

The standard version of the geopolitical implications of the second industrial revolution highlights Germany's challenge to British power. Germany's relative economic rise, according to

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[225] Chandler 1977. LS accounts in IR literature adopt this account. See, for example, Kim and Hart 2001.
[226] Scranton 1997, 7.
[227] Bureau of the Census 1913, 40-43. For a justification and product group map of the division into four types of producer formats (custom, batch, bulk, and mass), see Scranton 1997, 12.
[228] Scranton 1997, 17.
[229] Scranton 1997, 7.
[230] Kitschelt 1991, 472.

this account, derived from its advantage in industrial research and scientific infrastructure, which enabled it to capture the gains from new industries such as electricity and chemicals. However, a range of economic indicators points to the U.S. as the rising power that surpassed Britain in this period. The case of the U.S.'s industrial ascent in the IR-2 illustrates that dominating innovation in leading sectors is not the crucial mechanism in explaining the rise and fall of great powers. Indeed, Britain's decline was not a failure in innovation but in diffusion. Reflecting on the IR-2 during renewed fears of British decline in the late 1950s, the renowned economist Sir William Arthur Lewis once said, "Britain would have done well enough if she merely imitated German and American innovations."[231]

The second industrial revolution case further supports that cross-national differences in the ability to widely diffuse GPTs is the key driver of long-term growth differentials. The U.S. succeeded in widening its talent base in mechanical engineering, which proved critical for its relative advantage in adapting machine tools across a broad range of industries. Like all GPT trajectories, this process was a protracted one, but it aligns better with when the U.S. surpassed Britain in productive leadership than the more dramatic breakthroughs in chemicals, electricity, and automobiles. To further investigate how the LS mechanism breaks down and why the GPT mechanism holds up, we turn to U.S. and Japan high-tech competition in the 20th century, or what some label the third industrial revolution.

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[231] Lewis 1957, 583.

Chapter 6
Japan's Challenge in the 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 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.[1] Amidst this upheaval, many thought Japan would follow in the footsteps of Britain and the U.S. to become the "Number One" industrial power.[2]

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.[3] In the late 1980s and early 1990s, a torrent of works bemoaned the loss of U.S. technological leadership to Japan.[4] "Japan has...become the undisputed

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[1] See Galambos 2013, 2-4 for a review of work on the history of the IR-3. As was the case with drawing temporal bounds around the IR-1 and IR-2, the periodization of the IR-3 is disputed. Rostow, for instance, marks the second half of the 1970s as the start of a new industrial revolution (Rostow 1985, 285).

[2] 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."

[3] Gilpin 1991, 15.

[4] 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.

world economic champion," declared Clyde V. Prestowitz, Jr, a former U.S. trade negotiator, in his best-selling book on U.S.-Japan relations.[5]

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.[6] Prominent thinkers, including Henry Kissinger, warned that Japan would convert its economic strength into threatening military power.[7] 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.[8]

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.[9] 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 strategy in electronics in recent decades are striking."[10] Many voices

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[5] Prestowitz, Jr. 1989, 2.

[6] Gilpin 1996, 428; Heritage 1992, 1; Huntington 1993, 71-82; Rostow 1985; Thompson 1990.

[7] 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.

[8] Oreskes 1990; cited in Mastanduno 1991, 74. In the 1970s Western analysts also recognized that the Soviet economy was mired in stagnant productivity growth, which made it less of a threat to U.S. power in the future. Trachtenberg 2018.

[9] Freeman 1987; Kennedy 1987, 529; Nelson and Wright 1992; Piore and Sabel 1984.

[10] Mowery and Rosenberg 1991, 80; cited in Drezner 2001, 18-19.

called for the U.S. to mimic Japanese institutional arrangements, which they viewed as crucial to Japan's growing excellence in leading sectors.[11]

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.[12] Becoming the world's leading producer in high-tech industries did not catalyze Japan's overtaking of the U.S. as the leading economy.

The IR-3 case is particularly damaging for the LS theory. 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. Yet, as the case study evidence will reveal, an economic power transition did not occur even though all these conditions were present. The Japanese challenge to American technological leadership (1960s-2000s), therefore, primarily functions as a deviant consistency case, or a falsifying case, for the LS mechanism.[13]

From a different perspective, the case evidence shows that Japan did not lead the U.S. in the diffusion of general-purpose information technologies, which means the conditions for an economic power transition under the GPT mechanism were not present in the IR-3. Since there could be many reasons why an economic power transition does *not* occur, the absence of a

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[11] 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.

[12] Jin 2016.

[13] Beach and Pedersen 2018, 861-863.

mechanism in a negative case does not provide additional evidence that explains how and when technology-driven economic power transitions do occur.[14] 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. This advantage stemmed from the U.S.'s superior ability to cultivate the computer engineering talent necessary to advance computerization. In this respect, the IR-3 case demonstrates that deviant cases can help form better mechanism-based explanations.[15]

I drew from many diverse sources to re-examine Japan's supposed technological advantages in the 1980s. Surprisingly, few scholars have revisited claims that Japan's leadership in leading sectors meant that it was on its way to economic pre-eminence.[16] Decades of hindsight bring not just perspective but also more sources to pore over. Regarding how the U.S.-Japan productivity gap evolved in this period, revised estimates and the greater availability of data help paint a more granular picture. To narrow down the crucial technological trajectories to trace, I pieced together histories of key technologies and technological paradigms such as semiconductors and computing, comparative histories of technological development in U.S. and Japan, and general economic histories of the IR-3. Assessments of ICT engineering education by Japanese agencies and U.S. associations help flesh out the state of GPT skill infrastructure in the IR-3.

The evaluation of the GPT and LS mechanisms against historical evidence from the IR-3 proceeds as follows. Section 6.1 makes clear that a U.S.-Japan economic power transition did not

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[14] Chapter 3 provides a detailed explanation of this point.

[15] Beach and Pedersen 2019, 102.

[16] The international political economy scholars who have tackled this question mainly rely on a LS framework. See, for example, Borrus and Zysman 1997.

take place. Section 6.2 reviews and then organizes the technological breakthroughs of the IR-3 into candidate leading sectors and GPTs. Section 6.3 examines whether all the components of the GPT or LS mechanism were present in this case. Since the outcome did not occur in this case, it is important to trace where the mechanisms break down. While all the aspects of the LS mechanism were present in the IR-3, the GPT mechanism was not operational because Japan fell behind the U.S. in diffusing information technologies across a broad range of sectors. Based on evidence from the previous section, section 6.4 explains why institutional explanations rooted in LS trajectories are unconvincing. It then analyzes whether GPT-institutional complementarities were a factor in sustained U.S. leadership. Section 6.5 tackles alternative factors and explanations. Section 6.6 concludes.

6.1 Power transition unfulfilled: Japan's rise stagnates

In a 1983 article for *Parade*, David Halberstam described Japan's industrial ascent as America's "most difficult challenge for the rest of the century" and "a more intense competition than the previous political-military competition with the Soviet Union."[17] By the end of the century, however, "there [was] little talk about Japan displacing the United States as the technological hegemon."[18] The economic power transition that accompanied the IR-1 and IR-2 did not materialize in this case. Indeed, the economic indicators exhibit a general trend: Japan's economy catches up in the 1980s, stagnates in the 1990s, and ultimately fails to overtake the U.S. economy.

GDP per capita indicators

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[17] Halberstam 1983, 4-5. Though the rivalry between the U.S. and the Soviet Union also raised concerns about a power transition, the Soviet Union was not at the forefront of advances in electronics and information technologies. Thus, this rivalry is less relevant for tracing the mechanism that connects technological revolutions and economic power transitions.

[18] Drezner 2001, 19.

During the three decades after 1960, Japan's economy experienced remarkable growth, reaching a GDP per capita in 1990 that was 81 percent of the U.S. figure that year. In the following ten years, known as Japan's "lost decade," Japan's growth in GDP per capita stalled. By 2007, Japan's GDP per capita dropped back down to 73 percent of that of the U.S (Figure 6.1).

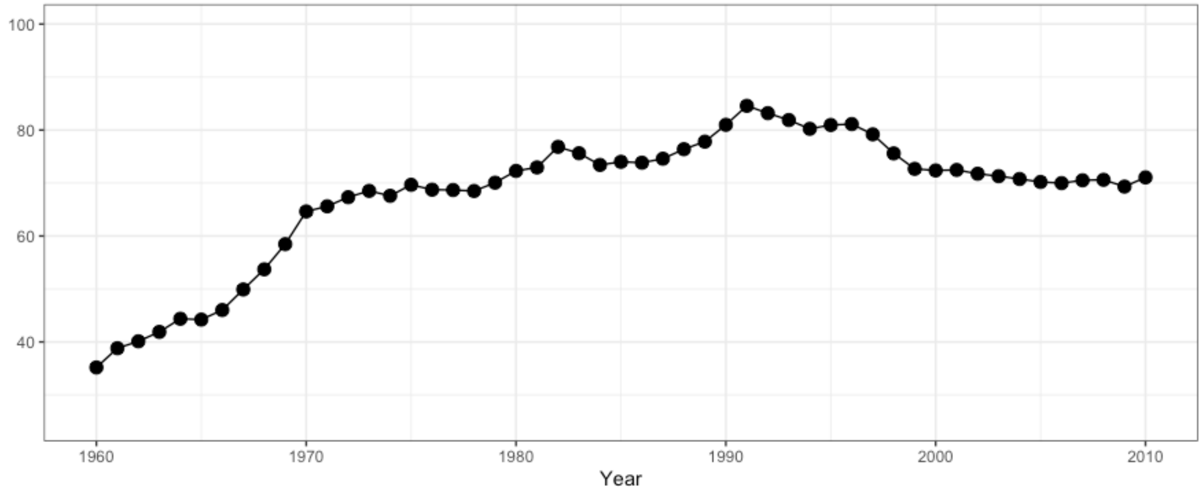

Figure 6.1: Japan's Catch-up to U.S. in GDP per capita Stalls in 1990s

Japan's real GDP per capita as percentage of U.S. figure (in 2011$ prices)

Source: Maddison Project Database, version 2020 (Bolt and van Zanden 2020).

Industrialization indicators

Comparative industrialization statistics also demonstrate the absence of a U.S.-Japan economic power transition. In terms of global manufacturing output, Japan gained on the U.S. through the 1970s and 1980s and nearly matched the U.S. at 20 percent of global manufacturing output in the early 1990s. Since then, Japan's share of global manufacturing output declined to around 10 percent in 2010, while the U.S.'s share increased in the 1990s and held at 20 percent until 2010.[19] In manufacturing industries, Japan's labor productivity growth from 1995-2004 only averaged 3.3 percent, whereas the U.S. averaged 6.1 percent in the same category.[20]

Productivity indicators

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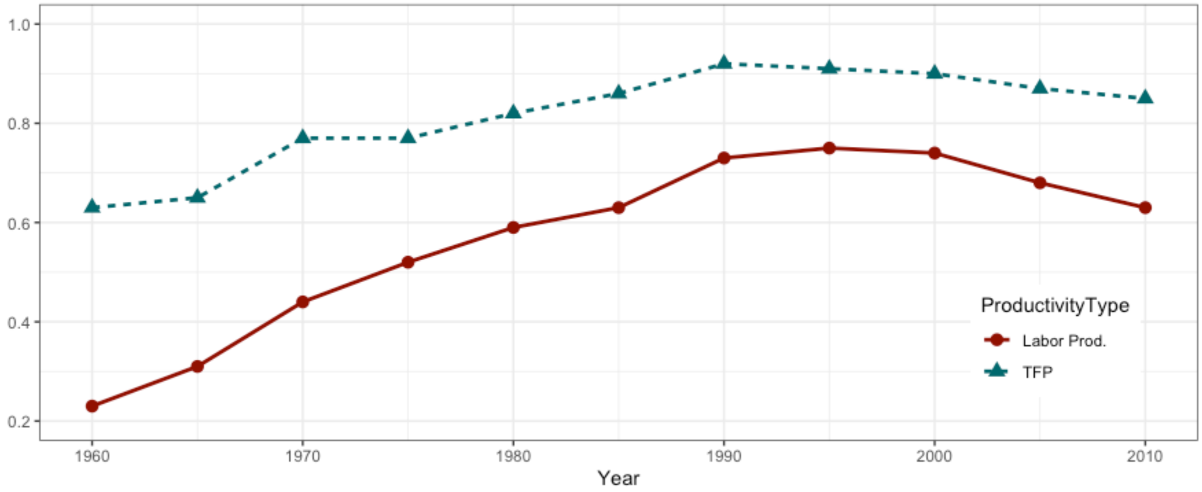
[19] R. Baldwin 2016, 87-88.

[20] This data comes from the OECD Structural Analysis database, which only has figures on Japanese productivity growth by industry from 1995 through 2016. Baily et al. 2020, 18.

The productivity statistics also reveal a general trend of convergence without overtaking. From a total factor productivity of just half that of the U.S. in 1955, Japan's TFP grew steadily. By 1991, the productivity gap between the U.S. and Japan was only 5 percent. As was the case with the GDP per capita and industrialization figures, Japan's productivity growth slowed, and the gap between the U.S. and Japan widened during the 1990s (Figure 6.2). Throughout this decade, Japan averaged just .2 percent annual TFP growth.[21] By 2009, Japan's TFP dropped to only 83 percent of that of the U.S.[22]

Figure 6.2: Japan's Catch-up to U.S. in Productivity Stalls in 1990s

Ratio of Japan's productivity to U.S. level



Source: Jorgenson et al. 2018, 18.

6.2 Key Technological Changes in the IR-3

Parsing through the different trajectories of technological change is a necessary first step to evaluate whether the LS and GPT mechanisms were operative in this period. This task is complicated by the tremendous technological changes that emerged in the IR-3, such as the first microprocessor (1971), production of recombinant DNA (1972), the VHS format for video

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[21] Comin 2011.

[22] Jorgenson et al. 2018, 18. Japan's average capital productivity did maintain a small lead over U.S. capital productivity, according to Jorgenson's figures. As outlined in Chapter 3 on methods, I take TFP and labor productivity as comprehensive measures of productivity growth. Moreover, the capital productivity indicators do not support that Japan overtook the U.S. during this period, as Japan's capital productivity was already higher than the U.S. in 1960 and 1970.

recording (1976), and the first personal computer (1981). Guided by past scholars' efforts to map the key nodes of the information revolution as well as analytic measures for leading sectors and GPTs, this section takes stock of key technological drivers that affected the U.S.-Japan economic power balance.

6.2.1 Proposed leading sectors

Amidst a shifting technological landscape, the most likely sources of LS trajectories were information and communications technologies (ICTs). Certainly, scholars have highlighted technological developments in a wide range of industries as possible leading sectors, including lasers and robotics.[23] Nonetheless, Japan's success in the computer, consumer electronics, and semiconductor industries were most relevant for its prospects of overtaking the U.S. as the foremost economic power. In each of these three leading sectors, Japan dominated the production of key components.[24]

All three relatively new industries achieved extraordinary growth off the back of technological breakthroughs, fulfilling the established criteria for leading sectors. In the U.S. economy during the 1980s, computer and data-processing services ranked as the fastest growing industry in terms of jobs added.[25] From 1960 to 1990, U.S. semiconductor production increased much faster than production in other rapidly growing industries, including motor vehicles and aerospace.[26] The U.S. electronics industry also experienced a remarkable surge during the late 20th

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[23] Modelski and Thompson (1996, 213) compiled leading sectors proposed by eleven technology wave experts during the 1979-1990 period. The resulting list included a diverse range of technologies including: biotechnology, computers, energy/food/environment technologies, lasers, microelectronics, robotics, scientific instruments, telecommunications, and watch industries.
Modelski and Thompson 1996, 213.

[24] Inman and Burton, Jr. 1990; Kennedy 1987, 525; Kitschelt 1991, 480; Mastanduno 1991, 101-102.

[25] Plunkert 1990, 10.

[26] Thompson 1990, 230.

century, growing thirty times faster than other manufacturing industries by some estimates.[27] These trends in computers and electronics held across advanced industrialized countries.[28]

6.2.2 Proposed GPTs

Given that the IR-3 is often known as the "information revolution," clusters of ICT innovations naturally serve as the most likely sources of GPT trajectories. Efforts to map this era's GPTs specifically highlight computers,[29] semiconductors,[30] and the internet.[31] Each of these technological domains exhibited great scope for improvement and complementarities with other technologies. Some scholars identify the general category of ICT, alongside electricity, as one of the two most important GPTs in history.[32]

Because advances in computers, semiconductors, and the internet were all closely connected, I group technological developments in these three domains under *computerization*, the process in which computers take over tasks such as the storage and management of information. The growing prevalence of software-intensive systems enabled computers to become more general-purpose. Advances in both semiconductors, which reduced costs for investments in IT equipment, and the internet, which connected computers in efficient networks, also fed into computerization.[33]

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[27] The real growth rate of the computer and electronics industry from 1987 to 2011 was 30 times higher than rate for the other manufacturing sectors in the U.S. Baily and Bosworth 2014, 5-6. See also US Congress 1998, 121.

[28] Rausch 1998.

[29] David 1990; Lipsey et al. 2005.

[30] Bresnahan and Trajtenberg 1995.

[31] Gordon 2005, 12, 22; Harris 1998; Lipsey et al. 2005.

[32] David 1990; Jovanovic and Rousseau 2005.

[33] The commercialization of the microprocessor, a type of integrated circuit, facilitated the spread of desktop computers across many functions and industries. In 1994 computer applications accounted for 52 percent of end-use demand for commercial sales of integrated circuits. Langlois and Steinmueller 1999, 53. The internet's spectacular expansion in the 1990s also extended networks of computing machines. Langlois 2013, 152.

6.2.3 Sources of LS and GPT trajectories

In sum, the IR-3's candidate leading sectors and GPTs all revolved around ICTs (Table 6.1). Other technical advances, in lasers, new sources of energy, and biotechnology also drew attention as possible key industries or sources of GPT trajectories. I do not trace developments in these technologies because their potential was largely unrealized, at least within the periodization of the IR-3.

Table 6.1: Key Sources of Technological Trajectories in the IR-3

Candidate Leading Sectors	Candidate GPTs
Computer industry	Computerization
Consumer electronics industry	
Semiconductor industry	

Though candidate leading sectors and GPTs converge on ICTs, they diverge on the key trajectories. The GPT perspective emphasizes the process by which firms transferred tasks and activities to computers. In contrast, LS accounts spotlight the growth of key industry verticals. For example, the consumer electronics industry fits the mold of previous candidate leading sectors like automobiles and cotton textiles, which were characterized by large size and fast growth rates but limited in their linkages to other industries. Taking stock of candidate leading sectors and GPTs merely functions as a preliminary filter. The rest of the chapter will further flesh out the differences between the LS- and GPT-based explanations of how these technologies affected the U.S.-Japan economic rivalry.

6.3 GPT vs. LS mechanism: The (non) spread of ICTs across Japan's economy

In both the IR-1 and IR-2 cases, a technological revolution sparked a shift in global economic leadership. The case study evidence helped determine whether theories based on GPT diffusion or LS product cycles better explained how technological advances set in motion an economic power transition. Disruptive breakthroughs also emerged in the IR-3, but an economic power transition never occurred. If the case analysis reveals that Japan dominated innovation in LSs or adoption of GPTs during this period, then the IR-3 case could provide disconfirmatory evidence against both mechanisms.

6.3.1 LS mechanism present: Japan dominates production of key ICTs

A bevy of evidence reveals that the LS mechanism was operative during the IR-3. From the mid-20th century through the 1980s, Japan captured a growing global market in new industries tied to major technological discoveries in semiconductors, consumer electronics, and computers. In dynamic random-access memory (DRAM) chips, one of the highest-volume verticals in the semiconductor industry, Japanese firms controlled 76 percent of the global market share.[34] By one U.S. federal interagency working group estimate, from 1980 to 1987 the U.S. lost the lead to Japan in more than 75 percent of critical semiconductor technologies.[35]

Japanese industry also gained competitive advantages in consumer electronics. From 1984 to 1990, U.S. firms lost global market share in 35 of 37 electronics categories, as Japanese firms took over the production of many electronic products.[36] Japan occupied the largest share of global production of color television and DVDs.[37] It was also the first to commercialize HDTV systems, a highly touted part of the consumer electronics market.[38]

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[34] Vogel 2013, 351; see also: Pollack 1982; Kitschelt 1991, 485-486.

[35] National Science Foundation 1987.

[36] Gover 1993, 61. See also Tyson 1993, 24.

[37] Japan produced over half of the world's color televisions by 1977. Freeman et al. 1982, 105; Japan produced 95 percent of the world's DVDs in 1997 (Vogel 2013, 351).

[38] Inman and Burton, Jr. 1990; OTA 1990, 27.

A similar trend held in computers, especially in computer hardware components like flat panel displays.[39] The U.S. trade balance in computers with Japan turned from a surplus in 1980 into a $6 billion deficit by 1988.[40]According to Yearbook of World Electronics Data, in 1990 Japan's share of global computer production eclipsed the U.S.'s share, which had previously led the world.[41]

Comparisons of LS growth rates also indicate that Japan was poised to overtake the U.S. as the economic leader. In an *International Organization* article published in 1990, Thompson posited that average annual growth rates in leading sectors across major economies heralded shifts in economic leadership. Over the 19th century Britain's growth rate in leading sectors peaked in the 1830s before flattening between 1860 and 1890, a period when the U.S. and Germany outstripped Britain in LS growth rates.[42] Crucially, the LS growth rate in Japan surpassed the U.S. equivalent from 1960 to 1990 (Figure 6.3).[43] Linking these historical trends, Thompson identified Japan as the U.S.'s main competitor for "systemic leadership."[44]

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[39] In 1997 Japan held 100 percent of the global market share in liquid crystal display panels, which are used for computer monitors. Vogel 2013, 351. In the early 1990s Japan also led in producing laptops and other portable computers, which were the fastest-growing markets at the time. Longworth 1992.

[40] Ferguson 1990.

[41] Kraemer and Dedrick 2001, 9.

[42] Thompson 1990, 221, 226.

[43] Thompson (1990, 230) calculates LS growth rates based on indicators for production in chemicals, steel, motor vehicles, electricity, electronics, and aerospace. The figure highlights electronics because I identify the industry as a candidate LS in this period. Thompson's (1990, 213) measure of electronics is production of semiconductors.

[44] Thompson 1990, 232.

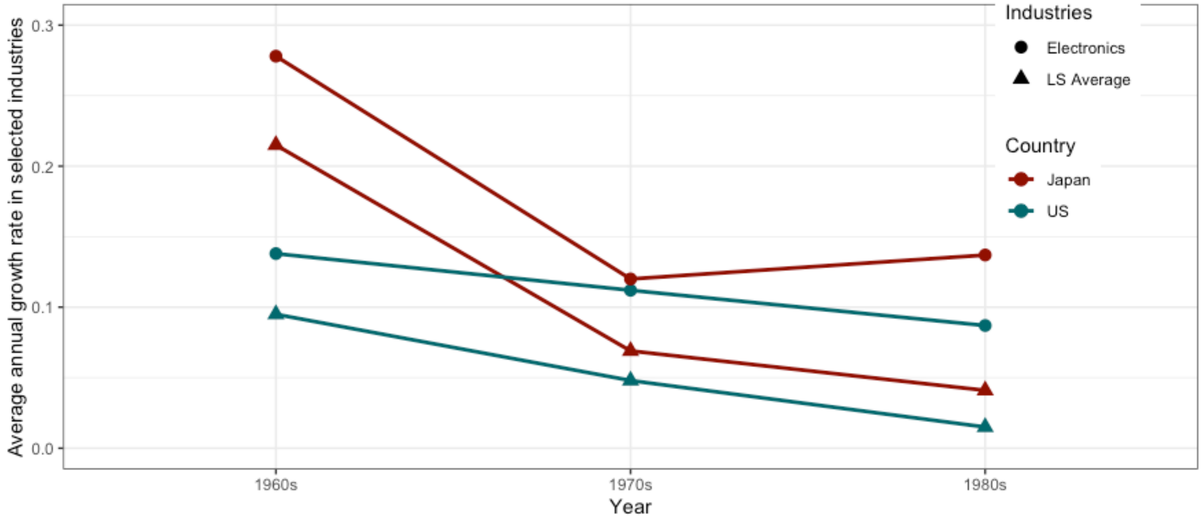

Figure 6.3: Japan Outpaces U.S. in LS Growth Rate, 1960-1990

Source: Thompson 1990.

Comprehensive assessments of Japan's relative industrial strength support the data on LS growth rates. A plethora of reports by U.S. government, academia, and industry warned of Japan's growing global market share and exports in key technologies. One review of six such reports, all published between 1987 and 1991, found a growing consensus that U.S. capabilities in many of these technologies were declining relative to Japan's.[45] A 1990 Department of Commerce report on trends in twelve emerging technologies, including supercomputers, advanced semiconductor devices, and digital imaging technology, projected that the U.S. would lag behind Japan in most of these technologies before 2000.[46] The 1989 MIT Commission on Industrial Productivity's *Made in America: Regaining America's Productive Edge* serves as a particularly useful barometer of Japan's position in leading sectors.[47] *Made in America* argued that the U.S. was losing out to Japan in eight manufacturing sectors, including three of the candidate leading sectors: consumer electronics, semiconductors, and computers. As Langlois concludes, "By the

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[45] Mogee 1991, 24-25.

[46] Department of Commerce 1990.

[47] Dertouzos et al. 1989. Organized by a group of leading MIT economists and political scientists, this massive effort drew from 550 interviews and visits to over 200 corporations across the U.S., Europe, and Japan, making it arguably the most influential of all the publications about America's industrial decline in this period. Inkster 1991, 159.

mid-1980s, by most accounts, America had 'lost' consumer electronics and was in imminent danger of losing semiconductors and computers."[48]

Some argued that Japan's advantage in these leading sectors was rooted in certain institutional arrangements. Japan's *keiretsu* system, organized around large, integrated business groups, regularly featured as the key institutional factor in its success in leading sectors. The MIT Commission's *Made in America* report, for instance, questioned whether the U.S. system of industrial organization could match up against "much stronger and better organized Japanese competition."[49] This aligned with a common narrative in the mid-1980s that "American firms should become more like Japanese firms."[50]

Others pointed to Japan's industrial policy, led by its Ministry of International Trade and Industry (MITI), as the key institutional competency that explained Japan's success in leading sectors. Many academics and policymakers advocated for the U.S. to imitate Japan's industrial policy approach, which they perceived as successful because of MITI's ability to strategically coordinate support for key technologies.[51] In contrast, the U.S.'s aversion to industrial policy and decentralized economic policymaking apparatus was allegedly detrimental to innovation in the IR-3's new technologies.

By the turn of the millennium, these arguments were no longer being put forward. Despite capturing key LS industries and rapidly catching up to the U.S. in the 1980s, Japan did not ultimately overtake the U.S. as the lead economy. Contrary to the expected outcome of the LS mechanism, Japan's control of critical sectors in semiconductors and consumer electronics did not snowball into sustained, strong economic growth. Given that the LS mechanism's

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[48] Langlois 2013, 159.
[49] Dertouzos et al. 1989, 20; cited in Langlois and Steinmueller 1999, 20.
[50] Langlois 2013, 159.
[51] The most influential account is Johnson 1982; see also Inman and Burton, Jr. 1990.

components were all in place, this non-outcome challenges the validity of the LS mechanism in the IR-3 case.

6.3.2 GPT mechanism absent: US leads Japan in ICT diffusion

Does evidence from the IR-3 also discredit the GPT mechanism? If the components of the GPT mechanism, like the LS mechanism, were present during this period, then the IR-3 case would also undermine the explanatory power of GPT diffusion theory. However, in contrast to its success in key leading sectors, Japan lagged in adopting computerized technologies. Thus, GPT diffusion theory would not expect Japan to have overtaken the U.S. in the IR-3.

To account for sustained U.S. economic leadership in the IR-3, this section traces the developments of the IR-3 in the U.S. and Japan across the three dimensions that differentiate GPT from LS trajectories. First, relative to the LS mechanism, the impact timeframes of the IR-3's technological breakthroughs are more elongated. Developments in ICTs did not spread to a wide range of economic applications until the 1990s. Second, though Japan excelled in the production of computers and electronics, it fell behind in the general pace of computerization across the economy. Lastly, Japan's advantages were concentrated in a narrow range of ICT-producing industries, whereas the U.S. benefited from broad-based productivity growth.

Timeframe of Impact

Computers traveled a gradual and slow road to widespread use. By the late 1980s, many observers bemoaned the computer revolution's failure to induce a surge of productivity growth. In 1987 the renowned economist Robert Solow distilled this "productivity paradox" in a famous quip: "We see the computers everywhere but in the productivity statistics."[52] A decade later, however, the growing adoption of information technology triggered a remarkable surge in U.S.

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[52] David 1990, 355.

productivity growth.[53] It took some time, but the American economy did eventually see the computers in the productivity statistics.

The advance of computerization, like past GPT trajectories, demanded a prolonged period of organizational adaptation and complementary innovations. In the 1960s, mainframe computers powered by integrated circuits marked the early use of computers for a limited range of commercial purposes, such as producing bank statements and managing airline reservations. Spurred by the introduction of the personal computer in the 1970s, the functionalities of computers greatly expanded.[54] With the internet's rise in the 1990s, new information and communication networks further spread computerization to different business models, such as e-commerce.[55] Alongside this stream of complementary technical advances, firms needed time to build up their computer capital stock and re-organize their business processes to match the needs of information technology.[56]

The landscape of U.S.-Japan technology competition looks very different when accounting for this elongated impact timeframe from the emergence of computerization to its widespread diffusion. Japan's control over key segments of ICT production in the 1970s and 1980s did not correspond to an advantage in GPT diffusion. A more patient outlook illuminates that the delayed impact of computerization aligns with when the U.S. extended its productivity lead over Japan. After 1995, while Japan's economic rise stalled, labor and total factor productivity grew rapidly for a decade in the U.S. The difference was that the U.S. benefited greatly from an ICT-driven productivity acceleration.[57]

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[53] Crafts 2002; Gordon 2016, 576; Oliner and Sichel 2000.

[54] Bruland and Mowery 2006, 369. Langlois (2013, 155) recaps, "By the early 1980s, a microcomputer (personal computer) costing $3,500 could do the work of a $10,000 stand-alone word processor, while at the same time keeping track of the books like a $100,000 minicomputer and amusing the kids with space aliens like a 25-cents-a-game arcade machine."

[55] Gordon 2016, 441-442.

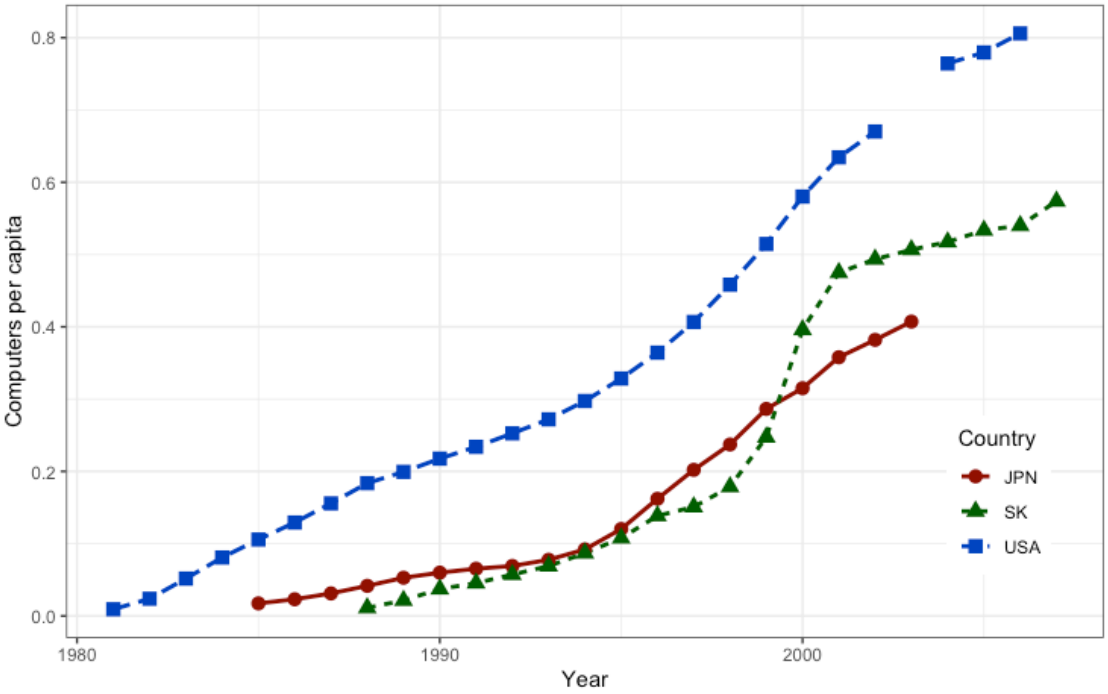
[56] Brynjolffson et al. 2017, 23-25.

[57] Fueki and Kawamoto 2009, 325; Crafts 2002.

Key Phase of Relative Advantage

If the GPT mechanism was operative for Japan's rise in the IR-3, Japan should have led the U.S. in computerization. While Japan continued to contest U.S. leadership in the production of certain computer architectures and devices,[58] it failed to keep up with the U.S. in the adoption of computers across industries. As Figure 6.4 reveals, the gap between the U.S.-Japan in computerization widened in the 1990s. In fact, South Korea, which lagged behind Japan in generating new innovations in computer systems, surpassed Japan in computer usage rate during the 1990s. Taken together, these indicators suggest that Japan's problem was with GPT diffusion, not innovation.

Figure 6.4: U.S.-Japan Computerization Gap Widens in 1990s



Source: Milner and Solstad 2021; Comin 2011, 381.

The pathway by which ICTs drove the U.S.-Japan productivity gap is particularly revealing. In ICT-*producing* sectors, Japan's TFP acceleration was similar to the U.S.'s trajectory;

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[58] Modelski and Thompson 1996, 222.

however, in sectors that intensively *used* IT, Japan's TFP growth lagged far behind that of its rival.[59] 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.[60] 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.[61]

Japan eventually adopted the GPT trajectory associated with ICT. Like all advanced economies at the frontier, Japan could draw from the same technology pool as America. Using a growth accounting framework that accounts for cyclical factors, Fukei and Kawamoto trace Japan's post-2000 resurgence in TFP growth to the extension of ICT revolution to a broader range of IT-using sectors.[62] By then, however, Japan was at least five years behind the U.S. in taking advantage of computerization.

Breadth of Growth

Alongside the dispersion of ICTs throughout the U.S. economy, the sources of productivity growth also spread out. In the U.S., spillovers from ICT advances, especially in services, contributed to economy-wide TFP growth. Industry-level patterns of TFP growth reveal that U.S. productivity growth became noticeably more broad-based after 1995, a trend that accelerated further after 2000.[63]

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[59] Fukao and Miyagawa 2007; Jorgenson and Motohashi 2005.

[60] Moe 2009, 219; Pilat et al. 2002, 60-61. The same comparison could be made between the U.S. and European countries, which were also able to keep pace with the U.S. with respect to productivity gains in IT-producing sectors but not in ICT-using sectors. Bloom et al. 2012.

[61] The contribution of ICT-using services to labor productivity growth, measured in percent annual average contribution to the value added to the total economy per person employed. From 1990-95 to 1996-2000, this figure declined from just over .6 percent to under .2 percent. For the U.S., the figure increased from just over .2 percent to above 1.2 percent. Pilat et al. 2002, 61.

[62] Fueki and Kawamoto 2009.

[63] Basu and Fernald 2007; Inklaar and Timmer 2007.

In contrast, Japan's advantages in the IR-3 were concentrated in a narrow range of sectors. After 1995, Japanese productivity growth remained localized, only transitioning to a more broad-based pattern after 2000.[64] Porter's exhaustive account of national competitiveness across leading economies describes Japan as a "study in contrasts," with some of the most internationally competitive industries found side by side with some of the most uncompetitive.[65] Caught up in the hype over Japan's success in some leading sectors, analysts "often unwittingly generalize[d] from the experience of particular successful industrial sectors and tend[ed] to ignore the sectors in which Japanese industry ha[d] been less successful."[66]

6.3.3 LS mechanism and "Wintelism"

Some international political economy scholars divide trends in U.S. competitiveness into a phase of relative decline in the leading sectors of the 1980s (autos, consumer electronics, steel, and parts of the semiconductor industry) and a period of resurgence in the new leading sector of the 1990s (software electronics).[67] This explanation for why Japan's LS advantage did not convert into an economic power transition could conceivably restore credibility to the LS mechanism. However, even this generous interpretation fails to capture the dynamics of the IR-3.[68]

Consider one prominent line of LS-based thinking that emphasizes U.S. advantages in adapting to "Wintelism," a particular type of industrial structure best suited for new advances in software electronics. Wintelism, a portmanteau of Windows and Intel, refers to the transformation of the computer industry from a vertically integrated oligopoly toward a horizontally segmented structure dominated by components providers with controlling

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[64] Wirkierman 2014.

[65] Porter 1990, 394.

[66] Kitschelt 1991, 454.

[67] Hart and Kim 2002. Software electronics refers to technologies related to computer architecture, such as computer software and semiconductor chip designs. Kim and Hart 2002, 144.

[68] The stricter interpretation is that Japan's dominance in the leading sectors of the 1980s, per the propositions of the LS mechanism, should have propelled it to economic leadership. The analysis from earlier sections, however, clearly shows that an economic power transition did not transpire.

architectural standards, such as Intel and Microsoft.[69] Compared to Japan, the U.S.'s institutional environment was more supportive of horizontal, specialized value-chains in software electronics. It is put forward that Japan's inability to adapt to the Wintelist industrial paradigm explains why it was unable to overtake the U.S. as the leading economy.[70]

The Wintelism argument falls prey to general issues with the LS mechanism.[71] Like LS accounts of Japan's advantage in semiconductors and consumer electronics in the 1980s, the Wintelism argument still places too much value on ICT-producing industries. It mistakenly equates dominance of global market shares in the software electronics industry with effectiveness in translating new advances in software electronics to economy-wide success. The pathway from new technologies to overall productivity growth involves much more than just the success of companies like Microsoft and Intel.

One of the critical features of GPT trajectories, relatively ignored in LS models, is the scope for coordination between the GPT sector (producers of software electronics in this case) and the wide range of application sectors. That a country is home to the largest firms in the GPT industry is no guarantee that it will secure the most overall economic benefits from the GPT. In fact, as the GPT diffuses more widely, the existence of large GPT producers may hinder coordination between the GPT and application sectors. Both Microsoft and Intel, for instance, often restricted sharing information about their technology roadmaps, which hindered complementary innovations and adoption of microelectronics in applications sectors such as automobiles. In fact, the emergence of innovators in complementary technologies, aided by

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[69] Borrus and Zysman 1997, 162; Hart and Kim 2002, 1.

[70] Borrus and Zysman 1997; Hart and Kim 2002; Kitschelt 1991.

[71] To be fair, many discussions of Wintelism were oriented toward the outcome of success in new industries, not an economic power transition. I am primarily critiquing extension of the Wintelism argument to the latter outcome.

technological and regulatory forces that limited the influence of dominant firms, was crucial to widening the GPT trajectory of computerization.[72]

Overall, hindsight is not kind to LS-based accounts of Japan's institutional advantages in the IR-3. While matching institutional competencies to particularly significant technological trajectories is a sound approach, the LS trajectory fails to capture how technological changes opened opportunities for an economic power transition. Japan's industrial structure and sectoral targeting policies reaped economic gains that were temporary and limited to specific industries.[73] To understand why the U.S. gained lasting and broad-based advantages from computerization, a different set of institutional complementarities must be explored.

6.4 Institutional complementarities: GPT skill infrastructure in the IR-3

The inadequacies of LS-based accounts suggest that studying GPT-institutional complementarities could be fruitful. Again, finding evidence that the U.S. advantage in ICT-related skill infrastructure functioned as a crucial factor in the U.S. economy's computerization is *not* strong support for the validity of the GPT mechanism in the IR-3 case. Strictly speaking, the causal mechanism I am investigating is one that connects significant technological breakthroughs to an economic power transition, not a non-occurrence of a transition. Still, if one considers the IR-3 case as a close competition between the U.S. and Japan for economic leadership that resulted in the U.S. establishing a clear lead, then this case could further lend credence to the GPT mechanism.

6.4.1 Skill gap in computer scientists

Applying GPT diffusion theory to this case, the most valuable type of ICT-related skill infrastructure is computer engineering talent. As is the case with the development of all

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[72] Bresnahan and Malerba 2002, 50-52; Bresnahan and Trajtenberg 1995, 102.

[73] Langlois and Steinmueller 1999, 20.

technologies, the spread of ICT advances requires radical innovators (e.g., the discoverers of zero-knowledge proofs) as well as engineers (e.g., the programmers who take the insights of zero-knowledge proofs and apply them in routine and standardized ways to facilitate secure data sharing). The latter group, however, is more important for understanding skill constraints on GPT trajectories among advanced economies. Both Japan and the U.S. had the capability to either innovate or quickly absorb innovations in ICT-producing industries, but they faced challenges in disseminating ICTs across the wide range of potential adopters.

If human capital trends in the IR-3 back up the GPT diffusion theory, then advantages in computer engineering talent should factor decisively in Japan's inability to keep pace with U.S. computerization. Sure enough, many studies attribute Japan's delayed adoption of computerization to its chronic shortages of software engineers.[74] While differences in data reporting conventions make it difficult to precisely quantify the U.S.-Japan gap in ICT talent, rough comparisons capture the overall trend. According to one comparison, in 1995 the combined number of ICT graduates and immigrants entering computer-related professions in the U.S. was 68 percent greater than annual inflows into the domestic ICT talent pool in Japan. By 2001, the U.S. ICT talent pool was increasing by nearly three times as much per year than Japan's.[75] Therefore, in the years when the U.S. advantage in ICT diffusion was most pertinent, from the mid-1990s through the early 2000s, the skill gap between the U.S. and Japan in computer and software engineering talent grew even wider.

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[74] Arora et al. 2013; Cole 2013; Cusumano 1991, 52, 130; Moe 2007, 221.

[75] Arora et al. 2013, 771. They estimate inflows into the ICT talent pool by first aggregating bachelors', masters', and Ph.D.-level graduates in IT software- and hardware-related disciplines. Then, for the U.S. ICT labor force, they include H1-B immigrants entering computer-related professions. For Japan, they assume that half of all foreign workers newly admitted to Japan as "researchers," "engineers," or "intracompany transferees" are employed in IT industries — a generous assumption that likely overestimates the annual inflows into Japan's ICT talent pool.

Crucially, comparisons of overall engineering talent cannot displace the particular importance of computer engineering skills. For example, in the late 1980s a popular myth that Japan's quantitative advantage in engineers accounted for its success in manufacturing industries gained momentum. It featured in two State of the Union addresses by President Ronald Reagan and was endorsed by the National Science Foundation.[76] But these estimates of engineering talent excluded computer specialists, systems analysts, and programmers — a population which roughly doubled from 1970 to 1982 in the U.S.[77] This substantial and growing group of professionals, which received technical training to do work that was largely engineering in nature, was crucial to the U.S. advantage in computerization.

6.4.2 U.S.'s institutional advantages in widening the base of ICT engineering skills

The U.S. economy was particularly effective at adapting to the computerization paradigm because of its institutional advantages in widening the skill base in ICTs. Specifically, the U.S. systematized these skills in computer science, the latest in a line of engineering disciplines that emerge in the wake of a GPT. By 2007, some 20 percent of software engineers in the U.S. possessed a graduate school degree, compared to just 10 percent in Japan.[78] The U.S. system of higher education was more well-suited to cultivating the necessary skill infrastructure for widespread computerization.[79]

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[76] Kinmonth 1991, 328.

[77] National Research Council 1985, 9.

[78] Nakata and Miyazaki, 2011, 100; cited in Cole 2013, 3.

[79] The U.S. also benefited from a system open to tapping foreign software talent. This intersects with my family's own story. My dad emigrated from China to the U.S. in 1995 to study computer science. He has worked as a software engineer for more than 20 years. Compared to Japan, the U.S. was better able to draw upon a foreign supply of ICT talent through high-skilled immigration and software offshoring. Crucially, imported talent widened the base of software engineering talent in America. Arora et al. (2013, 772) write, "Relatively few of these imported experts may have been software architects of the highest order, capable of undertaking transformative innovation. However, creating, testing, and implementing software for IT innovation requires both fundamental innovators and programmers undertaking more routine and standardized kinds of software engineering. America's ability to tap into an increasingly abundant (and increasingly foreign) supply of the latter may have raised the productivity of the former and enabled American firms to outpace their rivals."

U.S. universities successfully adapted to changes in the computerization trajectory. Led by pioneers like Stanford and the Association of Computing Machinery, U.S. institutions piloted new training programs in computer science. These adaptations paved a sustainable pathway for the transfer of technical know-how gained by experienced computer specialists and programmers to up-and-coming computer engineers.[80] From 1979 to 1989, the number of undergraduate computer science degrees awarded annually in the U.S. grew by more than a factor of three. The number of individuals who held doctorates and taught computer science also more than tripled over the same period.[81] In 2011 computer science became the most popular choice of major for Stanford undergraduates.[82] The recognition of computer science as an independent discipline, as evidenced by the early and rapid growth of computer science departments in the U.S, helped to systematize the skills necessary for the spread of computerization.[83]

Japanese universities, on the other hand, were slow to adapt their curriculum to the new field of computer science. In both 1997 and 2007, the Information Processing Society of Japan modeled its computing curriculum revisions on American efforts that had happened six years earlier. The University of Tokyo, Japan's leading university, did not establish a separate department of computer science until 1991, which was 26 years later than Stanford.[84] Overly centralized governance of universities inhibited the development of computer science as an independent discipline in Japan.[85] "The organizational and disciplinary flexibility of U.S.

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[80] Vona and Consoli 2014, 1404.

[81] National Research Council 1992, 47.

[82] Meyer 2012.

[83] Steinmueller 1996, 42. It is important to note that the U.S. military played a key role in cultivating the computer science discipline in its early years. Beginning in the 1960s DARPA helped create centers of excellence in computer science, which disseminated computer science skills to other research universities and commercial markets. National Research Council 1999, 221; Newell 1984. This is discussed in further detail in the alternative explanations section.

[84] Cole 2013, 8.

[85] Cole 2013, 9-10; Kitschelt 1991, 482.

universities in computer science has not been matched in any of the competing economies," Hart and Kim conclude.[86]

In both the IR-1 and IR-2 cases, the eventual technological leader cultivated a GPT skill infrastructure that allowed for dense connections between educational institutions and industry. This was also true for the U.S. in the IR-3 case. The U.S.'s sustained economic leadership benefited from extremely close partnerships between universities and industry in computer science.[87] This was rooted in the autonomy of state governments to support linkages between public universities and industry demands for research.[88] Closer university-industry linkages in the U.S. system of higher education, compared to arrangements in Japan or Europe, provided a much "thicker basis" for skill adjustments to the trajectory of computerizations.[89]

Japan maintained a very different skill infrastructure for computerization. Centralized control of universities, exercised through the Japanese Ministry of Education, Sport and Culture, hampered cooperative networks between universities and industry.[90] Bureaucratic rivalries prevented universities from finding alternative sources of funding, which limited reforms such as partnerships between new departments of information science and corporate labs where much of the computing talent was concentrated. Japan's overall budget level for university facilities in 1992 remained the same as it was in 1975. Additional government funds went, instead, to independent centers of excellence, which impoverished the training of Japan's basic researchers and technicians.[91]

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[86] Hart and Kim 2002, 10.
[87] Moe 2007, 221.
[88] Drezner 2001, 22-23.
[89] Hart and Kim 2002, 10.
[90] Drezner 2001, 20-22.
[91] Anderson and Myers 1992, 565, 569.

6.5 Alternative factors

How do alternative explanations perform in this case? Threat-based theories struggle to account for differences in the U.S.'s and Japan's technological performance in this period. Under his creative insecurity framework, Taylor holds up both Japan and the U.S. as success stories during the IR-3 period, arguing that they owed their technological success, in part, to the galvanizing effects of a threatening international environment.[92] Japan's persistent "cult of vulnerability," was the driving force behind its remarkable industrialization; similarly, "the secret to American innovation" was its "national security state," which developed amidst the geopolitical environment of the Cold War.[93] Unfortunately, this does not help explain differences in technological outcomes between the U.S. and Japan, namely why the U.S. was more successful in ICTs than Japan.

One threat-based alternative explanation, which does claim to explain U.S. success in ICTs, argues that military procurement was essential to the computerization of American industries. As was the case with its influence on the American System of Manufacture in the IR-2, the U.S. military undoubtedly advanced the development of computers and semiconductors. Military procurement provided the demand for initial investments in computers and semiconductors. In the 1940s and 1950s the U.S. military was the key patron behind computing breakthroughs.[94] Assured by large military procurements, innovative firms undertook risky, fundamental research which produced spillovers to many other industries. For instance, the first all-purpose electronic digital computer, the University of Pennsylvania's Electronic Numerical Integrator and Calculator (ENIAC), was developed during World War II. The ENIAC was

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[92] Taylor 2016, 110.
[93] Taylor 2016, 357n10.
[94] Ruttan 2006; Weiss 2014, 78-82.

supported by funding from the Army Ballistics Research Laboratory, and the first program run on the computer was a simulation of the ignition of the hydrogen bomb.[95]

Could other entities, in place of the military, have provided this initial, large demand for ICTs? Other large demanders, including Bell Labs and IBM, did also fund fundamental breakthroughs in ICTs. According to Bresnahan and Trajtenberg, it was "only a coincidence" that U.S. government demand played such a pivotal role in semiconductor development.[96] Others argue that while commercial advances in semiconductors and computers would likely still have occurred absent the impetus of military funding, they would have come at a substantial delay.[97]

Clearly grasping the GPT trajectories is crucial to resolving this debate. Those who emphasize the importance of military procurement often hold up the importance of first-mover advantages in the American computer industry.[98] However, decades after the military had helped develop the first computers and transistors, Japan had cornered the market in many of the related industries. The critical period is not a GPT's incubation but its dissemination. By 1960, the start of the IR-3 period, ICT development in the U.S. was already much less reliant on military support. In 1955, the demand for Bell's transistors from two large telephone networks alone was nearly ten times more than from all military projects.[99] In fact, as the commercial sector increasingly drove momentum in ICTs, military involvement arguably hindered continued advances in the commercial sector, as there was tension between the different technical cultures.[100]

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[95] Ruttan 2006, 92.
[96] Bresnahan and Trajtenberg 1995, 95.
[97] Edwards 1996, 60-65; Flamm 1988, 251.
[98] Flamm 1988.
[99] Misa 1985, 177.
[100] See Alic et al. 1992 for a review of the limitations to technology transfer from the military to commercial domain. In Misa's (1985) account of the development of semiconductors, he acknowledges the U.S. military's role as an "institutional entrepreneur" (268), but he also notes that military contracting and procurement compromised efficient commercial development of semiconductors later on in the technology's life cycle (277-280, 286-7).

The varieties-of-capitalism (VoC) approach provides another possible explanation for why the U.S. economy benefited more than Japan's from the innovations of the IR-3.[101] According to the VoC framework, firms in coordinated market economies (CMEs) provide industry-specific training that is more conducive to incremental innovation, whereas worker training in more general skills in liberal market economies (LMEs) proves more favorable for radical innovations. VoC scholars point to some evidence from the international pattern of innovation during the IR-3 that supports these expectations. Based on patent data from 1983-84 and 1993-94, Hall and Soskice find that Germany, a CME, specialized in technology classes characterized by incremental innovation, whereas the United States, a LME, specialized in domains characterized by radical innovation.[102] Therefore, the VoC perspective expects that Japan, a CME like Germany, was unable to keep up with the U.S. in the IR-3 because high-tech sectors such as computer software and biotechnology demanded radical innovations.[103]

This VoC-derived explanation provides an incomplete account of the IR-3 case. First, comprehensive empirical investigations into the innovative performance of CMEs and LMEs, especially the success of Japan as a radical innovator, undermine the explanatory power of VoC theory for the IR-3 period. Hall and Soskice's initial analysis was based on four years of data on patent counts from only two countries, the U.S. and Germany. Taylor's more extensive analysis, which covered 36 years (1963-99) of patent counts and forward citations for all LME and CME countries, found that that the predictions of VoC theory are not supported by the empirical

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[101] This represents a favorable distillation of the VoC theory's predictions for the IR-3. As described in section 6.3, some analysts argued that, in order to meet the challenge of Japanese high-tech competition, American firms needed to imitate parts of Japan's CME structure, including its keiretsu system of organization. That the U.S. sustained its economic lead without reforming its system of industrial governance is disconfirmatory evidence for this line of thinking. Others dispute whether the U.S. was an exemplar LME in this period (Weiss 2014, 195-197) as well as Japan's CME status. Witt and Jackson 2016, 794.

[102] Hall and Soskice 2001, 41-44.

[103] Hall and Soskice 2001, 35.

data.[104] In fact, contrary to the expectations of the VoC explanation, Japan was a leader in radical innovation, ranking second only to the U.S. in patent counts weighted by forward citations, which are a strong proxy for the radicalness of innovations.[105]

Second, VoC theory does not make distinctions between different types of general skills, which varied in their significance to national success in the IR-3. Regarding general training in terms of foundational schooling, Japan was making substantial improvements in average years of schooling, enrollment ratio, and access to higher education.[106] GPT diffusion theory specifies the key general skills as those that best suited the advance of computerization. Consistent with these expectations, the case study evidence points to the U.S.-Japan gap in software engineering, a set of general skills that permeated sectoral boundaries, as the crucial factor in the U.S.'s success with widespread computerization.

6.6 Summary

Through much of the late 20th century, it was only a matter of time until Japan achieved economic preeminence — at least in the eyes of many analysts and scholars. Invoking the assumptions of the LS mechanism, they expected that this economic power transition would be brought about by Japan's advantages in new sectors such as consumer electronics, semiconductor components, and computer hardware. Paul Kennedy's *The Rise and Fall of the Great Powers*, the most influential of these accounts, highlighted Japan's surge in the global market share of these high-tech industries.[107]

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[104] Taylor 2004.

[105] Taylor 2004, 621-623. Indeed, Japan introduced many radical innovations in video games and digital technologies, according to one study that views changes in the meaning of a product as a form of radical innovation. Norman and Verganti 2014.

[106] Freeman et al. 1982, 188, 194; Godo 2010.

[107] Kennedy 1987, 462-463, 525.

Today, after Japan's decade-long slowdown in productivity growth, there is virtually no discussion of it overtaking the U.S. as the leading economic power. Looking back, it appears that history has vindicated past critics who labeled the claims of Japan's imminent ascension to technological hegemony as "impressionistic,"[108] as well as the retrospective analyses that called out such projections for being "premature."[109] This chapter's conclusions offer a different interpretation. It is not that the prognoses of LS-based accounts were too early or too subjective. The real issue is that they were based on faulty assumptions about the pathway by which technological advances translate into economic power transitions. Indeed, the IR-3 case provides strong negative evidence against the LS mechanism, revealing that the expected outcome of an economic power transition failed to materialize in part because of the U.S.'s advantage in GPT diffusion. The relative success of the U.S. in diffusing the trajectory of computerization across many ICT-using sectors, in line with GPT diffusion theory, was due to institutional adaptations to widen the skill base in computer engineering. Thus, the IR-3 case evidence shows that the U.S.'s advantage in GPT diffusion accounts for why the economic power transition expected by LS accounts failed to transpire.

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[108] Huntington 1988, 77.
[109] Drezner 2001, 19.

Chapter 7
U.S.-China competition in AI and the Fourth Industrial Revolution

On July 26, 2018, Chinese President Xi Jinping delivered a speech at the BRICS Summit, convened on the theme: "BRICS in Africa: Collaboration for Inclusive Growth and Shared Prosperity in the Fourth Industrial Revolution."[1] Underscoring the theme's significance, Xi remarked, "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."[2] After citing recent breakthroughs in cutting-edge technologies like artificial intelligence, Xi argued, "Today, we are experiencing a larger and deeper round of technological revolution and industrial transformation."[3]

Two months after Xi's speech, a commentary posted on the website of the Central Party School's publication *Study Times* expanded on the implications of the fourth industrial revolution for the international balance of power, described as "great changes unseen in a century."[4] The commentary recounted familiar cases of industrial revolutions and shifts in productivity leadership: "Britain seized the opportunity of the first industrial revolution and established a world-leading productivity advantage...After the second industrial revolution, the United States

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[1] Klaus Schwab, founder and executive chairman of the World Economic Forum, first popularized the term "Fourth Industrial Revolution." Schwab 2017.

[2] Qiushi 2018; cited in Doshi 2020, 3.

[3] Qiushi 2018.

[4] Xi Jinping has also employed the phrase "great changes unseen in a century" [百年未有之大变局] to describe the current international situation.

seized the dominance of advanced productivity from Britain."[5] Along with the third industrial revolution, which the *Study Times* commentary also discusses as a boost to U.S. economic leadership, these cases match up with the three covered in this dissertation.

This broad frame of power transition by way of technological revolution also resonates with U.S. leadership. The Obama White House's 2016 report on "Artificial Intelligence, Automation, and the Economy" compares the productivity-boosting effects of new advances in AI to previous industrial revolutions.[6] At the SXSW conference in 2019, Congressman Will Hurd said, "We are in a race with China, period, end of story. They want to be the leader in 10 technologies that are going to be the leaders of the fourth industrial revolution by 2043."[7]

While leading thinkers and policymakers in the U.S. and China clearly both draw connections from past technology-driven power transitions to grapple with the present landscape, this chapter argues that they have drawn the wrong ones. Specifically, the leading-sector perspective holds undue influence over thinking about the relationship between technological change and the possibility of a U.S.-China power transition. Yet, careful analysis of historical cases has revealed that the GPT mechanism provides a better model for how industrial revolutions generate the potential for a power transition. If applied to the evolving U.S.-China power relationship, GPT diffusion theory provides different predictions about how the technological breakthroughs of today will affect the U.S.-China power balance, as well as the optimal strategies for the U.S. and China to pursue.

The rest of this chapter sketches out how, if history rhymes, the technological advances of the Fourth Industrial Revolution (IR-4) will affect the U.S.-China power balance. Section 7.1

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[5] Li 2018; cited in Doshi 2020, 3.

[6] Executive Office of the President 2016, 8.

[7] Smalera 2019. The 2043 date may be a reference to the centenary of Mao Zedong's ascendance to leadership of the Chinese Communist Party. The more commonly referenced benchmark year is 2049, which is the centennial of the PRC's founding.

analyzes the current productivity gap that exists between the U.S. and China, with particular attention to concerns that China's relatively low productivity vis-a-vis the U.S. invalidates analogies to previous rising powers. Section 7.2 reviews the array of technologies that have drawn consideration as the next GPT or next LS. Acknowledging the speculative nature of technological forecasting, I narrow my focus to developments in the AI field because of its unique potential both to revitalize the growth of ICT industries, viewed as the source of the next LS, and transform the development trajectories for all other potential GPTs. Section 7.3 compares the implications of the LS and GPT mechanism for how advances in AI will affect a possible U.S.-China economic power transition. In contrast to prevailing opinion, which hews closely to the LS template, GPT diffusion theory suggests that the effects of AI on China's rise will materialize through the widespread adoption of AI across many sectors in a decades-long process. In section 7.4, I describe the institutional complements for supplying AI skills that will determine whether the U.S. or China will more successfully benefit from AI advances. Section 7.5 spells out how the implications of GPT diffusion theory for the U.S.-China power balance differ from those derived from alternative explanations. Section 7.6 concludes.

7.1 Power transition in progress?

Over the past four decades, there has been no greater shift in the global economic balance than China's economic rise. China is either already the world's largest economy, if measured by purchasing power parity (PPP) exchange rates,[8] or is projected to soon overtake the United States, based on nominal exchange rates.[9] China's impressive growth in economic size has led many to proclaim that the era of U.S. hegemony is over.[10]

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[8] According to data from the International Monetary Fund, China became the world's largest economy in 2014 on a PPP basis. Morrison 2019, 10.

[9] The Japan Center for Economic Research projects that China will overtake the U.S. in nominal GDP in 2029. Ueharal and Tanaka 2020.

[10] Beckley (2018a, 42n144) lists some of the most prominent accounts.

Economic size puts China in contention with the U.S. as a great power competitor, but China's economic efficiency will determine whether a power transition will occur. Countries like Switzerland outpace the U.S. on some measures of economic efficiency, but they lack the economic size to contend. Other rising powers, such as India, boast large economies but lag far behind in economic efficiency. Beckley concludes "*If* the United States faces a peer competitor in the twenty-first century...it will surely be China."[11] For this conditional to be true, China's productivity growth is critical.[12] After all, this is not the first time in history that China has had the world's largest economy. It held that distinction when Britain rose to economic preeminence on the back of the First Industrial Revolution. If China wants to rewrite that historical episode, it will need to leverage the GPT diffusion mechanism to sustain long-term economic growth via productivity improvements.

Where does China currently stand in comparison to the productivity frontier? Based on 2018 figures, China's real GDP per capita is about 30 percent that of the U.S. number.[13] From 2000 to 2017, China's total factor productivity (TFP) never surpassed 43 percent of that in the United States (Figure 7.1).[14] In 2015, labor productivity in China remained at only 30 percent of that in the United States, though this figure has doubled over the past two decades.[15]

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[11] Beckley 2018b, 32. Emphasis mine. See also Brooks and Wohlforth 2016, 32-33.

[12] Beckley 2018a, 43-44, 48.

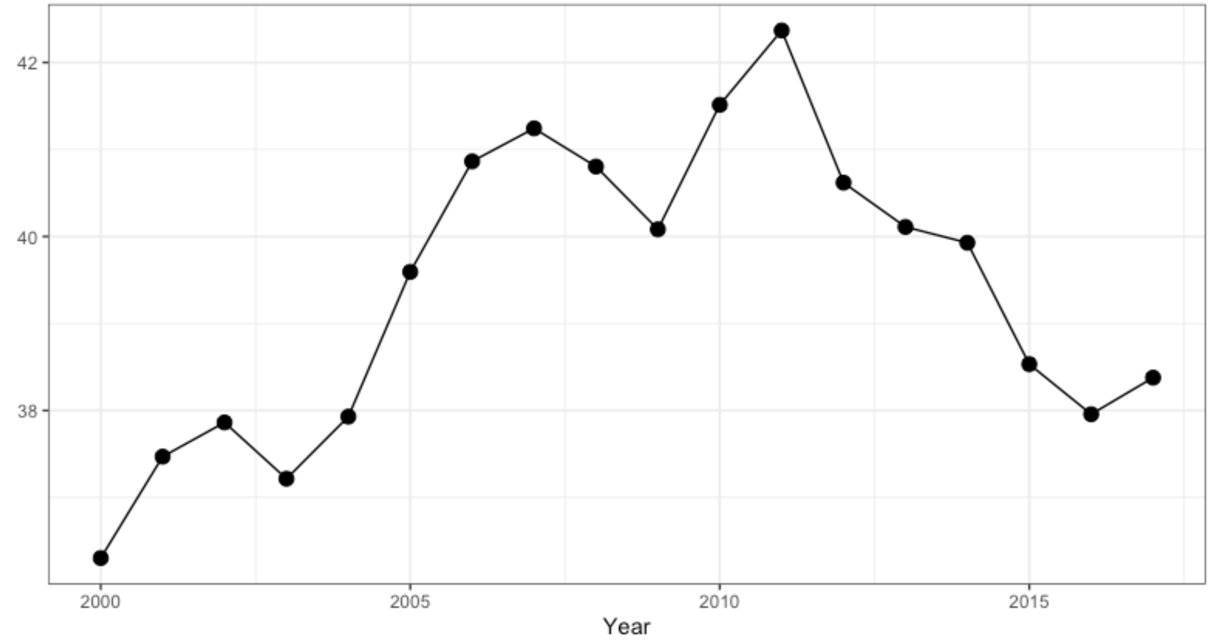
[13] Real GDP per capita at 2010 purchasing power parities. Guillemette and Turner 2018, 19.

[14] Data from Penn World Table version 9.1, available for download at http://www.ggdc.net/pwt. Feenstra et al. 2015.

[15] International Monetary Fund 2019, 13.

Figure 7.1: U.S.-China Productivity Gap, 2000-2017

China's TFP as percentage of U.S. figure



Source: Penn World Table version 9.1, Feenstra et al. 2015

These numbers suggest that China sits much farther from the productivity frontier than past rising powers. If the U.S.-China power relationship is fundamentally different from those in previous eras, the relevance of conclusions from previous cases could be limited.[16] For instance, in the early years of the IR-1, Britain was only slightly behind the Netherlands, the productivity leader at the time. The UK's GDP per capita was 80 percent of Dutch GDP per capita in 1800.[17] Similarly, at the beginning of the IR-2, the U.S. trailed Britain in productivity by a small margin. In 1870, labor productivity and TFP in the U.S. were 90 percent and 95 percent, respectively, of labor productivity and TFP in Britain.[18] During the 1870s, average GDP per capita in the UK was about 15 percent higher than average GDP per capita in the states.[19]

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[16] Relatedly, Brooks and Wohlforth 2016 (9, 32-36) argue that China, unlike past rising powers, is at a "much lower technological level" relative to the leading state.

[17] Bolt and van Zanden 2014, 637. Other productivity comparisons are for the year that marks the start of the case (1870 for the IR-2, 1960 for the IR-3), but this was the earliest available data.

[18] Broadberry 2006, 109-110.

[19] Calculations based on Maddison Project Database, version 2020. Bolt and van Zanden 2020.

Still, that China *could* surpass the U.S. in productivity leadership is not outside the realm of possibility.[20] The IR-3 case is a better comparison point for the current productivity gap between the U.S. and China. In 1960, the start of the IR-3 case, Japanese GDP per capita was 35.2 percent that of the U.S.[21] At the time, Japan's TFP was 63 percent of the U.S.'s TFP, and Japan's labor productivity was only 23 percent of the U.S.'s labor productivity, a lower proportion than the China-U.S. ratio at present.[22] Despite the initial chasm, the TFP gap between the U.S. and Japan narrowed to only 5 percent in 1991.[23]

Indeed, productivity growth is crucial for China to sustain its economic rise in the long-term. For the 1978-2007 period, Xiaodong Zhu decomposed the sources of China's economic growth into labor deepening, human capital, capital deepening, and total factor productivity growth. He found that growth in TFP accounted for 78 percent of China's growth in GDP per capita.[24] Improvements in TFP will take on even more responsibility for driving China's economic growth in the future, as other drivers of China's growth miracle, including urbanization and demographic dividends, fade.[25]

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[20] According to most projections, this is not a likely scenario. Per the OECD's long-term outlook for the world economy in 2060, China's real GDP per capita will only reach half that of the United States. Its labor efficiency in 2060 will "remain well below those of most OECD countries." Guillemette and Tuner 2018, 18. The OECD"s conception of labor efficiency is closely related to total factor productivity. Still, even though China's overtaking of the U.S. in productivity leadership is not likely, it is still valuable to better understand the pathways by which this transition could occur.

[21] Broadberry et al. 2015.

[22] Jorgenson et al. 2018, 18. By 1970, these percentages were 77 and 44 percent in TFP and labor productivity, respectively.

[23] Jorgenson et al. 2018, 18. This was before Japan's productivity growth slowed in the 1990s. Others compare China to the Soviet Union. Citing the Soviet Union's per capita GDP in 1960, which was 36 percent of the U.S. number, they describe the Soviet Union as "richer vis-à-vis the United States during the peak of the Cold War than China is today." (Brooks and Wohlforth 2016, 42n109). However, over the next couple decades, the Soviet Union, unlike Japan, was unable to sustain its productivity growth (Trachtenberg 2018).

[24] Zhu 2012, 108. Applying this approach to the growth of China's GDP per capita relative to the U.S., Zhu also found that the shrinking of the U.S.-China GDP per capita gap was "mainly driven by the growth of China's relative total factor productivity" (Zhu 2012, 120).

[25] Naughton 2018, 178.

Whether China can sustain productivity growth in the coming decades will depend on its ability to take advantage of technological advances. Plagued by inefficient infrastructure outlays, China's aggregate TFP growth has declined from 2.8 percent in the decade before the global financial crisis to .7 percent in the decade after (2009-2018).[26] If calculated using alternative estimates of GDP growth,[27] China's TFP growth was actually negative from 2010 to 2017, averaging -.5 percent.[28] This productivity slowdown is not unique to China. Even before the 2008 global financial crisis, there was a slowdown in TFP growth among advanced economies due to the waning effect of the information and communications technologies (ICT) boom.[29] How the U.S. and China fare in the next "boom" associated with a GPT will be central to the prospects of an economic power transition.

7.2 Key technological changes in the Fourth Industrial Revolution

ICTs, the key technological drivers of the IR-3, are still at the heart of the IR-4. There seems to be a wide-ranging consensus, from visionaries and daydreamers to economists and technology forecasters, that AI will breathe new life into the spread of digitization. The World Economic Forum describes AI as the "engine that drives the Fourth Industrial Revolution."[30] In his bestselling book titled *AI Superpowers: China, Silicon Valley, and the New World Order,* the former head of Google China, Kai-Fu Lee, boldly claims, "The AI revolution will be on the scale of the

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[26] Brandt et al. 2020, 7.

[27] Many of the statistics on China's economic growth draw from Chinese government figures, which some argue should be interpreted differently than statistics for other large economies. See Pettis 2017. For critiques of GDP indicators to measure the economic gap between the U.S. and China, see Scissors 2016. Chinese economic data should be used with caution, but they can still provide support for general trends. Key elements of China's economic growth, such as fiscal revenues and exports, have been fully verified by independent sources (Naughton 2018, 157-158). Even if China's GDP growth rates were adjusted downward by 1 to 2 percentage points per year — the maximum plausible adjustment — China's average growth rate over the past three decades "would still be the most sustained period of rapid economic growth in human history" (Naughton 2018, 159).

[28] The Conference Board 2020, 13. Beckley 2018b, 44.

[29] Foda 2016.

[30] Lee 2018, 4.

Industrial Revolution but probably larger and definitely faster."[31] In the following sections, I position AI as a potential leading sector and GPT in the 4-IR.

7.2.1 Candidate leading sectors

Forecasts of future waves of technological change by LS accounts confirm that ICTs will continue to drive economic transformation. As Table 7.1 shows, while these forecasts also highlight other candidate leading sectors, including new sources of energy and biotechnology, they converge on ICTs as the leading sector of the next wave of technological disruption. Likewise, in their analysis of the U.S.-China technological rivalry in the 21st century, Kennedy and Lim describe ICTs as "widely regarded as the current leading sector."[32]

Table 7.1: Proposed Leading Sectors in the 6th Kondratieff Wave, ~2020s to 2050s

	Goldstein 1988, 353	Thompson 1990, 232	Modelski and Thompson 1996, 216-22	Rennstich 2002, 159-161	Akaev and Pantin 2013, 868
ICT	**x**	**x**	**x**	**x**	**x**
Biotechnology	x	x			x
New sources of energy		x			x
Robotics		x			
Lasers		x			

Source: Compiled from lists in Modelski and Thompson 1996, 213-22; Rennstich 2002, 157

To evaluate the applicability of the LS mechanism to the U.S.-China case, I focus on AI because of its capacity to open up new trajectories in ICTs. Could advances in AI reset which countries control key segments of ICT industries, such as e-commerce and telecommunications?

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[31] Lee 2018, 151.

[32] Kennedy and Lim 2018, 561.

Chinese technology planners certainly think so, as China's national AI development plan outlines its ambition to become the world's leading center of innovation in AI by 2030.[33] Descriptions of China's AI strategy as aimed toward seizing "the commanding heights" of next-generation technologies reflect the belief that competition in AI will be over global market shares in strategic sectors.[34]

7.2.2 Candidate GPTs

GPT forecasts identify some technological trends in the current era that overlap with candidate leading sectors. Writing in 2001, Ruttan predicted that biotechnology, which also features prominently in LS accounts, will be the most important GPT in the early 21st century.[35] An empirical test, leveraging patent citation trends, also verifies the GPT potential of biotechnology.[36] Robotics, another candidate GPT, could underpin "the next production system" that will boost economy-wide productivity, succeeding the previous one driven by information technology.[37] Empirical estimates confirm the potential of robots as engines of growth. According to one study of seventeen countries from 1993 to 2007, the increased use of industrial robots accounted for 15% of economy-wide productivity growth. Based on this figure, the study's authors conclude that the contributions of robots to productivity growth is comparable to those of GPTs in previous historical periods, such as the steam engine.[38]

Among the possible GPTs that could significantly impact a U.S.-China economic power transition, AI has taken center stage. Like the literature on leading sectors, the GPT literature also converges on ICTs as a continued driver of technological revolution. Carlaw, Lipsey, and Webb,

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[33] Ding 2018.
[34] Araya 2019; Webster et al. 2017.
[35] Ruttan 2001, 368-422.
[36] Feldman and Yoon 2012.
[37] Atkinson 2019. Thurbon and Weiss (2019, 2) describe it as "a general purpose technology, with key applications in industrial, personal, and professional service spheres."
[38] Graetz and Michaels 2018, 765-766.

three pioneers of GPT-based analysis, identify programmable computing networks as the basic GPT that is driving the modern ICT revolution.[39] Specifically, advances in AI could transform and accelerate the ICT revolution. Recent breakthroughs in deep learning have improved the ability of machines to learn from data in fundamental ways that can apply across hundreds of domains, including medicine, transportation, and other candidate GPTs like biotechnology and robotics. This is why AI is often called the "new electricity" — a comparison to the prototypical GPT.[40] Economists view it as the "next GPT"[41] and "the most important general-purpose technology of our era."[42]

Several studies have found evidence for a GPT trajectory in AI. One study, using a novel dataset of preprint papers, finds that articles on deep learning conform with a GPT trajectory.[43] Using patent data from 2005-2010 to construct a three-dimensional indicator for the GPT-ness of a technology, Petralia ranks technological classes based on their GPT potential.[44] His analysis finds that image analysis, a field that is closely tied to recent advances in deep learning and AI, ranks among the top technological classes in terms of GPT-ness.[45]

7.2.3 A note on technological forecasting

Without the benefits of hindsight for identifying key drivers of previous technological revolutions, predicting technological futures in the Fourth Industrial Revolution is necessarily a

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[39] Carlaw et al. 2007.

[40] This comparison was popularized by Andrew Ng in a speech at the Stanford Graduate School of Business. As of April 28, 2020, a search for the exact phrase "AI is the new electricity" returns about 36,600 results. Kevin Kelly, founding editor of Wired, once said, "Everything that we formerly electrified we will now cognitize…business plans of the next 10,000 startups are easy to forecast: Take X and add AI." Kelly 2014.

[41] Trajtenberg 2018

[42] Brynjolfsson and McAfee 2017

[43] Klinger et al. 2021.

[44] Petralia 2020, 7.

The three dimensions correspond to the three characteristics of GPTs: scope for improvement, the variety of applications to products and processes, and complementarity with existing and new technologies. These are measured by patenting growth rates, a text-mining algorithm that looks for patterns in technology-specific vocabulary, and co-occurrence of claims in patents. Petralia 2020, 9-10.

[45] Petralia 2020, 7. Image analysis ranks 5th. The technological classes that rank higher, from highest to lowest, are: television, telecommunications, radiant energy, illumination, and electrical communications.

more speculative exercise. It is difficult to find true promise amidst the hype. The task is made harder by the fact that even experts and technological forecasting bodies regularly miss the next big thing. In 1945, a team led by Dr. Theodore von Kármán, an eminent aerospace engineer, published *Toward New Horizons, a* 32-volume text about the future of aviation. The study failed to foresee major new horizons such as the first human in space, ICBMs, and solid-state electronics — all of which emerged within fifteen years.[46] In the early 1990s, the U.S. Army conducted a technology forecast assessment to identify the technologies most likely to transform ground warfare in the next century. When the forecast was evaluated in 2008 by the Army's senior scientists and engineers, it graded out at a "C." Among its most significant misses was the development of the internet.[47]

I am no Cassandra. It is very possible that if I was writing this book in 2000, this chapter would focus on the promise of nanotechnology, not AI. At that time, President Bill Clinton had just unveiled the National Nanotechnology Initiative. In a 2003 speech, Philip J. Bond, the Under Secretary for Technology at the Department of Commerce at the time, declared, "[N]ano's potential rises to near Biblical proportions. It is not inconceivable that these technologies could eventually achieve the truly miraculous: enabling the blind to see, the lame to walk, and the deaf to hear; curing AIDS, cancer, diabetes and other afflictions; ending hunger; and even supplementing the power of our minds, enabling us to think great thoughts, create new knowledge, and gain new insights."[48] Decades later, there is a collective exhaustion of the hype surrounding the field, a phenomenon one scientists labeled "nanofatigue."[49]

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[46] Hellmeier 1976, 6.
[47] Lyons et al. 2008.
[48] Quoted in Kimbrell 2008.
[49] Maynard 2016.

One lesson that stands out from mapping the technological landscape in past industrial revolutions is that the most significant GPTs of an era often come from humble origins. In the IR-2, new innovations in electricity and chemicals garnered the most attention, but it was advances in machine tools, first introduced decades earlier, that actually powered America's rise. Taking a page from Edgerton's work, "old" GPTs like electricity could still shock the world.[50] Today, there is still a lot of potential for expanded industrial electrification, which could have a major impact on productivity.[51] Similarly, high-capacity battery technologies could transform productivity on a broad scale.[52] Interestingly, patent data also demonstrates the continued importance of electrical technologies. Among the top ten GPT candidates, ranked by Petralia's indicator of GPT-ness, there were as many technological classes in the Electrical & Electronic (E&E) category as there were in the Computers & Communications (C&C) category.[53]

For my purposes, it is reassuring that this "Shock of the Old" phenomenon also applies to the case of AI. In the U.S., the legitimization of AI as an important field of research dates back to the 1960s.[54] Thus, though the rest of the chapter takes AI as the most important GPT for the near future, it does so with a humble mindset, acknowledging that looking forward to the future often starts with digging deeper into the past.

7.3 GPT vs. LS mechanism in the IR-4

There has been no shortage of speculation about whether the U.S. or China is better fit for the new AI revolution. Each week, it seems, there is a new development in the "AI arms

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[50] Edgerton 2007.
[51] Burwell 1983.
[52] Gross identifies high-capacity battery technologies as a candidate GPT of this era. Gross 2014, 32.
[53] Petralia 2020, 7.
[54] National Research Council 1999, 204.

race" between the U.S. and China.[55] Many believe that China is an AI superpower on the verge of overtaking the U.S. in the key driver of the IR-4.[56]

Drawing expressly on past technological revolutions as guideposts for the current period, much of the existing discussions about U.S.-China competition in AI follows the LS template. For instance, two Oxford scholars, Carl Frey and Michael Osborne, compared claims that China is on the verge of overtaking the U.S. in AI to overestimates of Japan's technological leadership in computers in the 1980s. In their view, just like Japan, China will fail to overtake the U.S. as the world's technological leader because of its inability to produce radical innovations in AI. In fact, they conclude the prospects are even more bleak this time around. "China, if anything, looks less likely to overtake the United States in artificial intelligence than Japan looked to dominate in computers in the 1980s," they write.[57]

Taking inspiration from a different technological revolution, Kai-fu Lee's book *AI Superpowers* provides a much rosier view on China's chances to lead the AI revolution. Drawing a parallel to mass electrification in the IR-2, Lee argues that the current AI landscape is shifting from an age of discovery, when the country with the highest quality AI experts wins out, to an age of implementation, when the country with the largest quantity of sound AI engineers is advantaged.[58] Thus, Lee concludes, "China will soon match or even overtake the United States in developing and deploying artificial intelligence."[59]

Compared to both of these works, I provide a different perspective on U.S.-China competition in AI. Frey and Osborne rightly point out that the U.S. is most likely to produce the next radical innovation in AI; however, I argue that the key driver of a possible U.S.-China

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[55] Zwetsloot et al. 2018.
[56] For assessments that provide a more grounded view of China's AI prowess, see Ding 2018; Ding 2019.
[57] Frey and Osborne 2020.
[58] Lee 2018, 12-13, 83.
[59] Lee 2018, 18.

economic power transition is the relative success of the U.S. or China in diffusing AI throughout their economies. As the IR-3 case study reveals, the perpetuation of U.S. technology leadership relative to Japan was due to the U.S.'s advantage in ICT diffusion, not ICT innovation. Although Lee's emphasis on AI implementation is more in line with GPT diffusion theory, his optimism about China's relative advantage in adopting AI also draws on mistaken assumptions tied to the LS account. As the following sections will flesh out, GPT diffusion theory presents different dimensions for evaluating whether the U.S. or China will best capitalize on AI's potential. It is still early innings in the GPT trajectory of the IR-4, but it is not too early to assess which team's roster is better equipped for victory.

7.3.1 Timeframe of impact

If guided by the LS mechanism, one would expect the impacts of AI on U.S.-China power competition to be very significant in the early stages of the technology's trajectory. Indeed, many prominent voices have articulated this perspective. Consider, for example, a report titled "Is China Beating the U.S. to AI Supremacy?," authored by Professor Graham Allison, the Director of Harvard Kennedy School's Belfer Center for Science and International Affairs, and Eric Schmidt, former CEO of Google and co-chair of the National Security Commission on Artificial Intelligence. For Allison and Schmidt, the decisive years in U.S.-China AI competition are just around the corner. Assuming that AI advances will be rapidly adopted across many economic domains, their aim is to "sound an alarm over China's rapid progress and the current prospect of it overtaking the United States in applying AI in the decade ahead."[60] Shaped by a similar framework, Lee's 2018 book also predicts that China's productivity boost from AI will come to fruition in the 2020s.[61]

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[60] Allison and Schmidt 2020, 1.

[61] Lee 2018, 25, 154. Allison and Schmidt (2020, 4-5, 12n39) frequently draw on Lee's book in their analysis.

If GPT diffusion theory serves as the basis for analysis, these influential texts severely underestimate when China will be able to harness AI's full potential. It took at least four decades for previous technological leaders to reap the productivity benefits of previous GPTs. The deep learning revolution created a new paradigm in AI development in the early 2010s, so even under the fastest timeline of previous GPTs, a prolonged period of gestation should extend until around the 2050s. It is unlikely that the main productivity payoffs from AI will materialize before 2030.[62]

Of, course it is possible that other factors could affect AI's expected impact timeframe, including the possibility that the general process of technological adoption is accelerating. Some evidence indicates that the waiting time for a significant productivity boost from a new GPT has decreased over time.[63] Lee argues that the AI revolution will be faster than previous GPT trajectories due to the more frictionless distribution of digital algorithms and more mature venture-capital industry.[64] Nevertheless, preliminary evidence suggests AI will face similar implementation lags as previous GPTs, including bottlenecks in access to computing resources, human capital training, and business process transformations.[65]

7.3.2 Key phase of relative advantage

In debates over China's scientific and technological power, complex dynamics get reduced to a magic word — innovation.[66] Whether China can generate novel technologies is often the crux of debates over China's growing scientific and technological capabilities and a potential U.S.-China power transition. For Rapkin and Thompson the prospect of China

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[62] Campanella 2018.

[63] Crafts 2004.

[64] Lee 2018, 151-154.

[65] Brynjolfsson et al. 2017, 28-29. According to the most recent Census survey on the extent of AI penetration among U.S. firms in 2018, only 3.4 percent of firms reported testing or using AI technologies. U.S. Census Bureau 2019.

[66] Historians have decried the disproportionate attention paid to innovation — a phenomenon Edgerton labels "innovation-centrism." Edgerton 2010; Godin 2015.

overtaking the U.S. as the leading power is dependent on "China's capacity to innovate" — specifically as it relates to revolutionary technological changes that allow challengers to leapfrog the leader in economic and military competition.[67] "If...China's innovativeness continues to lag a considerable distance behind that of the U.S., then China overtaking the U.S. might wait until the twenty-second century," they posit.[68] China's innovation imperative, as Kennedy and Lim describe in language familiar to LS analysis, is motivated by the "*monopoly rents* generated by new discoveries."[69]

Innovation-centric views of China's AI capabilities paint an overly optimistic picture of China's challenge to U.S. technological leadership. Those bullish on China's long-term rise point to China's impressive performance along traditional indicators of innovation, such as R&D expenditures, scientific publications, and patents, which map China's capacity to generate new breakthroughs.[70] Arguments that China is poised to overtake the U.S. as an AI superpower also tend to rely on these indicators.[71]

If forecasts of U.S.-China competition in AI were centered on GPT diffusion theory, they would focus more on China's capacity to widely adopt AI advances. In this scenario, it is neither surprising nor particularly alarming that China, like other great power contenders such as Japan in the IR-3, Germany in the IR-2, France in the IR-1, is contributing to fundamental innovations in AI. One country cannot corner all the innovations in a GPT like AI. The key point of

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[67] Rapkin and Thompson 2003, 333. Tellis (2013, 112) states that the U.S. must "sustain its dominance in the new leading sectors of the global economy" to check China's growing power.

[68] Rapkin and Thompson 2003, 333.

[69] Kennedy and Lim 2018, 555. Emphasis mine.

[70] Kennedy 2015, 284.

[71] See, for example, Allison and Schmidt 2020; Frey and Osborne 2020. For a critique of some of these indicators, see Ding 2019.

differentiation will be the ability to adapt and spread AI innovations across a wide array of sectors.[72]

This diffusion-centric perspective suggests that China is far from being an AI superpower. Trends in ICT adoption reveal that there is a large gap between the U.S. and China. China ranks number 83 in the world on the International Telecommunication Union's ICT development index, which is a composite of ICT readiness (the level of networked infrastructure and access to ICTs), ICT intensity (the level of use of ICTs in the society) and ICT impact (the results/outcomes of more efficient and effective ICT use).[73] While China has achieved some impressive successes in ICT diffusion across consumer-facing applications — such as the spread of mobile payments and e-commerce — Chinese businesses have been slow to embrace digital transformation.[74] In fact, it is often Chinese scholars and think tanks that acknowledge these deficiencies. According to an Alibaba Research Institute report, China significantly trails the U.S. in penetration rates of many digital technologies across industrial applications, including digital factories, industrial robots, smart sensors, key industrial software, and cloud computing.[75] In 2017, U.S. firms devoted 29 percent of their total IT budget on cloud expenditures, more than double the comparable rate for Chinese firms.[76]

China's limitations in diffusing advances in robotics, a key application sector of AI, provide further confirmatory evidence. On the one hand, China leads the world in total

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[72] Naughton has argued that China needs to produce "unprecedented productivity growth from the service sector" in order to sustain its growth. Naughton 2018, 168.

[73] International Telecommunication Union 2017.

[74] Kannan and Thomas 2018. Recently, some analysts have argued that China's rising S&T prowess comes from its strategic advantage in deploying innovations at scale, which benefits from a globalized, open R&D system. See, for example, Breznitz and Murphree 2011; de La Bruyère and Picarsic 2020. These analyses draw from a few examples of Chinese success at large-scale deployment in domains such as high-speed rail and mobile payments. This section's comprehensive evaluation cautions against overestimating China's diffusion capacity.

[75] Alibaba Research Institute 2019. For other Chinese-language reports that cover China's struggles to transfer leading technologies from frontier firms to small and medium enterprises, see Synced 2020; Techxcope 2020.

[76] Kannan and Thomas 2018.

installations of industrial robots. China added 154,000 industrial robots in 2018, which was more than the U.S. and Japan combined.[77] On the other hand, China's robot rollout is much less impressive when assessing the proportion of its manufacturing base that has adopted robotic technology.[78] In 2018, Japan and the U.S. ranked 4th and 8th, respectively, in robot density, as measured by the number of robots installed per 10,000 manufacturing workers. China placed a distant 20th in robot density.[79]

7.3.3 Breadth of growth

The divergent perspectives on the breadth of growth in technological revolutions also separate LS-based and GPT-based views of the U.S.-China case. If technological competition in the IR-4 is limited to which country gets a bigger share of the market in new leading industries like AI, then a successful approach could be based on direct sectoral interventions in the mold of China's AI strategy. If, however, the breadth of growth in the IR-4 follows the GPT trajectory of the three previous industrial revolutions, then diffusion-centered approaches will be more effective.

China's AI strategy has closely hewed to the leading-sector template. This approach builds off a series of directives that prioritize indigenous innovation in select frontier technologies, which first appeared in the 2006 MLP.[80] In response to the financial crisis, China established a "Strategic Emerging Industries" initiative in 2010, which targets seven technological sectors because they present the opportunity to leapfrog ahead in new industries. China's "Made in China 2025," which recently became a key point of contention in U.S.-China trade disputes,

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[77] Based on statistics from International Federation of Robotics (IFR) 2019.

[78] The proportional figure is "the most commonly used metric" in comparing nations in terms of robot adoption. Atkinson 2019.

[79] Based on statistics presented in IFR 2019. Similar indicators show that the diffusion rate of welding robots in China is at least two times lower than in Germany and Japan. Pang 2019. Though some project that China will eventually lead the world in robot density (Atkinson 2019), China's installations of industrial robots have declined in recent years.

[80] Chen and Naughton 2016.

was issued in 2015 to further enhance China's self-sufficiency in ten strategic industries.[81] In its 2017 national AI development plan, the Chinese government expressed its ambition to "occupy the commanding heights" of AI technology.[82]

The economy-wide transformation that AI will enable, if it lives up to its potential as a GPT, demands a more broad-based response. Industrial policy can be effective at achieving singular technological feats but is less useful for targeting fragmented sectors.[83] A research center under China's own State Council, in a joint analysis with the World Bank, concluded in 2012, "A better innovation policy in China will begin with a redefinition of government's role in the national innovation system, shifting away from targeted attempts at developing specific new technologies and moving toward institutional development and an enabling environment that supports economy-wide innovation efforts within a competitive market system."[84]

When it comes to technology policy, there is always a push and pull between two ends of a spectrum. Vertical industrial policy, or "picking winners," targets certain technologies, often leading to top-down intervention to ensure the nation's firms are competitive in specific industries. Shying away from labeling certain technologies more significant than others, horizontal industrial policy promotes across-the-board technological development. This thesis argues that both camps have it partly right, at least when it comes to ensuring long-term economic growth. Picking technological winners gets it right in that some technologies do matter more than others; however, the "winners" are GPTs, which require a horizontal approach to diffuse across many application sectors.

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[81] There were 116 mentions of "Made in China 2025" in the U.S. Trade Representative's Section 301 report in March 2018, which was one of the first volleys in the U.S.-China trade war. The ten strategic sectors included high-end numerical control machinery and robotics, energy-saving and new energy vehicles, biopharmaceuticals and high-performance medical devices, etc. Laskai 2018.

[82] Webster et al. 2017.

[83] Ma 2017.

[84] State Council 2016; cited in Liu et al. 2017, 664.

7.4 Institutional complementarities: GPT skill infrastructure in the IR-4

In 2014, Baidu, one of China's leading tech giants, hired Andrew Ng away from Google, poaching the co-founder of Google's deep learning team. Three years later, Baidu lured Qi Lu away from Microsoft, where he served as the architect of the company's AI strategy. Their departures were headline news and spurred broader discussions about China's growing AI talent.[85]

When Alibaba, another one of China's tech giants, celebrated its listing on the Hong Kong stock exchange in November 2019, it showcased a different form of AI talent. In one picture of the gong-ringing celebration, Yuan Wenkai, who works for an Alibaba-affiliated logistics warehouse, stood third from the right. A former tally clerk who graduated from a run-of-the-mill Guangdong vocational school, Yuan is now an expert in automation management. He was present at the ceremony because he increased the sorting capacity of the 4PX logistics warehouse by 20,000 orders per hour.[86]

In its distilled form, GPT diffusion theory argues that China's chances to lead the AI revolution will rest more on the Yuan Wenkais of the world than the Andrew Ngs. It suggests that the important institutional complementarities in the IR-4 are those that widen the skill base in AI. Sound AI engineers, not the AI researchers who produce the flashiest research results, are critical.[87] Some preliminary evidence supports this prediction. When asked about obstacles to adopting AI in their operations, executives of pioneering AI companies in both the U.S. and China identify shortages of AI talent as the most pressing bottleneck.[88] One analysis of Burning Glass job postings from 2010 to 2019 found absolute demand for AI-adjacent jobs, which

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[85] See, for example, Hempel 2017.
[86] Pang 2019.
[87] Much existing AI talent comparisons center on elite AI talent, such as PhD graduates in AI from the top universities or researchers who have published in top AI conferences. For example, see Zwetsloot et al. 2019; Mozur and Metz 2020.
[88] Gerbert et al. 2018.

increased from about 1 million to 3 million jobs, far exceeded that of "core AI" jobs.[89] As both the U.S. and China make a transition from initiating a new GPT trajectory, where the best and the brightest AI experts play a pivotal role, to converting a GPT into broad and varied AI applications that will boost economy-wide productivity, investing in the broader AI-adjacent skill base will be increasingly crucial.

At present, the U.S. is better positioned than China to develop the skill infrastructure for the AI revolution. It is not just that the U.S. has cultivated the widest pool of AI talent.[90] The connective tissue that enmeshes AI engineers in cross-cutting networks with entrepreneurs and scientists, as previous industrial revolutions have demonstrated, is essential to successful GPT diffusion. While the AI trajectory is still evolving, some preliminary indicators suggest that this connective tissue is especially strong in the U.S. It leads the world with the highest number of academic-corporate hybrid AI publications, co-authored by at least one researcher from industry and academia, more than doubling the amount from China.[91]

Moreover, the U.S. approach to AI standard setting could be more optimal for coordinating information flows between labs working on fundamental AI advances and specific application sectors. The U.S.'s market-mediated, decentralized standardization system may be particularly favorable for advancing the development of AI, a domain characterized by significant uncertainty about future trajectories.[92] In such fields, governments confront a "blind giant's quandary" when attempting to influence technological development through standards-setting.[93]

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[89] Toney and Flagg 2020, 3-4. Core AI jobs increased from 23,000 to 320,000 postings across the same time span.

[90] According to data from the end of 2017, China ranks second to the U.S. in terms of total AI scientists and engineers. Interestingly, China is more competitive with respect to AI implementers. Based on where the most productive and highly cited AI scientists are located, China ranks sixth in the world, with the U.S. also ranking first in this metric. SCMP Research 2020.

[91] Zhang et al. 2021, 23. This finding is based on a dataset of peer-reviewed AI publications between 2015 and 2019. For more on the challenges of science-industry linkages in China, see Tagscherer 2015.

[92] Chan et al. 2019; Ding 2020.

[93] David 1987; David 1995.

The period when government involvement can exert the most influence over the trajectory of an emerging technology coincides with when the government possesses the least technical knowledge about the technology. Government intervention, therefore, could lock in inferior AI standards compared with market-driven standardization efforts.

In that light, China's state-led approach to technical standards development could hinder the sustainable penetration of AI throughout its economy. For example, the Chinese central government plays a dominant role in China's AI Industry Alliance, which has pushed to wrest leadership of standards setting in some AI applications away from industry-led standardization efforts.[94] Excessive government intervention has been a longstanding weaknesses of China's standardization system, producing standards not attuned to market demands and bureaucratic rivalries that undermine the convergence of standards.[95] Wang Ping, described as "China's leading standards guru,"[96] has argued that China needs to reform its standardization system to allow private standards development organizations more space to operate, like the U.S.'s Institute of Electrical and Electronics Engineers in the U.S. and the European Committee for Electrotechnical Standardization.[97]

The preceding conclusions offer a marked contrast with the emphasis of U.S. and Chinese policymakers on support for R&D in AI. Policy proposals for U.S. leadership in AI consistently call for more AI R&D as the highest priority. For example, the "Meeting the China Challenge: A New American Strategy for Technology Competition" report, published in 2020 by a working group of 28 China specialists and experts, provided 16 policy recommendations for how the U.S. should ensure leadership in AI and three other key technological domains. The very

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[94] Luong and Arnold 2021, 8.
[95] Ernst 2011, 85; Breznitz and Murphree 2013.
[96] Yates and Murphy 2019, 336.
[97] Wang and Zheng 2018.

first recommendation was for the U.S. to significantly expand investment in basic research, raising total R&D funding to at least 3 percent of GDP.[98] The Trump administration's American AI initiative, launched to maintain U.S. leadership in AI "in a time of global power competition," also listed AI R&D spending as its very first policy recommendation.[99]

The Chinese government also prioritizes investments in R&D over education. China's five-year plan (2021-2025) aims to raise basic research spending by over 10 percent in 2021, targeting AI and six other key technological domains.[100] Although China has consistently set and met ambitious targets for R&D spending, it has slacked when it comes to similar benchmarks for education funding.[101] Some scholars have pointed out this tradeoff between Chinese policymakers' focus on fostering innovation to enhance productivity growth versus "the adoption of more advanced technology...from high-income countries…[which] can provide a less costly and more certain source of growth over the medium term."[102]

Policies directed at widening and building more connective tissue in the AI talent base, such as supporting the role of community colleges developing the AI workforce, deserve more attention.[103] A strategy oriented around GPT diffusion doesn't necessarily exclude enhanced R&D funding. R&D spending, undoubtedly, will not just help cultivate novel AI breakthroughs but also contribute to widening the GPT skill infrastructure in AI. But all too often, it seems, boosting R&D spending is the boilerplate recommendation for any strategic technology.[104] GPTs like AI are not like other technologies, and they demand a different toolkit of strategies.

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[98] Working Group on Science and Technology in U.S.-China Relations 2020, 8.
[99] The White House Office of Science and Technology Policy 2020.
[100] Horwitz et al. 2021.
[101] Liu et al. 2017, 663.
[102] Brandt et al. 2020, 20.
[103] See West 2018, 112-113.
[104] For an analysis of the concept of strategic technologies, see Ding and Dafoe 2021.

7.5 Alternative factors

In exploring how the Fourth Industrial Revolution could bring about an economic power transition, it is important to compare the ramifications derived from the GPT diffusion mechanism to those of two other prominent explanations: neorealist theories of threat and Varieties of Capitalism (VoC).

First, one potentially dangerous implication of threat-based explanations is that war, or manufacturing the threat of war, is necessary for economic leadership in the Fourth Industrial Revolution. Crediting the U.S. military's key role in spurring advances in GPTs during the 20th century, Ruttan doubts that the U.S. could initiate and sustain the development of GPTs "in the absence of at least a *threat* of major war."[105] Extending Ruttan's line of thinking to the U.S. strategic context in 2014, Weiss expressed similar concerns that the end of the Cold War, and the absence of an existential threat, removed the impetus for continued scientific and technological innovation. Specifically, she wondered "why China has not yet metamorphosed into a rival that spurs innovation like the Soviet Union and Japan."[106] Weiss only needed a little more patience. A few years later, the narrative of a U.S.-China "Tech Cold War" gained momentum, as both sides of the bilateral relationship trumped up threats to push national scientific and technological priorities.[107]

GPT diffusion theory strongly refutes the notion that manufacturing external threats is necessary for the U.S. or China to prevail in the Fourth Industrial Revolution. The menace of an "Other" did not drive the U.S.'s rise in the IR-2. Across all cases, including the IR-2, military actors were involved in but not indispensable to spurring the development of GPTs, as many

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[105] Ruttan 2006, 184.

[106] Weiss 2014, 204.

[107] See, for example, Segal 2019; Zhong and Mozur 2018. Taylor (2016, 290-292) warns against this cynical application of threat-based theories. He argues that policymakers should, instead, emphasize nonstate, external threats, such as climate change, to spur innovation.

civilian entities also fulfilled the purported role of military investment in providing initial, large demand for incubating GPTs. Furthermore, anchoring national strategy about GPTs on which country can stimulate the first novel breakthroughs neglects the historical impact trajectory of these technologies. Even if stoking fears can galvanize support for grand moonshot projects, these do not determine which country is able to benefit most from the widespread adoption of advances in GPTs like AI. That rests on the more low-key toil of widening the engineering skill base and advancing interoperable standards in GPTs — not fear mongering.

The ramifications of VoC theory for U.S.-China competition in AI are more muddled. One interpretation is that liberal market economies (LME), of which the U.S. is the prototypical representative, are better able to adapt to radical innovations like GPTs.[108] Some argue that China's system, like Japan's, in which the state coordinates the largest companies, is more suited to incremental improvements.[109] Applying the VoC categorization scheme to China, however, is a tricky task. While some label China as a coordinated market economy (CME), others characterize it as an LME.[110] This confusion speaks to the substantial hybridity, rather than conformity to the LME or CME dichotomy, that characterizes most economies.

The GPT diffusion framework provides more specific implications for the U.S. and China in the IR-4. VoC explanations rightly point to the match between institutional structures and the technological developments of the Fourth Industrial Revolution, but the CME-LME distinction neglects the key factor: the fit between widespread adoption of AI and institutional adaptations to widen the skill base of AI engineers.

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[108] Hall and Soskice 2001.

[109] Abrami et al. 2014.

[110] For the former see Fligstein and Zhang 2011; For the latter, see Witt 2010. Others argue that China has different regional varieties of capitalism. Zhang and Peck 2016.

7.6 Summary

Do GPT diffusion theory's implications apply to the U.S.-China case? I have presented support for the GPT mechanism across a range of historical case studies, each of which cover at least four decades and two countries. Still, a number of factors could affect whether lessons from the past three industrial revolutions extend to the implications of present-day technological advances for a U.S.-China power transition. The most plausible transferability issues can be grouped into those that relate to the nature of great power competition and those that relate to the nature of technological change.

First, it is possible that the U.S.-China power relationship is different from power transitions of previous years. Brooks and Wohlforth argue that the gap between the U.S. and China in terms of military advantage is much larger than past gaps between rising powers and established powers. They also argue that it is much more difficult to convert economic capacity into military capacity now than it was in the past.[111] These arguments highlight the U.S.'s advantage in advanced weapons systems, which provides a certain form of unmatched military influence.[112] However, as Beckley argues, there remains a strong connection between economic development and countries' capabilities to "produce, maintain, and coordinate complex military systems."[113] Moreover, military effectiveness does not solely derive from the most specialized, high-end equipment. Production capacity does continue to provide the foundation for military power in many scenarios, including the rapid replacement of naval forces in a prolonged conflict.[114]

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[111] Brooks and Wohlforth 2016, 9.

[112] For a detailed account of why China can't catch up in these types of systems, see Gilli and Gilli 2019.

[113] Beckley 2010, 75. Further, many of the arguments against economic-to-military capability conversion focus on economic size rather than economic productivity.

[114] Pickrell 2020.

Second, the technological landscape itself is changing. The accelerating globalization of scientific and technological activities may reduce the likelihood of adoption gaps between advanced economies when it comes to emerging technologies.[115] Despite these considerations, there are also compelling reasons to think that the nature of technological change in this current period only magnifies the importance of GPT diffusion. Cross-country studies indicate that while new technologies are spreading between countries faster than ever, they are spreading to all firms within a country at increasingly slower rates.[116] Networks of multinational firms at the global technology frontiers have reduced cross-national lags in the initial adoption of new technologies, but the cross-national lags in the "intensive adoption" of new technologies, as measured by the time between the technologies' initial adoption to intensive penetration throughout a country, has only grown. According to another study of patents granted in the U.S. to multinational corporations over a 25-year span, innovation in GPTs is becoming more internationalized.[117] These trends give more weight to the GPT mechanism.

When some of the leading thinkers of our era declare that the AI revolution will be more significant than the IR-1, it is difficult to not get caught up in their excitement. We always tend to think that the times we are living in are the most interesting times of all. But our time might not be so different. Unpacking how AI could influence a possible U.S.-China power transition in the 21st century requires first learning the lessons of GPT diffusion from past industrial revolutions.

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[115] Archibugi and Michie 1997; Xie and Killewald 2012, 27-29.

[116] Andrews et al. 2015; Comin and Mestieri 2014.

[117] Innovation in GPT fields is also more internationalized than in non-GPT fields. Qiu and Cantwell 2018.

Chapter 8 Conclusion

8.1 Argument recap

Studies of how revolutionary technologies disrupt the economic balance of power often fixate on the most dramatic aspect of technological change — the Eureka moment. Consistent with this frame, the standard explanation for the technological causes of economic power transitions emphasizes a rising power's ability to dominate profits in leading sectors by generating the first implementation of radical inventions. This dissertation draws attention, in contrast, to the less spectacular process by which an innovation is eventually diffused throughout the economy. The rate and scope of diffusion is particularly relevant for GPTs, fundamental advances that have the potential to drive pervasive transformation across many economic sectors. Based on the process of GPT diffusion, this dissertation puts forward an alternative theory of how and when significant technological breakthroughs generate differential rates of economic growth among great powers.

GPT diffusion theory proposes that by more effectively adopting GPTs across many application sectors, some great powers can sustain higher levels of productivity growth than their competitors. When evaluating how technological revolutions affect economic power transitions, GPTs stand out as historical engines of growth that can provide major boosts to national productivity. While each is different, GPTs exhibit a common pattern of diffusion. Like a marathon on a wide road, the impact of GPTs on national productivity materializes only after they spread across a broad range of technology systems, a process which takes many decades, complementary innovations, and institutional changes. This markedly diverges from existing scholarship about the impact pathway of leading sectors, akin to a sprint on a narrow lane, which is characterized by monopoly profits that accrue to the country that dominates initial breakthroughs in the early growth periods of new industries.

Disruptive technological advances can bring about economic power transitions because some countries are more successful at GPT diffusion than others. This argument builds on scholarship that finds a nation's success in adapting to emerging technologies is determined by the fit between its institutions and the demands of those technologies. Thus, establishing the GPT trajectory, as opposed to the LS one, as the key driver of economic power transitions helps pinpoint the institutional factors of significance. The institutions that matter most are those that match the demands of GPT diffusion. Consequently, this dissertation highlights national institutional adaptations to exchange knowledge between the GPT sector and application sectors, in particular the ability of nations to widen the engineering skill base linked to a new GPT.

8.2 Summary of findings

Three historical case studies, designed and conducted in a way to assess the explanatory power of the GPT mechanism against the LS mechanism, provide support for GPT diffusion theory. The case studies cover periods characterized by both remarkable technological change — the "three great industrial revolutions" in the eyes of some scholars[1] — and significant fluctuations in the global balance of economic power. Overall, the case study evidence underscores the significance of GPT diffusion as the key pathway by which the technological changes associated with each industrial revolution translated into differential rates of economic growth among the great powers.

In the case of Britain's rise to economic pre-eminence during the first industrial revolution, the key GPT trajectory was mechanization spurred by expanded uses of iron in

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[1] von Tunzelmann 1997, 2.

machine-making. The gradual progression of mechanization matched when Britain's productivity growth outpaced that of France and the Netherlands. Britain's proficiency in adopting iron machinery across a wide range of economic activities, rather than the export advantages from dominating innovation in leading sectors such as cotton textiles, proved more central to its industrial ascent. Though its industrial rivals had superior systems of higher technical education for training expert scientists and top-flight engineers, British institutional adaptations, such as the growth of Mechanics' institutes, were more effective in widening the talent base of mechanically skilled engineers.

The second industrial revolution case also shows that the fit between institutions and key GPT trajectories accounts for which great powers better adapt to periods of remarkable technological change. The LS mechanism focuses on Germany's rapid achievements in new science-based industries, namely electrical equipment and chemicals, as the driving force behind its catching-up to Britain before World War I. However, the U.S., emerging as the preeminent economic power during this period, was more successful than Germany in exploiting the technological opportunities of the second industrial revolution. The key GPT trajectory that fueled the U.S.'s rise was the extension of interchangeable manufacturing techniques across many American industries, which was enabled by innovations in machine tools. Scientific infrastructure or industrial R&D capabilities, areas in which the U.S. lagged behind its industrial rivals, cannot account for its advantage in adopting special-purpose machinery across nearly all branches of industry. Rather, the U.S. benefited from successful institutional adaptations to widen the base of mechanical engineering talent, including through the expansion of technical higher education schools and the professionalization of mechanical engineering.

Evidence from the effects of the information revolution on U.S.-Japan economic rivalry exposes more gaps in the LS account. During the late 20th century Japan captured global market shares in new, fast-growing sectors such as consumer electronics and semiconductor components, prompting many to predict that it would overtake the U.S. as the leading economic power. Yet, this economic power transition, an inevitability according to the expectations of the LS mechanism, never occurred. Instead, the U.S. sustained higher rates of economic growth than Japan partly due to greater diffusion of computerization across many economic sectors. Japan's productivity growth kept up with the U.S. rate in sectors that produced information technology but lagged far behind in sectors that intensively used information technology. Once again, differences in institutional adaptations to widen the GPT skill base proved significant. While Japanese universities were very slow to adapt their training to the demand for more software engineers, U.S. institutions effectively broadened the pool of such skills by cultivating a separate discipline of computer science.

8.3 Main contributions

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.[2] 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.[3]

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[2] Drezner 2019, 289; Kennedy 2018; Tellis et al. 2000.

[3] Ogburn 1949, 15; Reuveny and Thompson 2001; Wohlforth 1999, 32.

Second, as Chapter 7 explores in detail, 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, as section 7.3.2 details, 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. 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.[4] This distinction makes a difference for precise and effective technology policy.

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[4] 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.

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.[5]

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.[6] 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.[7]

8.4 Future research

This thesis opens up many new directions of future research. First, more work should explore the institutional adjustments most conducive to adoption of GPTs at scale. I argue that institutions that broaden the skill base associated with GPTs, engineering talent in particular, are crucial to successful GPT diffusion. There are, however, many other institutional factors that could fulfill similar functions as GPT skill infrastructure, including national systems of standard-setting and technology transfer. Moreover, while my approach highlights the role of domestic networks of engineers, other literature emphasizes the importance of countries' access to

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[5] For a similar argument about reforming U.S. R&D policies in the context of deliberations over the Endless Frontier Act, which proposes to significant boost the National Science Foundation's budget, see Hammond 2021.

[6] Sprout 1983, 187.

[7] Dafoe 2015; Herrera 2006; Mayer et al. 2014.

international linkages, such as receptiveness to immigration, as a critical component of technological success.[8] Future work should probe deeper into the institutional factors that affect differing rates of GPT diffusion across leading economies.[9]

To further investigate testable implications of GPT diffusion theory, one possible approach is to disentangle the impact of institutional investments in GPT diffusion from those optimized for different technological pathways. Some existing scholarship provides a foundation. For example, Maloney and Caicedo study the effect of human capital investments on long-term growth trajectories. Leveraging U.S. county-level data, they trace income differences in the year 2000 back to two different types of human capital in 1880: one that captures more inventive activities, proxied by patenting density, and one capturing more adoptive activities, proxied by the density of engineers in a county. While both types had a positive effect on long-term growth trajectories, the effect of engineering density was stronger than the effect of patenting density.[10] Another analysis, which explores technological shocks in the U.S. economy in the postwar period, finds that two standard proxies of innovative activity, R&D intensity and patenting rates, have limited ability to predict fluctuations in total factor productivity. By contrast, activities related to broadly disseminating information about new products and processes track better with subsequent changes in productivity.[11] Future work could explore whether these differing institutional adaptations resulted in variation in GPT diffusion as well as extend the analysis to countries outside the U.S.

Additionally, this thesis underscores the significance of diffusion capacity to scientific and technological leadership. While most comparisons of national scientific and technological

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[8] Taylor 2016; Saxenian and Hsu 2001.

[9] On "technology diffusion institutions," see Shapira and Youtie 2017.

[10] Maloney and Caicedo 2017.

[11] Alexopoulos 2011. Her preferred indicator is based on new book titles published in the field of technology.

capabilities overwhelmingly center on countries' capacity to generate new-to-the-world breakthroughs, the historical evidence highlights rising powers' capacity to adopt innovations at scale. This fundamental insight can be fruitfully applied to the growing body of literature on assessments of a nation's scientific and technological power. Assigning greater weight to a state's diffusion capacity, as opposed to the usual emphasis on innovation capacity, could improve such assessments. As scientific and technological capabilities become increasingly central to a state's overall power resources,[12] diffusion-centric approaches could refine general assessments of power — a crucial intervening variable between structural shifts in the international system and how states react to the changing landscape.[13]

Finally, future work should explore the implications of GPTs on important outcomes in international politics besides the economic trajectories of great powers. Economists and economic historians, who do the vast majority of theorizing about GPTs, primarily analyze GPTs as drivers of long-term economic growth. International relations scholars have the opportunity to study the impact of GPTs on other outcomes of interest, including military effectiveness and the balance of military power. Indeed, although major theories of military innovation focus on relatively narrow technological developments, such as nuclear weapons or aircraft carriers, arguably the most profound military implications of technological change arise from more fundamental advances in GPTs, such as electricity and the computer. More work in this direction could contribute directly to existing policy debates about how AI will affect military power as well as to more general theories of military innovation.

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[12] Nye 1990, 34; Paarlberg 2004; Skolnikoff 1993.

[13] Friedberg 1988.

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