The Rise and Fall of Great Technologies and Powers

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Abstract

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

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How do technological revolutions affect the rise and fall of great powers? International relations scholars have long recognized that major technological advances often precede disruptions to the balance of power. As policymakers and scholars increasingly frame today's U.S.-China rivalry as a contest for technology leadership in the "Fourth Industrial Revolution," how will emerging technologies affect the U.S.-China power balance?[2]

It is generally acknowledged that the rise and fall of great powers originates from, as historian Paul Kennedy outlines, "differentials in growth rates and technological change, leading to shifts in the global economic balances, which in turn gradually impinge upon the political and military balances."[3] Previous work has established a connection between major technological innovations and the first outcome in Kennedy's causal chain — growth rate differentials.[4] Yet, few studies explore the processes that link disruptive technological breakthroughs and disruptions to the economic balance of power.[5]

Among those that do, the standard account stresses dominance over critical technological innovations in new, fast-growing industries (*leading sectors*). By exploiting a brief window to monopolize profits in cutting-edge industries, the country that dominates innovation in these sectors rises to become the world's most productive economy. The fit between domestic institutions and emerging technologies explains why the benefits of leading sectors tend to accrue in certain nations. Some scholars argue that national systems of political economy of rising challengers can more rapidly adapt to the demands of new, revolutionary technologies. Leading economies, by contrast, are victims of their past success, burdened by powerful vested interests that resist adaptation to disruptive technologies.[6] Other scholars outline more specific institutional factors, such as the degree of government centralization or industrial governance structures, that account for why some countries monopolize leading sectors.[7]

Though specific interpretations vary, the general outlines of the leading-sector (LS) explanation enjoy broad support across both academic and policy-making circles.[8] As Daniel Drezner summarizes, "Historically, a great power has acquired hegemon

2. Doshi 2020.

3. P. Kennedy 1987.

4. Akaev and Pantin 2014; Modelski and Thompson 1996; Thompson 1990.

5. Though I limit my analysis to economic power, hegemonic transitions also involve other factors. Emerging technologies could directly influence the military balance of power. Other work has convincingly demonstrated that the international order's distribution of identity is critical to hegemony. See Allan, Vucetic, and Hopf 2018.

6. Gilpin 1996; Moe 2009.

7. Drezner 2001; Kitschelt 1991.

8. Gilpin 1981, 1987; P. Kennedy 1987; Modelski and Thompson 1996; Rostow 1960; Tellis et al. 2000; Thompson 1990.

status through a near-monopoly on innovation in leading sectors."[9] This influence is reflected in current discussions about how emerging technologies could influence China's rise, which emphasize China's capacity to innovate in new leading sectors and to capture monopoly rents from new discoveries.[10]

I challenge the LS interpretation of technology-driven power transitions on empirical, methodological, and theoretical grounds. I develop an alternative explanation centered on general-purpose technologies (GPTs), fundamental advances that can spur economic transformation. Distinguished by their potential for continuous improvement, pervasive applicability throughout the economy, and synergies with complementary innovations,[11] GPTs make a substantial impact on economic productivity only after a "gradual and protracted process of diffusion into widespread use."[12] Electricity, the prototypical GPT, followed this extended trajectory. The first electric dynamo practical for industrial use emerged in the 1870s, but its impact on overall productivity took five decades to materialize.[13]

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

Clearly differentiating between these two pathways informs the institutional factors most crucial to economic leadership amidst technological revolution. If the LS trajectory holds, then the key institutional adaptations allow states to seize the market in new industries, such as scientific research investments that pioneer new technological paradigms and industry structures that monopolize LS innovation. If, however, the GPT model is operative, the key institutional complementarities facilitate widespread diffusion of GPTs, including education systems and technical associations that broaden the base of engineering skills associated with a GPT.

I test this argument with three historical case studies that set the GPT mechanism against the LS mechanism: Britain's rise to preeminence in the first industrial revolution (1780-1840); the U.S.'s overtaking of Britain in the second industrial

9. Drezner 2001, 7.
10. Kennedy and Lim 2018; Tellis 2013.
11. Bresnahan and Trajtenberg 1995.
12. David 1990, 356.
13. Devine 1982.

revolution (1870-1914); and Japan's challenge to America's technological dominance in the information technology revolution (1960-2000). The case studies cover periods characterized by both remarkable technological change — the "three great industrial revolutions" in the eyes of some scholars[14] — and significant fluctuations in the global balance of economic power. Though all three cases favor the LS account in terms of both background conditions and prior theoretical discussions, the case study evidence reveals that GPT diffusion was central to how each technological revolution translated into differential rates of economic growth among the great powers.

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

Theories of Technological Change and Power Transition

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

GPT diffusion theory, by contrast, draws attention to the less spectacular process by which fundamental innovations gradually diffuse throughout many industries. The rate and scope of diffusion is particularly relevant for GPTs. Recognized by economists and historians as "engines of growth," GPTs hold immense potential for boosting productivity.[15] Realizing that promise, however, entails continuous changes across a wide range of technology systems. Under this pathway, the key institutional competencies are those that facilitate GPT diffusion. Specifically, this explanation highlights the significance of education and training systems that widen the pool of engineering talent linked to new GPTs.

GPT Diffusion and LS Product Cycles

The dominant explanation for how technological change drives power transitions emphasizes a country's dominance in leading sectors, new industries that experience rapid growth on the back of new technologies. Cotton textiles, steel, chemicals, and the

14. Tunzelmann 1997, 2.
15. Bresnahan and Trajtenberg 1995.

automobile industry form a "classic sequence" of "great leading sectors," developed initially by economist Walt Rostow and adapted by political scientists.[16] Maintaining a monopoly on innovation in these emerging industries, according to the LS account, determines the rise and fall of lead economies.

This model of technological change and power transition builds on the international product life cycle, a concept pioneered by Raymond Vernon. Constructed to explain patterns of international trade, the product cycle begins with product innovation and the growth of sales in the domestic market. Once the domestic market is saturated, the product is exported to foreign markets, which eventually results in the diffusion of the manufacturing of the product, thereby eliminating the innovator's monopoly profits.[17] In fact, many LS-based studies explicitly reference the product cycle.[18] One scholar described Robert Gilpin's *U.S. Power and the Multinational Corporation*, an influential text for the LS mechanism, as "[having] drawn on the concept of the product cycle, expanded it into the concept of the growth and decline of entire national economies, and analyzed the relations between this economic cycle, national power, and international politics."[19]

The product cycle's assumptions illuminate the differences between the GPT and LS mechanisms along three key dimensions. In the first stage of the product cycle, a firm generates the initial product innovation and profits from sales in the domestic market before saturation. Extending this model to national economies, the LS mechanism emphasizes the clustering of LS innovations and the attendant monopoly profits in a single nation.[20] "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."[21] The GPT trajectory, in contrast, places more value on where technologies are diffused than where an innovation is first pioneered. I refer to this dimension as the *key phase of relative advantage*.

In the next stage, the product innovation spreads to global markets and the technology gradually diffuses to foreign competitors. Monopoly profits associated with a product innovation dissipate, as production of the innovation becomes routinized and transfers fully to other countries. Mirroring this logic, Modelski and Thompson write, "[Leading sectors] bestow the benefits of monopoly profits on the pioneer until diffusion and imitation transform industries that were once considered radically innovative into fairly routine and widespread components of the world economy."[22] Thompson states, "the greatest marginal stimulation to growth may therefore come

16. Rostow 1978; Thompson 1990, 104-109.
17. Vernon 1971.
18. Gilpin 1975, 78,197; 1987, 234-237; Moe 2007, 207; Tellis et al. 2000, 37.
19. Kurth 1979, 4.
20. Rasler and Thompson 1994, 7.
21. Modelski and Thompson 1996, 91; see also Thompson 1990, 217.
22. Modelski and Thompson 1996, 52.

early in the sector's development at the time when the sector itself is expanding rapidly."[23]

The GPT trajectory assumes a different *impact timeframe*. As noted earlier, because GPTs require major structural changes across countless industries, their greatest marginal stimulation to growth comes decades after their emergence.[24] It is precisely the period when diffusion transforms radical innovations into routine components of the economy — the stage at which LS scholars say the causal effects of leading sectors dissipate — that generates the productivity gap between nations.

The product cycle also reveals differences between the LS and GPT mechanisms regarding the *breadth of growth*. Like the product cycle's focus on an innovation's life cycle within a singular industry, the LS mechanism emphasizes the contributions of a limited number of new industries to economic growth in a particular period. GPT-fueled productivity growth, on the other hand, is dispersed across a broad range of industries.[25] Table 1 specifies how LS product cycles differ from GPT diffusion along the three dimensions outlined above. As the following section will show, the differences in these two technological trajectories shape the institutional factors that are most important for national success in adapting to periods of technological revolution.

TABLE 1. *Two Mechanisms of Technological Change and Power Transitions*

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

Institutions for GPT Diffusion: GPT Skill Infrastructure

New technologies agitate existing institutional patterns. They appeal for government support, generate new collective interests in the form of technical societies, and induce organizations that train people in relevant fields. If the institutional environment is slow or fails to adapt, the development of new technologies is hindered. As Gilpin articulates, a nation's technological "fitness" is rooted in the "extent of the congruence" between its institutions and the demands of evolving technologies.[26]

23. Thompson 1990, 211; see also Freeman, Clark, and Soete 1982, 80; Gilpin 1987, 112.
24. David 1990; Helpman and Trajtenberg 1994.
25. N. Crafts 2001, 306; David and Wright 1999, 12.
26. Gilpin 1996, 413; see also Perez 2002.

If GPTs drive economic power transitions, which institutions fit best with their demands? Institutional adaptations for GPT diffusion must solve two problems. First, the development of GPTs requires effective coordination between the GPT sector and numerous application sectors. Since the GPT sector is interacting with so many different application sectors, each end-user industry is uncertain about the likely direction of technical advance. Moreover, because they benefit from horizontal spillovers as the GPT develops, each application sector wants the other application sectors to bear more of the complementary innovation costs than is in their individual interest. This implies that application sectors will underinvest in the complementary innovations necessary to further spread the GPT.[27]

Second, GPTs demand human capital upgrading. Skilled labor is required for both innovation in the GPT sector and implementation of the new technology in each application sector.[28] Historical studies attribute the U.S.'s successful adoption of new electrical technologies to the "better match between the technologies advanced by electrification and the country's institutions of education and worker training."[29]

Education and training systems that foster relevant engineering skills for a GPT, or what I call GPT skill infrastructure, address both constraints.[30] These institutions not only supply engineering talent but also standardize best practices associated with GPTs, thereby coordinating information flows between the GPT sector and application sectors. Indeed, the emergence of distinct engineering specialties, such as chemical engineering and electrical engineering, have proved essential in widening knowledge bases in the wake of a new GPT.[31] Computer science, another engineering-oriented field, was central to U.S. leadership in the information revolution.[32]

The institutional competencies for exploiting LS product cycles are different. Historical analysis informed by this frame highlights heroic inventors like James Watt and pioneering research labs at large companies.[33] For example, Drezner argues that decentralized government structures are necessary for technological leaders to maintain innovation in leading sectors.[34] In his study of which countries benefited most from emerging technologies over the past two centuries, Herbert Kitschelt emphasizes the match between the properties of new technologies and sectoral governance structures. Under his framework, tightly coupled technological systems with high causal complexity, such as nuclear power systems and aerospace platforms,

27. Bresnahan 2010; Bresnahan and Trajtenberg 1995.

28. Aghion and Howitt 2002.

29. David and Wright 2006, 154.

30. GPT skill infrastructure is one of many factors that could affect GPT diffusion. Other institutions, such as industry standards bodies, could also resolve coordination problems. Since human capital upgrading spills over to all these other institutions, GPT skill infrastructure serves as a useful indicator for other institutions that facilitate GPT diffusion.

31. Rosenberg 1998, 169.

32. Vona and Consoli 2014, 1403-1405.

33. See, for example, A. Kennedy 2018, 54.

34. Drezner 2001.

were more likely to flourish in countries that allowed for extensive state support.[35] These approaches equate technological leadership with a state's success in capturing market shares and monopoly profits in new industries.

Competing interpretations of leadership in chemicals during the IR-2 crystallize these differences. Under the LS model, institutional competencies in science and basic research gain priority. The standard account of technological leadership in the IR-2 accredits Germany's late-19th century dominance in the chemical industry to its investments in scientific research and highly skilled chemists.[36] These institutional adaptations supported Germany's control over 90 percent of world production of synthetic dyes — a key segment of the chemical industry and a LS taken to explain Germany's overall industrial dominance.[37]

GPT diffusion spotlights other institutions that complemented the extension of chemical processes to a wide range of industries beyond synthetic dyes, such as food production, metals, and textiles. Under the GPT model, the U.S., not Germany, achieved leadership in chemicals because it first institutionalized the discipline of chemical engineering. Despite its disadvantages in synthetic dye production and chemical research, the U.S. was more effective in broadening the base of chemical engineering talent and coordinating information flows between fundamental breakthroughs and industrial applications.[38]

My argument differs from existing explanations. Many scholars attribute the international competitiveness of nations to institutional factors, including democracy, decentralized government, industrial governance, national innovation systems, and varieties of capitalism.[39] Since this paper is limited to the study of shifts in productivity leadership at the technological frontier, many of these factors — such as those related to basic infrastructure and property rights — will not explain differences among technologically advanced nations.

In addition, many of the institutional factors put forth to explain the productivity of nations are technology-agnostic, in that they treat all forms of technological change equally. In contrast, I am specific about GPTs as the sources of shifts in competitiveness at the technological frontier. Other theories identify key technologies but leave institutional factors at a high level of abstraction. Some scholars posit that the lead economy's monopoly on leading-sector innovation eventually erodes because of "ubiquitous institutional rigidities."[40] Unencumbered by vested interests that resist disruptive technologies, rising challengers inevitably overtake established powers. Because these explanations are underspecified, they cannot account for cases when

35. Kitschelt 1991; see also Kim and Hart 2001; Moe 2009.
36. Drezner 2001, 13-18; Moe 2007, 125.
37. Moe 2007, 253-255; Thompson 1990.
38. Rosenberg and Steinmueller 2013.
39. For a review, see Breznitz 2009.
40. Rasler and Thompson 1994, 81; see also Gilpin 1981, 179; 1996; Moe 2009.

established leaders sustain their advantage.[41]

Assessing GPT Diffusion Across Industrial Revolutions

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

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

I employ within-case congruence tests and process-tracing to evaluate the predictions of the two mechanisms against the empirical record.[42] In each historical case, I first trace how leading sectors and GPTs developed in the leading economies, with particular attention to adoption timeframes, the technological phase of relative advantage, and the breadth of growth — three dimensions which differentiate GPT diffusion from LS product cycles. I then turn to the institutional factors that could explain why some countries were more successful in adapting to a technological revolution, with a focus on the institutions best suited to the demands of GPTs and leading sectors. While my priority is on demonstrating the explanatory power of GPT diffusion theory relative to the LS account, I also consider evidence for alternative explanations of technology-driven power transitions.

The universe of cases most useful for assessing the GPT and LS mechanisms are technological revolutions (cause) that produced an economic power transition (outcome) in the industrial period.[43] Following guidance on testing competing

41. Taylor 2004, 604.
42. Blatter and Haverland 2012, 144; George and Bennett 2005, 181-204.
43. For justification of the first industrial revolution as a "unique break" in history, separating pre-industrial periods of slow technological advance and modern times characterized by rapid technological change, see

mechanisms that prioritize typical cases where the cause and outcome are clearly present, I investigate the first industrial revolution (IR-1) and second industrial revolution (IR-2).[44] Both cases featured periods of particularly disruptive advances, highlighted by many studies as "technological revolutions,"[45] and economic power transitions, when one great power sustains growth rates at substantially higher levels than its rivals.[46] I also study Japan's challenge to American economic leadership in the third industrial revolution (IR-3), which ultimately failed. This deviant case can disconfirm mechanisms and help explain why they break down.[47]

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

Second Industrial Revolution

In the late nineteenth century, the technological and geopolitical landscape transformed in ways familiar to observers of today's environment. "AI is the new electricity," goes a common refrain that compares current advances in machine intelligence to electrical innovations from 150 years ago. Those fundamental breakthroughs, alongside others in steel, chemicals, and machine tools, sparked a "Second Industrial Revolution" (IR-2), which unfolded from 1870 to 1914.[48] According to some scholars, one would be hard-pressed to find another period with a higher density of important scientific advances than the beginning years of the IR-2.[49]

By the end of the period, Britain's decline and the rise of Germany and the U.S. yielded a new balance of economic power, which one historian describes as a "shift from monarchy to oligarchy, from a one-nation to a multi-nation industrial system."[50] Indicators of per-capita industrialization, per-capita GDP, and labor productivity all confirm that the U.S. overtook Britain in productivity leadership near the 20th century.[51] While Germany significantly narrowed the gap, it did not surpass Britain in productive efficiency. Explaining how the U.S. successfully adapted to the IR-2, therefore, takes priority.

The IR-2 case favors the LS mechanism in terms of background conditions and existing theoretical explanations, making it a most-likely case for the LS mechanism

Clark 2014, 220.

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

45. Gilpin 1975, 69; Related terms include "technology waves" and "long waves" Milner and Solstad 2021; Goldstein 1988.

46. For related concepts, see Drezner 2001, 4; Modelski and Thompson 1996; Moe 2009; Reuveny and Thompson 2001.

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

48. Hull 1996; Mokyr 1998.

49. Mowery and Rosenberg 1991.

50. Landes 1969, 247.

51. Bairoch 1982, 294; Bolt and Zanden 2020; Broadberry 2006, 110.

and a good test for the GPT mechanism. In the 1880s, major technological innovations spurred the growth of electrical, chemical, and steel industries in Britain's rivals, which matches the general outlines of the LS explanation.[52] Many international relations scholars hold up the IR-2 as a classic case of power transitions caused by LS product cycles.[53] According to this perspective, Germany surpassed Britain in the IR-2 because it was "the first to introduce the most important innovations" in key sectors such as electricity and chemicals.[54] Scholarship on today's rising powers follows a similar template, comparing China's scientific and technological capabilities to Germany's ability to develop major innovations in chemicals.[55]

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

Instead, the IR-2 case supports the GPT mechanism. Spurred by inventions in machine tools, the industrial production of interchangeable parts, known as the "American system of manufacturing," embodied the key GPT trajectory. The U.S. did not lead the world in producing the most advanced machinery; rather, it had an advantage over Britain in adapting machine tools across almost all branches of industry. Though the American system's diffusion also required a long gestation period, the timing matches with America's industrial rise. Incubated by the growing specialization of machine tools in the 1830s and 1840s, the application of interchangeable parts across a broad range of manufacturing industries was the key driving force of America's relative economic growth in the IR-2.

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

52. Rostow 1960, 175.
53. Gilpin 1981, 1987; A. Kennedy 2018, 51; Modelski and Thompson 1996.
54. Akaev and Pantin 2014, 869.
55. See, for example, Beckley 2011, 63-72.

GPT vs. LS Mechanism in the IR-2

Which technological changes could have sparked the economic power transition before World War I? The IR-2 was an age of dizzying technological breakthroughs, including but not limited to the electric dynamo (1871), the first internal combustion engine (1876), the Thomas process for steel manufacturing (1877), and the synthesis of indigo dye (1880). Tracking down how every single technical advance could have affected the growth differentials among Britain, Germany, and the U.S. is an unmanageable task, so I focus on technological changes that could have initiated LS and GPT trajectories. Confirmed to meet the established criteria for leading sectors or GPTs, these technological drivers serve as the fields of reference for assessing the validity of the GPT and LS mechanisms in this case. Specifically, I study the chemicals, electrical equipment, automobile, and steel industries as candidate leading sectors, as well as chemicalization, electrification, the internal combustion engine, and interchangeable manufacture as candidate GPTs.[56]

Equipped with a better grasp of the possible technological drivers of the economic power transition in the IR-2, I now assess the explanatory power of the LS mechanism against the GPT mechanism along three dimensions: impact timeframe, relative phase of advantage, and breadth of growth.

GPT diffusion and LS product cycles present two competing interpretations regarding the IR-2's impact timeframe. Shortly after radical technological breakthroughs, the LS mechanism expects associated growth to be explosive. Under this view, new leading sectors emerged in the 1870s and 1880s off the back of major breakthroughs in electricity, chemicals, the internal combustion engine, and steel. Then, according to the expected timeline of the LS mechanism, these new industries stimulated substantial growth in the early stages of their development, bringing about a pre-WWI upheaval in the industrial balance of power.[57] This leads to the first hypothesis:

H1.LS: The electrical equipment, chemical, automobiles, and/or steel industries made a significant impact on the U.S.'s rise to productivity leadership before 1914.
The GPT trajectory gives a different timeline for when the productivity benefits from major technological breakthroughs were realized on an economy-wide scale. Before stimulating economy-wide growth, the candidate GPTs that emerged in the 1880s — tied to advances in electricity, chemicals, and the internal combustion engine — required many decades of complementary innovations in application sectors and human capital upgrading. These candidate GPTs should have only contributed modestly to the U.S.'s industrial rise before World War I, with impacts, if any, materializing toward the very end of the period.

If the GPT mechanism was operational, the full impact of advances in machine tools should have taken effect during this period. By the start of the IR-2, mechanization

56. For an explanation of GPT and LS selection, which also discusses the overlap between candidate GPTs and leading sectors, see supplementary appendix. Available at: https://jeffreyjding.github.io/research
57. Gilpin 1987, 98,112; Thompson 1990, 226.

spurred by advances in machine tools was at a later stage of development than other candidate GPT trajectories. While crude versions of machine tools were employed in national armories in the early decades of the 19th century, independent machinery-producing firms began to emerge in the leading industrial nations between 1840 and 1880. The mid-19th century saw many important innovations in machine tools, including the turret lathe (1845), the universal milling machine (1861), and the automatic lathe (1870).[58]

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

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

Developments in chemicals, electricity, and internal combustion provide evidence against the LS interpretation. First, 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.[59] Yet, in 1914, the U.S. was home to only seven dye-making firms.[60] Major U.S. chemicals firms did not establish industrial research laboratories like those of German counterparts until the first decade of the 20th century. Du Pont, for instance, opened its first industrial research facility in 1902.[61]

At first glance, the growth of the German chemical industry aligns with LS expectations. Germany was the first to incorporate scientific research into chemicals production, resulting in the synthesis of many artificial dyes before 1880.[62] Overtaking Britain in leadership of the chemical industry, Germany produced 140,000 tons of dyestuffs in 1913, more than 85 percent of the world total.[63]

While Germany's rapid growth trajectory in synthetic dyes was impressive, the greater economic impacts of chemical advances materialized after 1914 through a different pathway: "chemicalization," or the spread of chemical processes across ceramics, food-processing, glass, metallurgy, petroleum refining, and many other industries.[64] Prior to key chemical engineering advances in the 1920s, industrial chemistry was focused on making chemical products, such as synthetic dyes, with limited attention to unifying principles across the manufacture of different products. The rapid expansion of chemical-based industries in the 20th century owed more to these later improvements in chemical engineering than earlier progress in synthetic dyes.[65]

Electrification's impact on U.S. productivity growth mirrored that of chemicaliza-

58. Hobsbawm 1968, 147.
59. Modelski and Thompson 1996, 69; Moe 2007, 426.
60. Ilgen 1983.
61. Bruland and Mowery 2006, 358-366.
62. Hull 1996, 195.
63. Drezner 2001, 12; Murmann and Landau 1998, 30.
64. Noble 1977, 18-19.
65. Little 1933, 7; Rosenberg 1998, 171-176.

tion. From 1880 to 1930, power production and distribution systems gradually evolved from shaft and belt drive systems driven by a central steam engine or water wheel to electric unit drive, a system where electric motors powered individual machines. Unit drive became the predominant method in the 1920s only after vigorous debates over its relative merits in technical associations, the emergence of large utilities that improved access to cheap electricity, and complementary innovations like machine tools that were compatible with electric motors.[66] Estimates of electric motors' share of horsepower in manufacturing as well as the causal effects of electrical patenting activity on per capita growth, along with other quantitative indicators, confirm that electrification's impact on U.S. economic productivity became significant only after 1914.[67]

The diffusion of internal combustion engines across application sectors was also slow. Despite its initial promise, the internal combustion engine never accounted for more than 5 percent of the generation of total horsepower in U.S. manufacturing from 1869-1939.[68] In 1900, there were only 8,000 cars in the entire U.S., and the U.S. motor vehicle industry did not overtake its French competitor as the world's largest until 1904.[69] Furthermore, the turning point for mass production of automobiles, the Ford's installation of a moving assembly line for making Model Ts, transpired in 1913.[70]

When assigning credit to certain technologies for major upheaval in global affairs, awe of the new often overwhelms respect for the old. Yet, careful tracing reveals the persevering impact of earlier developments in machine tools and the steel industry. First, interchangeable manufacture, the GPT trajectory linked to machine tools, was incubated much earlier than electrification and chemicalization. During the IR-2, technical advances in machine tools were incremental, continuous improvements that helped disseminate transformative breakthroughs from the mid-19th century, such as the turret lathe and the universal milling machine.[71] Accordingly, GPT diffusion theory predicts that interchangeable manufacture, unlike other candidate GPTs, did diffuse widely enough to make a significant impact on U.S. industrial productivity before 1914.

Profiles of key application sectors and quantitative indicators validate this expected timeline. Marking 1880 as when "the proliferation of new machine tools in American industry had begun to reach torrential proportions," Rosenberg outlines how three application sectors — sewing machines, bicycles, and automobiles — successively adopted improved metal-cutting techniques from 1880 to 1910.[72] The number of potential machine tool users multiplied fifteen-fold from just 95,000 workers in 1850

66. Devine 1982, 17-45; 1983, 368-371.
67. N. Crafts 2002; Devine 1982, 46-47; Rosenberg 1979, 48.
68. Du Boff 1967.
69. Smil 2005, 121, 136; in 1912, France exported more automobiles than the U.S. Locke 1984, 9n18.
70. Hounshell 1985, 218; Moe 2007, 166-168.
71. Thomson 2010, 10.
72. Rosenberg 1963, 433; see also Hounshell 1985; Piore and Sabel 1984, 20.

to almost 1.5 million in 1910.[73] By 1914, the machine tool industry had grown to 409 firms with a total output of around $31.5 million.[74] Patenting data identifies the last third of the 19th century as when extensive technological convergence characterized the machine tool industry and application sectors.[75]

Of all the candidate leading sectors, the steel industry best fits the expectations of the LS mechanism regarding when industries transformed by the IR-2 stimulated growth in rising powers. Over the course of the IR-2, the U.S. and Germany exploited technological advances that enabled the mass production of steel, such as Bessemer's converter (1856). Both Germany and the U.S. overtook Britain in total steel production by the early 1890s, which matches the timeline of Britain's relative economic decline.[76] U.S. steel output grew from one-fifths of British production in 1871 to almost five times more than British steel output in 1912.[77]

When spelling out how the IR-2 produced an economic power transition, the two mechanisms also stress different phases of technological change. According to the LS mechanism, Britain's industrial prominence waned because it lost its dominance of innovation in the new industries of the IR-2. The U.S. and Germany benefited from the monopoly profits linked to being lead innovators in electricity, chemicals, automobiles, and steel. Germany's industrial rise in this period garners a disproportionate share of attention. Many LS accounts attribute Germany's rise to its dominance of innovations in the chemical industry, "the first science-based industry."[78] 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.[79]

GPT diffusion has different expectations regarding the key driver of productivity differentials. From this alternative perspective, where innovations are adopted more effectively is more important than where they are first introduced. The GPT mechanism expects that Britain lost its industrial preeminence because the IR-2's candidate GPTs diffused more intensively in the U.S. and Germany. This sets up the following hypotheses:

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

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

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

73. Thomson 2010, 9.
74. Census 1918, 269.
75. Thomson 2010, 26.
76. Sanderson 1972, 15.
77. Author's calculations based on crude steel output figures in Mitchell 1998, 466-467; 1993, 356-358.
78. Moe 2007, 125; Drezner 2001, 11-18.
79. Thompson 1990.

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

Cross-country historical evidence on the 2IR's technological drivers illustrates that the U.S.'s true comparative advantages over other advanced economies were rooted in absorption and diffusion capabilities. In electricity, for example, innovation leadership was fiercely contested among the industrial powers. The U.S., Germany, Britain, and France all built their first central power stations, electric trams, and AC power systems within a span of nine years, but the U.S. clearly led in the diffusion of these systems: the spread of incandescent lighting in the U.S. nearly tripled the next closest competitor in 1887; there were ten times as many miles of electric trams in the U.S. than in the next closest competitor in 1900; and U.S. generating capacity in AC power more than doubled that of the next closest competitor in 1912/1913.[80] As for Britain, despite introducing some of the most significant electrical innovations, including the steam turbine, it lagged behind in adopting electrification at scale.[81]

In chemicals, the success of both the U.S. and German chemical industries suggests that no one country monopolized innovation in this sector. Germany's synthetic dye industry excelled not because it generated the initial breakthroughs in aniline-violet dye processes — in fact, those were first pioneered in Britain — but because it had perfected these processes for profitable exploitation.[82] Similar dynamics characterized the U.S. chemical industry.[83]

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. The British share of global chemical exports almost doubled the U.S. share in 1913.[84] Overall, the U.S. derived only eight percent of its national income from foreign trade in 1913, whereas the corresponding proportion for Britain was 26 percent.[85] Even though the U.S. led in electrification, Germany captured around half of the world's exports in electrical products.[86]

If monopoly profits in any leading sector propelled the U.S. and Germany's industrial rise, it would be the steel industry. Germany and the U.S. made remarkable gains in total steel output over this period, and scholars commonly employ crude steel production as a key indicator of British decline and the shifting balance of industrial power in the decades before World War I.[87]

Inspecting the advanced economies' steel industries in further detail, however, undermines the significance of total steel output to this period's economic power

80. Taylor 2016, 189.
81. Institution of Electrical Engineers on Electrical Legislation 1902.
82. Drezner 2001, 12; Hull 1996, 195.
83. Bruland and Mowery 2006, 362; Murmann 2003, 399.
84. Murmann 2003, 401.
85. P. Kennedy 1987, 244.
86. Henderson 1975, 189-190.
87. P. Kennedy 1987, 199-200; Thompson 1990, 213; Modelski and Thompson 1996, 87-88.

transition.[88] In fact, Britain pioneered many major innovations in steelmaking.[89] As trade data shows, the British iron and steel industries maintained a revealed comparative advantage over their rivals throughout the IR-2.[90] How to square this with Germany's dominance in total steel output? In truth, new steelmaking processes created two separate steel industries. Britain shifted toward producing open-hearth steel, which was higher in quality and price. According to the British Iron Trade Association, Britain produced about four times more open-hearth steel than Germany in 1890.[91] Germany produced cheap Thomas steel and exported a large amount at dumping prices. Some of Germany's steel exports went to Britain, where they were processed into higher-quality steel and re-exported. This evidence questions what one scholar calls "the myth of the technological superiority and outstanding productivity of the German steel industry before and after the First World War."[92]

In line with the implications of GPT diffusion, comparative estimates confirm a substantial U.S. lead in mechanization in the early 20th century. In 1907, machine intensity in the U.S. was more than two times higher than rates in Britain and Germany.[93] In 1930, the earliest year for which data on installed machine tools per employee is available, Germany trailed the U.S. in this metric by 10 percent, with an even wider gap in the tools most crucial for mass production.[94]

This disparity in mechanization was not rooted in the U.S.'s exclusive access to special innovations in machine tools. In terms of quality, British machine tools were superior to their American counterparts throughout the IR-2 period, German firms also had advantages in certain fields like sophisticated power technology.[95] Rather, the distinguishing feature of the U.S. machine tool industry was excellence in adapting innovations across industries.[96] Reports by British and German study trips to the U.S. provide some of most detailed, reliable accounts of transatlantic differences in mechanization. German observers traveled to the U.S. to learn from and eventually imitate American interchangeable manufacturing methods.[97] British inspection teams reported that America's competitive edge came from the "adaptation of special apparatus to a single operation in almost all branches of industry"[98] and "eagerness with which [the Americans] call in the aid of machinery in almost every department of industry."[99] When evaluating the significance of certain technological

88. For criticism of the Composite Indicator of National Capability's reliance on steel production as a measure of industrial power, see Beckley 2018; Wohlforth 1999, 13.
89. Hobsbawm 1968, 159.
90. *Yearly Index of Forging and Heat Treating* 1922, 357.
91. Wengenroth 1994, 384.
92. Ibid. 390.
93. Calculations based on data in Timmer, Veenstra, and Woltjer 2016.
94. Ristuccia and Tooze 2013, 959-960.
95. Floud 1976, 68.
96. Saul 1960, 22; Rosenberg 1963, 417.
97. Timmer, Veenstra, and Woltjer 2016, 882-883.
98. Machinery of the United States of America 1855, 32.
99. Whitworth 1969, 387.

innovations to economic leadership in this period, economic historians also elevate machine tools and agree, elevating machine tools and the American system above chemical and electrical innovations.[100]

Regarding the third dimension on which the two mechanisms diverge, breadth of economic growth, the LS trajectory expects that a narrow set of modernized industries drove productivity differentials, whereas the GPT trajectory holds that a broad range of industries contributed to productivity differentials. Given that the pattern of U.S. economic growth is most relevant since it overtook Britain as the economic leader, these differences produce the following testable hypotheses:

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

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

Historical data support the GPT model's predictions of pervasive U.S. productivity growth. Kendrick's detailed study of U.S. productivity growth in this period depicts a relatively balanced distribution. Among the industries studied, nearly 60 percent averaged between one to three percent increases in output per labor-hour from 1899 to 1909.[101] Despite employing 40 percent of all research scientists in 1920, the chemical industry was responsible for only 7 percent of U.S. TFP growth throughout the following decade.[102] Per updates to Kendrick's estimates, "great inventions", roughly corresponding to the candidate leading sectors, accounted for only 29 percent of American total factor productivity (TFP) growth from 1899-1909.[103] From 1899 to 1941, 33 of 38 sectors averaged at least 1 percent annual TFP growth.[104]

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

Although spillovers from interchangeable manufacturing were not boundless, the extension of the American system boosted productivity in a wide range of sectors. Applications of this system of special tools reshaped the processes of making firearms, furniture, sewing machines, bicycles, automobiles, cigarettes, clocks, boots and shoes, scientific instruments, typewriters, agricultural implements, locomotives, and naval ordnance.[105] Its influence covered "almost every branch of industry where articles

100. Hobsbawm 1968, 151; Mokyr 1990, 136.
101. Kendrick 1961.
102. Bakker, Crafts, and Woltjer 2019, 2290.
103. Bakker, Crafts, and Woltjer 2019, 2285; "great inventions" encompass sectors that correspond to chemicals and pharmaceuticals, electricity, the internal combustion engine, and modern communications technologies; see also Bruland and Mowery 2006, 276.
104. Bakker, Crafts, and Woltjer 2019, 2288.
105. Anderson 1877; Hounshell 1985; Rosenberg 1963; Thomson 2010.

have to be repeated."[106] Per a 1930 inventory of American machine tools, the earliest complete survey, nearly 1.4 million metalworking machines were used across 20 industrial sectors.[107] Progress in "certain types of new products developed by the machinery and other producer industries (that) have broad applications across industry lines" were a key source of the "broad, pervasive forces that promote efficiency throughout the economy."[108]

Institutional Complements: GPT Skill Infrastructure in the IR-2

Why was the U.S. more successful than Britain in adapting to the demands of mechanization? According to GPT diffusion theory, the historical data should reveal that the U.S.'s edge was based on education and training systems that broadened and systematized mechanical engineering skills. These institutional adaptations would have resolved two key bottlenecks to the spread of interchangeable manufacture: a shortage of mechanical engineering talent and ineffective coordination between machine producers and users.

The U.S. built a superior system for spreading skills and knowledge about the IR-2's defining GPT. Before 1870, dependence on informal apprenticeships to train mechanical engineers constrained mechanization's potential.[109] Over the next few decades, the U.S. cultivated technical education in mechanical engineering in a diverse set of institutions, including independent centers like Philadelphia's Franklin Institute, specialized engineering programs at higher education institutions such as the University of Cincinnati's cooperative engineering course, technical high schools, and machine tool associations.[110] Stimulated by the passage of the Morrill Act, the number of U.S. engineering schools grew from six in 1862, when the act was passed, to 126 in 1917.[111]

Beyond boosting the number of trained mechanical engineers, these institutional adaptations also improved knowledge flows between the machine tool industry and application sectors. Standardization in various machine processes and components, such as screw threads, helped spread mechanization across disparate markets and communities.[112] Additionally, professional associations of mechanical engineers helped build up the repository of engineering skills to translate advances in machine tools to production systems across many sectors. The most prominent of these were the American Society of Mechanical Engineers, founded in 1880, the American Section of the International Association for Testing Materials, set up in 1898, and the Franklin Institute, which became America's leading technical society around the start of the

106. Anderson 1877.
107. Thomson 2010, 6.
108. Kendrick 1961, 181, 178.
109. Locke 1984, 61; Lundgreen 1990, 55; Scranton 1997, 60; Thomson 2010, 14-15.
110. Nelson and Wright 1992, 1942; Rosenberg and Steinmueller 2013, 1130; Scranton 1997, 65-71.
111. Noble 1977, 24; see also Maloney and Caicedo 2017, 12-13.
112. Hounshell 1985; Noble 1977.

IR-2. These associations coordinated to share best practices and address labor supply issues in mechanical engineering.[113]

Both Britain and Germany fell short of the U.S. standard in GPT skill infrastructure. For Britain, the key gap was in the supply of mechanical engineering talent. During the IR-2, the U.S. outpaced Britain in national engineering density, measured by the number of university-educated engineers per 100,000 male laborers.[114] In 1906, the U.S. had approximately ten times as many engineering students as Britain; at that time, the University of Oxford still had not established an engineering professorship.[115] While British mechanical engineers took pride in their informal apprenticeships, American engineers systematically experimented with machine redesigns, benefiting from training at universities and technical institutes.[116]

Germany's problems were with machine standardization. Though Germany produced many educated mechanical engineers, it was slow to incorporate interchangeable parts and advanced machine tools. According to one of the few scholars to analyze German standard-setting in this period, "no national standards movement was inaugurated in [the machine industry] until after the outbreak of [World War I]."[117] Key German standards bodies and technical colleges prioritized scientific and theoretical education at the expense of practical skills — a trend "most pronounced in mechanical engineering."[118]

Adapting to the new opportunities of interchangeable manufacture was not about cultivating highly skilled scientific talent. The U.S. trailed both Britain and Germany on this front.[119] 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.[120] This accords with research that quantifies the impact of engineering capacity on American industrialization during this period, which finds that indicators of engineering human capital had a stronger effect on income than indicators of novel technology generation.[121]

Analyzing the education and training systems for chemical advances provides a secondary test of which institutions are most apt for national success in technological revolutions. LS accounts point to Germany's scientific education system and industrial research laboratories as key determinants of its competitiveness in chemicals.[122]

113. Noble 1977, 76; Scranton 1997, 69.
114. Ahlström 1982; Maloney and Caicedo 2017.
115. Sanderson 1972, 24-39.
116. Locke 1984; Thomson 2010, 40.
117. Brady 1933, 149; see also Yates and Murphy 2019, 36.
118. Gispen 1989, 122.
119. Hughes 1994, 433; Nelson and Wright 1992, 1940; Rosenberg and Steinmueller 2013, 1129; Nor do differences in general education explain productivity divergences in this period. Romer 1996, 202; Williamson 1996, 296.
120. Bruland and Mowery 2006, 359-360.
121. Maloney and Caicedo 2017, 16.
122. Drezner 2001, 12n33; Henderson 1975, 186; Moe 2007, 4, 142.

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.[123]

Based on another model of when and how advances in chemicals translated into substantial economic gains — the chemicalization trajectory described earlier — GPT diffusion theory highlights a different set of institutional competencies. The U.S. pioneered a chemical engineering discipline that facilitated the gradual chemicalization of many industries. American institutions of higher education, most notably MIT, quickly adopted the unit operations model and helped cultivate a common language and professional community of chemical engineering.[124] 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."[125]

Germany was slow to develop an infrastructure for supporting chemical engineers. Up through the interwar period, "a unique occupation combining mechanical and chemical expertise failed to coalesce in Germany."[126] Chemical engineering did not become a distinct academic subject area in Germany until after the Second World War. German universities did not equip chemists with engineering skills, thereby shifting the burden of training to firms.[127]The German chemical industry maintained a strict division of labor between chemists and mechanical engineers. This resulted in more secrecy, less inter-firm communications, and a failure to exploit externalities from common chemical processes.[128]

Alternative Explanations

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.[129] My aim is not to sort through all possible causes of British decline. Rather, I am probing the mechanisms behind an established connection between the IR-2's technological breakthroughs and 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

123. Sanderson 1972, 23; see also Locke 1984, 61.
124. Guédon 1980, 45-76; Noble 1977, 26-27; Rosenberg 1998, 171.
125. Rosenberg and Steinmueller 2013, 1145.
126. Divall and Johnston 1998, 204.
127. Rosenberg 1998, 192.
128. Guédon 1980; On Britain's delayed adaptation to chemical engineering, see Divall and Johnston 1998, 212; Rosenberg and Steinmueller 2013, 1146.
129. P. Kennedy 1987, 228.

economic leadership. Aside from the LS mechanism, which has been examined in detail, two other explanations, related to neorealist theories of threat and varieties of capitalism, deserve further examination.

How did external threats influence technological leadership in the IR-2? Scholars have argued that U.S. military investment, mobilized against the threat of a major war, was crucial to the development of many GPTs.[130] Likewise, in the early 19th century U.S. national armories subsidized the production of small arms with interchangeable parts, which some studies argue was crucial to the diffusion of the American system to other industries in the second half of the century.[131]

Though firearms production was an important experimental ground for mechanized production, military support was not necessary to the development of the American system. Questioning the necessity of government funding and subsidies for the spread of the American system, one study credits the development of interchangeable manufacture to four civilian industries: clock manufacturing, axe manufacturing, typewriter manufacturing, and watch manufacturing.[132] In particular, the clock industry played a crucial role in diffusing mechanized production practices. More attuned to the dynamics of the civilian economy than the small arms manufacturers, clockmakers demonstrated that interchangeable manufacture could drastically increase sales and cut costs.[133]

Moreover, this argument ignores that the spread of the American system, 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 less than .3 percent of value-add in American industry from 1850-1940.[134]

Another threat-based argument posits that countries that face more external threats than internal rivalries will achieve more technological success.[135] 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).[136] 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.[137] This explanation, therefore, provides limited leverage in the IR-2 case.

A second set of alternative explanations posits that giant managerialist firms were crucial to U.S. success. Related to the varieties of capitalism tradition, this explanation

130. Ruttan 2006.
131. Deyrup 1948; Smith 1985.
132. Hoke 1990.
133. Hounshell 1985, 50-61.
134. Deyrup 1948, 6.
135. Taylor 2016.
136. The Spanish-American War in 1989 is an exception, but this lasted one year and occurred late in the period.
137. Taylor 2016, 238.

highlights U.S. industrial governance structures that enabled big business and the resulting economies of scale and scope that came from mass production.[138]

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.[139] From 1899 to 1909, sectors that relied on batch and custom production, including machine tools, accounted for a third of value added in manufacturing.[140] 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.[141]

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 automobiles and other mass-produced goods, networks of medium-sized firms still dominated important segments of new industries, including the production of electric motors. One third of the fifty largest manufacturing plants in the United States made custom and specialty goods.[142] "No single governance structure matched the requirements of production in all areas," notes Kitschelt.[143]

First Industrial Revolution

Few historical events have shaken the world like the IR-1 (1780-1840). Among the manifold contours and consequences of the IR-1, two phenomena stand out for my purposes. The first is the remarkable technological progress that inaugurated the IR-1 period. Everything was changing in part because so many things were changing — water frames, steam engines, puddling processes not least among them. The second is Britain's rise to unrivaled hegemony. Britain became the world's most advanced industrial power by the mid-19th century. Crucially, Britain's economic dominance was 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."[144] Starting in the 1820s, Britain sustained productivity growth at levels substantially higher than France and the Netherlands.[145]

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

138. Chandler 1990; Kim and Hart 2001.
139. Scranton 1997, 7.
140. Census 1913, 40-43.
141. Scranton 1997, 17.
142. Ibid. 7.
143. Kitschelt 1991, 472.
144. A. Kennedy 2018, 53.
145. Bairoch 1982, 322; Bolt and Zanden 2020, 9; N. F. R. Crafts 1995, 752.

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

The process-tracing evidence from the IR-1 case challenges many of these stylized views. Previous accounts conflated the significance of technical advances with their rapid diffusion. Many prominent breakthroughs, including the steam engine, only made limited contributions to Britain's rise to industrial prominence in this period due to their delayed diffusion.[146] 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.[147] While the growth of British cotton exports was remarkable, British industrialization drew from widespread technological advances connected to access to cheap iron and mechanization.[148] 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, institutional adjustments raced to cultivate the skills required to keep pace. As expected by GPT diffusion theory, Britain benefited from a superior system for disseminating GPT-related knowledge, especially its institutional advantages in widening the talent base of mechanically-skilled engineers. In contrast to the common refrain that Britain's leadership was rooted in the genius of individual innovators like James Watt, the historical data shows that Britain owed its success to the "tweakers" and "implementers" who facilitated mechanization across many industries.[149] In fact, France and other industrial rivals were far ahead in the institutions of higher technical education that trained expert scientists and engineers.[150] 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.[151]

146. Nuvolari, Verspagen, and Tunzelmann 2011, 292; Tunzelmann 1978.
147. Berg 1985, 265; MacLeod and Nuvolari 2009.
148. Horrell, Humphries, and Weale 1994, 557; MacLeod and Nuvolari 2009, 223; Sullivan 1990, 354.
149. Meisenzahl and Mokyr 2011, 446; see also Cookson 2018, 154.
150. Moe 2007, 42-43.
151. Crouzet 1967, 239; Lundgreen 1990; Jacob 1997.

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 "Third Industrial Revolution" (IR-3) came to refer to an epochal shift from industrial systems to information-based and computerized systems.[152] Amidst this upheaval, many thought Japan would follow in the footsteps of Britain and the U.S. to become the "Number One" industrial power.[153]

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.[154] In the late 1980s and early 1990s, a torrent of works bemoaned the loss of U.S. technological leadership to Japan.[155] "Japan has...become the undisputed world economic champion," declared Clyde V. Prestowitz, Jr, a former U.S. trade negotiator, in his best-selling book on U.S.-Japan relations.[156] Many even feared that Japan would convert its economic strength into military power and threaten international security.[157]

Historical precedents loomed over these worries. U.S. policymakers feared that falling behind Japan in key technologies would, like relative declines experienced by previous 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.[158] Often alluding to the LS mechanism, these comparisons highlighted Japan's lead in technologically progressive industries, such as consumer electronics or semiconductors. As Mowery and Rosenberg wrote in 1991, "Rapidly growing German domination of dyestuffs helped to propel that country into the position of the strongest continental industrial power. The parallels to the Japanese strategy in electronics in recent decades are striking."[159] Many voices called for the U.S. to

152. Galambos 2013, 2-4.
153. Vogel 1979.
154. Gilpin 1991, 15.
155. Dertouzos, Solow, and Lester 1989; Freeman, Clark, and Soete 1982, 166, 188; Nelson and Wright 1992, 1932.
156. Prestowitz 1989, 2.
157. Gilpin 1996, 428; Kissinger 1987.
158. Freeman 1987; P. Kennedy 1987, 529; Nelson and Wright 1992; Piore and Sabel 1984.
159. Mowery and Rosenberg 1991, 80.

mimic Japan's innovation system, characterized by the *keiretsu* system of industrial organization and the activist role of the Ministry of International Trade and Industry, which was viewed as critical to its strength in leading sectors.[160]

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, Japan's economy did grow at a remarkable pace, averaging an annual 2.4 percent increase in TFP between 1983 and 1991. However, Japan's TFP growth stalled in the 1990s at an average of .2 percent per year — a period known as its "lost decade." By 2002, the per capita GDP gap between Japan and the U.S. was larger than it had been in 1980.[161] Becoming the world's leading producer in high-tech industries did not catalyze Japan's overtaking of the U.S. as the lead economy. Japan took advantage of the IR-3's opportunities by cornering the market in new, technologically progressive industries, fulfilling the conditions posited by the LS mechanism for Japan to become the foremost economic power. This makes the IR-3 case evidence particularly damaging for the LS theory.

From a different perspective, the case evidence shows that Japan did not lead the U.S. in the diffusion of general-purpose information and communications technology (ICT), which means the conditions for an economic power transition under the GPT mechanism were not present in the IR-3. During this period, Japan's TFP growth in ICT-*producing* sectors was similar to the U.S.'s trajectory; however, in sectors that intensively *used* IT, Japan's TFP growth lagged far behind that of its rival.[162] 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.[163] 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.[164]

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

160. Freeman, Clark, and Soete 1982, 198-199; Prestowitz 1989.
161. Jin 2016.
162. Fukao and Tsutomu 2007; Jorgenson and Motohashi 2005.
163. Moe 2009, 219; Pilat, Lee, and Van Ark 2003, 60-61.
164. Pilat, Lee, and Van Ark 2003, 61.

Japan's per year.[165] Closer university-industry linkages in the U.S. system of higher education, compared to arrangements in Japan or Europe, provided a "thicker basis" for skill adjustments to computerization.[166] In this respect, evidence from this deviant case points toward GPT diffusion as the preferred explanation.

Conclusion

This article has introduced and defended a novel explanation for how and when technological revolutions affect economic power transitions. My findings fill significant gaps in existing scholarship on how technological change affects the global balance of power, with broader implications for studying the effects of technological change on international politics. Scholars recognize that technological revolutions can disrupt the economic balance of power, but few have systematically investigated how this process occurs. GPT diffusion theory challenges the standard explanation based on leading sectors, which exerts enduring influence in policy and academic circles.[167] Since shifts in economic leadership often precede disruptions to the military balance of power and hegemonic conflict, this paper also contributes to questions power transition scholars have long grappled with related to when and why hegemons come and go.[168]

Additionally, GPT diffusion theory challenges accepted thinking about how AI and other revolutionary technologies could affect the current U.S.-China power balance, which often draws on the LS template. If the key technological trajectory is the relative success of the U.S. and China in adopting GPTs across many industries in a gradual, decades-long process, the most important institutional factors 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.[169] Future research should also probe the limitations of translating lessons from past industrial revolutions to the current period. This might address factors such as the globalization of innovation, qualities unique to digital technologies, and changes in the overall pace of technological change.

More broadly, this paper demonstrates a method to unpack the causal effects of technological change on international politics. One obstacle to this form of inquiry, 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.[170] This article takes the middle ground. Technology does not determine the rise and fall of great powers, but

165. Arora, Branstetter, and Drev 2013, 771.
166. Hart and Kim 2002, 10.
167. Drezner 2019, 289; Tellis et al. 2000.
168. Reuveny and Thompson 2001; Wohlforth 1999, 32.
169. Space limitations prevent a more comprehensive application of GPT diffusion theory to U.S.-China technological competition. The supplementary appendix includes an extended discussion.
170. Sprout 1963, 187.

some technological trends, such as 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.[171]

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171. Dafoe 2015.

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