Engines of Power: Electricity, AI, and General-Purpose Military Transformations

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Abstract

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, however, come from more fundamental advances arising from "general-purpose technologies" (GPTs), such as the steam engine, electricity, and the computer. Building from scholarship on GPTs and economic growth, we argue that the effects of GPTs on military effectiveness are broad, delayed, and shaped by indirect productivity spillovers. We label this impact pathway a "general-purpose military transformation" (GMT). Contrary to studies that predict GPTs will rapidly diffuse to militaries around the world and narrow gaps in military capabilities, we show that GMTs can reinforce existing balances if leading militaries have stronger linkages to a robust industrial base in the GPT than challengers. Evidence from electricity's impact on military affairs, covering the late 19th and early 20th centuries, supports our propositions about GMTs. To probe the explanatory value of our theory and account for alternative interpretations, we compare findings from the electricity case to the military impacts of submarine technology, a non-GPT which emerged in the same period. Finally, we apply our findings to contemporary debates about artificial intelligence, which could plausibly cause a profound GMT.

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I. Introduction

"AI is the new electricity," as the common refrain goes. It is now standard for social scientists and policymakers to compare artificial intelligence (AI) with electricity, the quintessential general-purpose technology (GPT). Military innovation scholars acknowledge this comparison, yet they have done little systematic research into the implications of GPTs. Much work treats AI as a relatively narrow technological advance, in the mold of nuclear weapons or aircraft carriers.[1] It does not reckon with AI as a GPT, differentiated by its pervasiveness, scope for continual improvement, and strong synergies with other technologies. The comparison is gestured at but not seriously examined.

How do GPTs, like electricity and AI, influence the military balance of power? Taking economic productivity as an analogue for military effectiveness,[2] we extend insights on GPTs and economic growth to the implications of GPTs for military transformations. Differing from narrower technologies, GPTs influence military effectiveness through a pathway characterized by three features: breadth of impact spread across many military innovations, delayed timeline of widespread adoption, and indirect productivity spillovers. We call this process a *general-purpose military transformation* (GMT).

Equipped with a better understanding of how GPTs shape military effectiveness, we posit that GMTs differentially advantage militaries connected to a robust industrial base in the associated GPT. Regarding narrower technologies, differentials in their military adoption can be explained by the fit between a single military innovation and a military's culture, financial resources, organizational

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[1] The burgeoning narrative of an "AI arms race" exemplifies this point. Zwetsloot, Remco, Helen Toner, and Jeffrey Ding. "Beyond the AI Arms Race." *Foreign Affairs*, November 16, 2018.

[2] Military effectiveness is "the process by which armed forces convert resources into fighting power." Millett, Allan R., Williamson Murray, and Kenneth H. Watman. "The Effectiveness of Military Organizations." *International Security* 11, no. 1 (1986): 37–71, 37. They and others argue that the efficiency of this conversion process, not just total combat power, is central to military effectiveness. Brooks, Risa A., and Elizabeth A. Stanley, eds. *Creating Military Power: The Sources of Military Effectiveness*. 1st edition. Stanford, Calif: Stanford University Press, 2007, 10, 13.

capital, tactical incentives, etc.[3] Whiles these factors affect the adoption of *specific* military innovations linked to a GMT, a military's ability to draw on a robust industrial base in the GPT affects *all* military innovations linked to a GMT. To effectively exploit a GMT, militaries must draw on talent, industry, and infrastructure in the civilian realm, where the momentum for a GPT's development lies.

To empirically support our reasoning about GMTs, we examine the evolution of electricity in military affairs. Surprisingly, very little scholarship directly examines the military consequences of electricity — widely recognized as one of the most significant technological innovations in history.[4] In the latter half of the 19th century, a cluster of electrical innovations, including the electric dynamo (1866) and the transformer (1886), helped create a versatile energy system with many industrial applications in lighting, communications, transportation, and machinery. A GPT was born. Looking back after World War II, informed observers ranked electricity among the three great influences on naval warfare in the 20th century.[5] Eliminating the "naval" qualifier would not be a stretch.

Military electrification exhibited the three theorized features of a GMT. First, the impact of electricity on military power materialized through a broad range of military applications, including communications, fortifications, transportation, and weapon control systems. Second, electricity significantly upgraded industrial productivity, which increased military production potential. Third,

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[3] Adamsky, Dima. *The Culture of Military Innovation: The Impact of Cultural Factors on the Revolution in Military Affairs in Russia, the US, and Israel* (Stanford, CA: Stanford University Press, 2010); Gilli, Andrea, and Mauro Gilli. "The Spread of Military Innovations: Adoption Capacity Theory, Tactical Incentives, and the Case of Suicide Terrorism." *Security Studies* 23, no. 3 (July 3, 2014): 513–47; Horowitz, Michael. *The Diffusion of Military Power: Causes and Consequences for International Politics* (Princeton, NJ: Princeton University Press, 2010). For a persuasive account of how battlefield experience and doctrinal adjustments shape transatlantic gaps in military adaptation to information technology, see Farrell, Theo, and Sten Rynning. "NATO's Transformation Gaps: Transatlantic Differences and the War in Afghanistan." *The Journal of Strategic Studies* 33, no. 5 (2010): 673–99.

[4] Brown, Shannon Allen. "Annihilating Time and Space: The Electrification of the United States Army, 1875-1920." University of California at Santa Cruz, 2000; Headrick, Daniel R. *The Invisible Weapon: Telecommunications and International Politics, 1851-1945* (Oxford, New York: Oxford University Press, 1991); Hezlet, Arthur Richard. *The Electron and Sea Power* (London: P. Davies, 1975).

[5] Hezlet, *The Electron and Sea Power*.

like the slow progression of electrification across economic sectors, the spread of electrical innovations across military branches and divisions took many decades.

In line with our hypothesis, the extent to which militaries took full advantage of electrification depended on their connection to a robust base of electrical talent, industry, and infrastructure in the civilian economy. Taking advantage of a GMT goes beyond acquiring a single electric dynamo or adopting one electricity-related military innovation. The Russian military, for instance, pioneered the use of electronic countermeasures in combat in 1904. However, unlike Britain, a leader in military electrification, Russia's weak industrial base of electrical technology prevented it from fully exploiting the electrification GMT.[6] Evidence of Russia's ability to keep pace with Britain in adopting submarines, a non-GPT, help separate the effects of the GPT dimension from other factors that could explain this military electrification gap.

This article directly engages with key academic and policy debates. First, we develop a novel explanation for how GPTs alter the military balance of power. The limited literature on GPTs and military power posits that because GPTs are characterized by private sector dominance and relatively low fixed costs, they rapidly diffuse from technological leaders to laggards, thereby narrowing gaps in military capabilities.[7] We argue, instead, that laggards do not inevitably catch up in GMTs. Rather, the long, slow process of a GMT differentially advantages militaries that can tap into a robust industrial base in the GPT. By highlighting the unique effects of GPTs, we contribute to a growing approach to studying the impacts of emerging technologies on international security, which focuses

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[6] Russia's per capita production of electricity did not reach the UK's 1910 levels until 1930, per our calculations based on data in Comin, Diego A, and Bart Hobijn. "The CHAT Dataset." Working Paper. National Bureau of Economic Research, September 2009.

[7] Drezner, Daniel W. "Technological Change and International Relations." *International Relations* 33, no. 2 (June 2019): 286–303, 300; Horowitz, Michael. "Artificial Intelligence, International Competition, and the Balance of Power." *Texas National Security Review* 1, no. 3 (2018)., 39.

on specific technological dimensions such as complexity,[8] disruptiveness,[9] and dual-use.[10] Moreover, departing from the tendency to focus on relatively narrow technological developments, such as new weapons systems,[11] our study of electricity broadens the universe of cases for investigating the military implications of technological change.[12]

Second, our research directly bears on current debates over how AI could shift the balance of military power.[13] To date, much of the discussion emphasizes the narrow effects of specific AI applications, such as autonomous weapons.[14] AI's potential influence on military power through its effects on industrial productivity is rarely considered. Some scholars also suggest that AI will significantly transform military effectiveness in a relatively short timeframe, and that AI will enable rising powers to leapfrog the U.S. in military strength. As the conclusion will show, a GMT-based approach points toward different conclusions on all these fronts.

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[8] Gilli, Andrea and Mauro Gilli. "Why China Has Not Caught Up Yet: Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage." *International Security* 43, no. 3 (February 1, 2019): 141–89.

[9] Mukunda, Gautam. "We Cannot Go On: Disruptive Innovation and the First World War Royal Navy." *Security Studies* 19, no. 1 (February 26, 2010): 124–59.

[10] Stowsky, Jay. "Secrets to Shield or Share? New Dilemmas for Military R&D Policy in the Digital Age." *Research Policy* 33, no. 2 (March 1, 2004): 257–69.

[11] See one systematic review of 60 different cases of military innovation, sourced from 73 books and articles on the subject. Horowitz, Michael C., and Shira Pindyck. "What Is A Military Innovation And Why It Matters." SSRN Scholarly Paper. Rochester, NY: Social Science Research Network, 2020. https://doi.org/10.2139/ssrn.3504246.

[12] The "Revolution in Military Affairs" concept (see, for example, Krepinevich, Andrew F. "Cavalry to Computer: The Pattern of Military Revolutions." *The National Interest* 37 (1994): 30–42) references how basic innovations in the commercial domain can drive military-technical revolutions. Our contribution is to elucidate a specific pathway by which GPTs could have a significant impact on military effectiveness. On the related concept of military transformation, see Farrell, Theo. "The Dynamics of British Military Transformation." *International Affairs (Royal Institute of International Affairs 1944-)* 84, no. 4 (2008): 777–807.

[13] Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power"; Kania, Elsa B. "Battlefield Singularity: Artificial Intelligence, Military Revolution, and China's Future Military Power." Center for a New American Security, 2017; Payne, Kenneth. "Artificial Intelligence: A Revolution in Strategic Affairs?" *Survival* 60, no. 5 (September 3, 2018): 7–32. For an important study that highlights how AI could affect states' perceptions of the balance of power via the emerging AI-nuclear strategic nexus, see Johnson, James. "Inadvertent Escalation in the Age of Intelligence Machines: A New Model for Nuclear Risk in the Digital Age." *European Journal of International Security*, October 15, 2021, 1–23.

[14] Some texts analyze autonomous weapons because they present thorny legal and governance challenges. Bode, Ingvild, and Hendrik Huelss. "Autonomous Weapons Systems and Changing Norms in International Relations." *Review of International Studies* 44, no. 3 (July 2018): 393–413; Garcia, Denise. "Future Arms, Technologies, and International Law: Preventive Security Governance." *European Journal of International Security* 1, no. 1 (February 2016): 94–111; Scharre, Paul. *Army of None: Autonomous Weapons and the Future of War* (New York ; London: W. W. Norton & Company, 2018).

In what follows, we first deduce key propositions about the impact of GPTs on military affairs by adapting insights from economic and historical studies of GPTs. Our theory of GMTs is composed of three features influencing how and when GPTs affect military affairs, along with an explanation for why GMTs differentially advantage certain militaries. Leveraging primary and secondary accounts, we then illustrate the explanatory value of our theory with a historical case study: the evolution of electricity in military affairs. Finally, we conclude by discussing the limitations of our analysis and reflect on the military implications of artificial intelligence, which is plausibly a GPT as impactful as electricity.

II. Theory: GPTs and Military Power

Economists and economic historians largely agree that GPTs are defined by three characteristics. First, GPTs offer *great potential for continual improvement*. While all technologies offer some scope for improvement, a GPT supports an entire research paradigm that drives forward adaptations and modifications. Second, GPTs are characterized by their *pervasiveness*. A wide range of sectors apply GPTs in a wide variety of uses. Third, GPTs have *strong technological complementarities*, which means their full benefits come from adjustments in related technologies. [15] For instance, complementary advances in machine tools were critical to factory electrification, enabling a power distribution system in which electric motors drove individual machines.[16] Tying all three characteristics together, David describes GPT adoption as an "extended trajectory of incremental

[15] Bresnahan, Timothy, and Manuel Trajtenberg. "General Purpose Technologies 'Engines of Growth'?" *Journal of Econometrics* 65, no. 1 (1995): 83–108; Lipsey, Richard G, Kenneth Carlaw, and Clifford Bekar. *Economic Transformations: General Purpose Technologies and Long-Term Economic Growth* (Oxford; New York: Oxford University Press, 2005).
[16] Devine, Warren D. "From Shafts to Wires: Historical Perspective on Electrification." *The Journal of Economic History* 43, no. 2 (June 1983): 347–72.

technical improvements, the gradual and protracted process of diffusion into widespread use, and the confluence with other streams of technological innovation."[17]

Capitalizing on this extended GPT trajectory is neither easy nor automatic. Variation across domestic institutions, international linkages, and other factors can generate significant cross-national differences in GPT adoption, even between advanced economies. Take, for example, the gap in computer usage between the U.S. and Japan from 2000-2005, decades after initial innovations in personal computing. During this period, according to our calculations based on the Cross-country Historical Adoption of Technology (CHAT) dataset, the U.S.'s computerization rate nearly doubled Japan's figure.[18]

TRANSLATING GPT THEORY TO MILITARY TRANSFORMATION

By adapting insights from studies of GPTs and economic productivity, we theorize about how GPTs transform military effectiveness. Taking military divisions and branches as application sectors for a GPT, we translate the pattern of how a GPT spreads across a national economy to a military context. We first deductively articulate three key features of GMTs. Equipped with a more complete view of GMTs, we then pinpoint why different militaries are better able to exploit GMTs.

For our translation to work, we must establish that the characteristics of GPTs also apply to military transformation. GPTs possess great potential for continual improvement, become pervasive in their wide variety and range of military applications, and have strong technological complementarities with existing military technology systems. The computer is one such example. Upon entering military systems, it continually improved along many technical dimensions, provoked

[17] David, Paul A. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *The American Economic Review* 80, no. 2 (1990): 355–61, 356. Like this quote, we use the term "diffusion" to refer to the spread, or adoption, of a technological change within one country's economic or military system. We recognize the rich IR literature on diffusion that discusses how norms and policies spread across countries (e.g., Finnemore, Martha, and Kathryn Sikkink. "International Norm Dynamics and Political Change." *International Organization* 52, no. 4 (1998): 887–917). When we discuss how electricity and other technologies spread from one military to another, we use the term "international diffusion."

[18] Our computerization indicator is computers per capita. Comin and Hobijn, "The CHAT Dataset."

significant structural changes, and eventually found a wide variety of uses across many branches and units.[19]

We can differentiate GPTs from militarily significant innovations that meet some but not all three of the GPT criteria. Consider dual-use technologies, which have both commercial and military applications. Some dual-use technologies, such as aircraft, exhibit continual improvement and offer strong technological complementarities. Aircraft propulsion systems, however, have a limited variety and range of applications which means we should not expect them to give rise to GMTs. The breadth of the transformations produced by GPTs often warrant the "-ization" suffix. The computerization, or digitalization, of the military describes how computer advances prompted a wide array of innovations across the entire military. There is no equivalent for aircraft engines.[20]

Of course, GMTs differ from GPT-driven economic transformations. Unlike the market dynamics of a nation's economy, intra-military competition involves different units pursuing a nominal shared mission and budget flows from one primary source. Military effectiveness and economic productivity are analogous but not the same; assessing the impact of technological innovations in the military realm is much more difficult than in the civilian economy.[21] Despite these differences, some of the ways in which GPTs interact with military organizations follow a similar trajectory as GPTs in economic systems. In particular, the first two features of GMTs, regarding their broad impact pathway and prolonged timeline of diffusion, draw directly from stylized facts in the existing GPT literature.

Like translations of all kinds, adapting the foundations of GPT theory to military affairs requires some modifications. The full effects of GMTs must include GPT-induced boosts to military

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[19] O'Hanlan, Michael. "A Retrospective on the So-Called Revolution in Military Affairs, 2000-2020." Washington, DC: Brookings, 2018, 20.
[20] All GPTs are dual-use, but not all dual-use technologies are GPTs. The diversity of potential applications for many dual-use technologies is limited.
[21] Rosen, Stephen Peter. *Winning the Next War: Innovation and the Modern Military* (Ithaca, New York: Cornell University Press, 1994), 46.

production capabilities. Additionally, militaries are typically reliant on the civilian economy to advance the GPT's development, particularly after its initial incubation, which means the trajectory of a GMT will depend on a military's connection to the evolution of a GPT in the civilian economy.[22] The rest of this section describes the three key characteristics of GMTs in more detail.

GMTS: THREE FEATURES OF GPT TRAJECTORIES IN MILITARY AFFAIRS

First, GPTs directly enhance military effectiveness by spurring a wide range of military innovations. Studies of military innovation often gravitate to the most visible and graphic part of warfare: the projectile or other mechanism of force.[23] In contrast to the impacts of weapons technology on military effectiveness, which materialize through a relatively narrow pathway, GPTs produce many downstream applications with various uses across the entire military. For instance, one function of computers, the capability to process large amounts of data, bears on military targeting, logistics management, decryption, and many other domains. The impact of a GPT on military effectiveness depends on the distribution over all such functions.

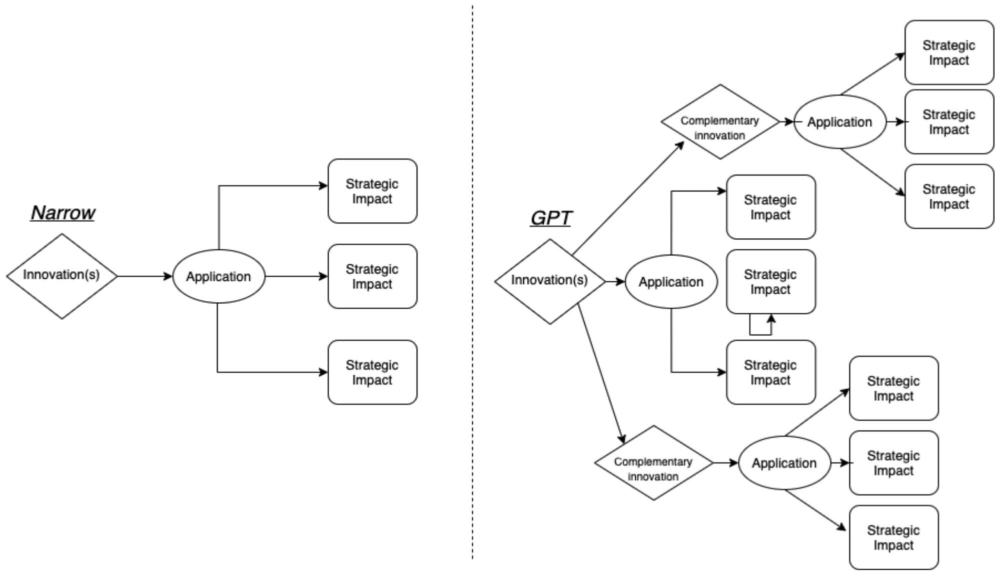
As a result, the foreseeability of a GPT's effect on the conduct of warfare is very limited. GPTs will influence military effectiveness in unanticipated ways, often through lengthy causal chains that involve complementary innovations in adopting military sectors. Although a certain degree of unpredictability applies to the effects of all technologies on military affairs, the breadth of military applications affected by technological changes can vary. Some innovations present a very limited set of applications, though these applications can interact with the strategic landscape in many ways (Figure 1). Nuclear fission technology, for instance, had a relatively bounded set of military

[22] An important literature emphasizes that military investment contributed to incubating some GPTs. See, for example, Ruttan, Vernon W. *Is War Necessary for Economic Growth?: Military Procurement and Technology Development* (Oxford; New York: Oxford University Press, 2006). Military investment, however, is not *necessary* for seeding GPTs, as the history of commercially initiated developments in steam engines and electricity show (Bresnahan and Trajtenberg, "General Purpose Technologies 'Engines of Growth'?" 95-96).

[23] Beckley, Michael. "Economic Development and Military Effectiveness." *Journal of Strategic Studies* 33, no. 1 (February 1, 2010): 43–79, 55.

applications — namely, nuclear weapons — but the interaction between nuclear weapons and the strategic landscape evolved in multifaceted, unpredictable ways. However, the set of possible military applications for GPTs is much larger than the corresponding set for other technologies.

Figure 1: The Military Technology Stack — Two Impact Pathways



Second, GPTs indirectly affect military effectiveness by significantly upgrading industrial production potential. This constitutes a key element of military power.[24] Analyzing hundreds of battles and wars from 1898 to 1987, Beckley finds a positive relationship between economic productivity and military effectiveness. Separate from its total economic output, a more economically efficient nation will translate its economic resources into superior weapons and military organization.[25]

Assessed on their own merits alone, some of the most transformative technological changes do not tip the scale far enough to significantly affect overall industrial productivity.[26] As "engines of growth," GPTs are different because their impact on productivity comes from accumulated

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[24] Kirshner, Jonathan. "Political Economy in Security Studies after the Cold War." *Review of International Political Economy* 5, no. 1 (January 1, 1998): 64–91., 66.
[25] Beckley, "Economic Development and Military Effectiveness."
[26] Fogel, Robert William. *Railroads and American Economic Growth: Essays Econometric History* (Baltimore: Johns Hopkin, 1964, 235).

improvements across a wide range of complementary sectors. Put simply, they cannot be judged on their own merits alone.[27] According to empirical studies of the steam engine, electricity, and information and communications technologies, the arrival of GPTs precedes a wave of economy-wide productivity growth.[28]

Third, the most consequential impacts of GPTs on military effectiveness occur only after a long period of gestation. In the 1980s, many observers bemoaned the computer's failure to induce a surge of productivity growth, leading to Robert Solow's famous quip: "We see the computers everywhere but in the productivity statistics." Eventually, we did see the computers in the productivity statistics. Compared to other technologies, GPTs exhibit a more pronounced diffusion lag due to their substantial demands for complementary innovations, organizational changes, and skills adjustments.[29] We expect similar delayed timelines in the military domain.

This extended trajectory raises difficult questions regarding when a GMT ends. One could trace recent advances military electronics and precision warfare back to 19th-century electrical innovations. For our purposes, we date this to when a GPT spreads across a wide range of military applications.[30] Oftentimes, other fundamental advances, such as transistor innovations in the 1940s, initiate a new GPT trajectory. Thus, advances in precision warfare, though built on a base of electrical advances, are more connected with the transistor GMT than the electrical one.

GMTS AND DIFFERENTIAL ADVANTAGES

We hypothesize that militaries more connected to a strong industrial base in the GPT are better positioned to exploit GMTs. The broad applicability of GPTs across many sectors, combined

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[27] Bresnahan and Trajtenberg, "General Purpose Technologies 'Engines of Growth'?"
[28] Ruttan, *Is War Necessary for Economic Growth*, 5; David, "The Dynamo and the Computer"; Brynjolfsson, Erik, Daniel Rock, and Chad Syverson. "Artificial Intelligence and the Modern Productivity Paradox: A Clash of Expectations and Statistics." National Bureau of Economic Research, November 6, 2017.
[29] Brynjolfsson et al., "Artificial Intelligence and the Modern Productivity Paradox"; David, "The Dynamo and the Computer."
[30] In the electricity case, this occurs during WWII.

with the fact that the civilian economy presents many more application scenarios than the military realm, means that the momentum for a GPT's evolution lies in the civilian realm. Successful adaptation to a GMT requires militaries be able and willing to accommodate civilian-guided GPT development, including by adopting commercial technical standards and managing imbalanced distribution of talent. This distinguishes GPTs from dual-use technologies like aircraft parts and nuclear power, where military and civilian development trajectories significantly diverge, and military capabilities are less dependent on civilian ones.[31]

This proposition engages with claims that GPTs level the military balance of power. Arguing that GPTs rapidly diffuse from technological leaders to laggards, Drezner posits that "general purpose tech has a greater leveling effect than prestige tech."[32] Horowitz also links GPTs to a leveling effect. "If commercially-driven AI continues to fuel innovation, and the types of algorithms militaries might one day use are closely related to civilian applications, advances in AI are likely to diffuse more rapidly to militaries around the world," he writes. "This could change the balance of power, narrowing the gap in military capabilities not only between the United States and China but between others as well."[33]

A clearer understanding of GPT adoption suggests modifications to arguments about leveling effects. In our view, a military's acquisition of a single electric dynamo should not count as successful adoption, as this does not capture whether the military has meaningfully incorporated the GMT associated with electricity. That GPTs are driven forward by civilian applications does not necessitate that they will diffuse quickly to militaries that are technological laggards. Instead,

[31] For instance, maintaining a strong nuclear weapons capability does not depend on the entire industrial base's strength in civilian nuclear applications.
[32] Drezner, "Technological Change and International Relations," 300. Prestige technologies such as space exploration programs, according to Drezner, have higher fixed costs and public sector involvement than GPTs.
[33] Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power," 39. Horowitz also notes countervailing factors in favor of non-leveling, including the constraint of computing costs, which could price out all but the wealthiest countries from adopting higher-end AI capabilities.

adapting to GMTs is a protracted, challenging process that differentially advantages militaries able to tap into a robust industrial base in the associated GPT. Therefore, a GPT will retrench existing military balances if the countries with strong militaries are also those that can tap into robust civilian sectors linked to the GPT.[34]

III. Case Study: The Electrification of Warfare (late 19th and early 20th centuries)

RESEARCH DESIGN AND CASE SELECTION STRATEGY

To evaluate our theory, we investigate the impact of electricity on military affairs. Electricity is considered the prototypical GPT, making it a representative case for studying GMTs. The frequent comparisons made between AI and electricity serve as an additional advantage of our case selection. The electrification of warfare is also substantively important. Despite being widely recognized as one of the most significant technological changes in history, electricity's military impact has not received much scholarly attention.[35]

If the evidence from the electricity case supports our theory, we should observe two main sets of implications. First, the impact of electricity on military effectiveness should exhibit the three features of a GMT: broad impact pathway, indirect productivity benefits, and prolonged gestation period. Second, we expect differentials in military electrification based on militaries' connections to a robust industrial base in the GPT.

To control for competing explanations of how GPTs affect the military balance of power, we compare military electrification to the impact of the submarine on military affairs. These two technologies differ with respect to whether they qualify as a GPT but are similar across most other

[34] We thank an anonymous reviewer for insights on this point.
[35] Exceptions include Brown, "Annihilating Time and Space"; Headrick, *The Invisible Weapon*; Hezlet, *The Electron and Sea Power*.

relevant features.[36] The submarine was not a GPT. While it generated some technological complementarities with advances in weapon systems and underwater propulsion, submarine technology did not have a wide variety and range of uses and had limited potential for continual innovation. Still, like electricity, the submarine was a disruptive innovation that changed the conduct of warfare.[37] Moreover, the introduction of submarines into military affairs occurred in the same period as the introduction of electricity into military affairs.[38] If we find that the two technologies affected the military balance of power in different ways, then these differences cannot be accounted for by technology-agnostic factors, such as the organizational competencies and cultures of the militaries in question, or time-dependent factors, such as the distribution of military power and the nature of military competition at the time. These overlapping trajectories help pinpoint the technological dimension of GPTs.

THE ELECTRIFICATION OF WARFARE — BACKGROUND

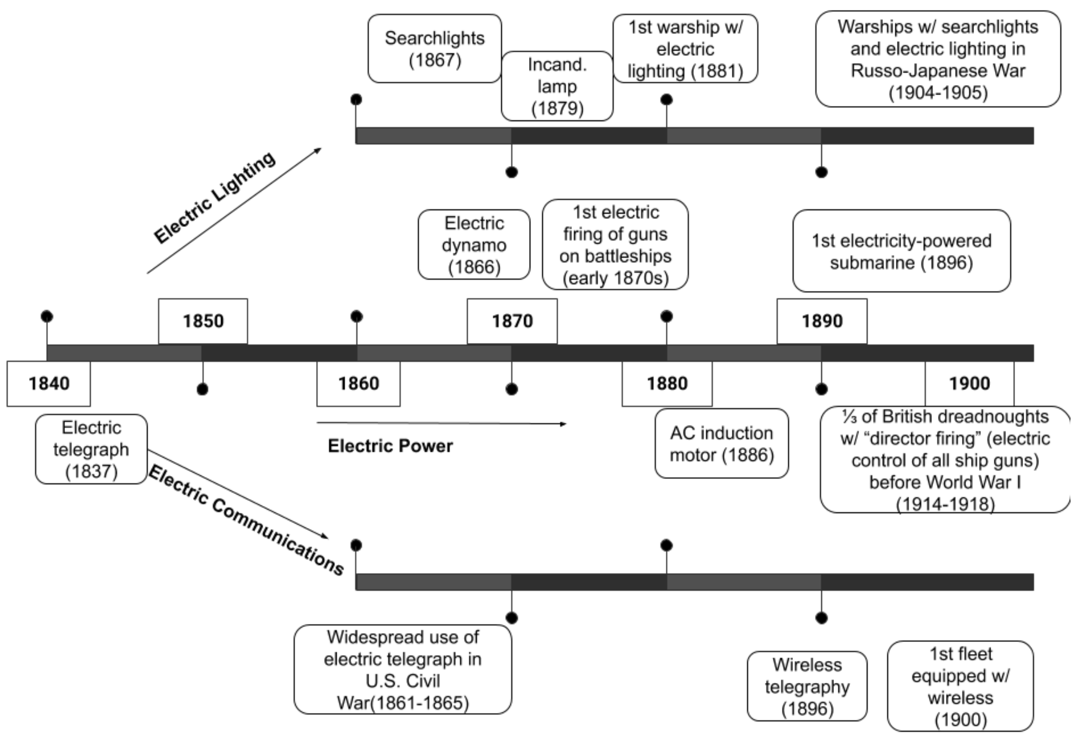
Much of our empirical analysis relies on primary sources, supplemented by historical work on electricity and military modernization These include trade journals like *The Electrician* and *The Electrical Review*, which discuss military electrification from the perspective of engineers. Archival evidence, such as military service appeal tribunal records, help evaluate the extent of military dependence on civilian electric power systems. Lastly, we benefit from writings and speeches by military innovators involved with incorporating electricity into military operations.

Our analysis mainly covers the period from the mid-1800s to the end of WWI. In the late 19th century, a cluster of electrical inventions — including the first practicable dynamos, the transformer, and the steam turbine — enabled the widespread application of electric power. This

[36] On most-similar-system comparisons, see Beach, Derek, and Rasmus Brun Pedersen. *Causal Case Study Methods: Foundations and Guidelines for Comparing, Matching, and Tracing* (Ann Arbor: University of Michigan Press, 2016, 239-240).
[37] Lautenschlager, Karl. "The Submarine in Naval Warfare, 1901-2001." *International Security* 11, no. 3 (1986): 94–140, 121.
[38] Before WWI, advances in the capacity of electric storage batteries expanded the submergence period of submarines.

versatile energy system transformed systems of lighting, manufacturing, transportation, and electronic devices. By tracing the evolution of military electrification, we show that the versatility of electrical applications in the economic realm extended to the military domain (Figure 2).[39] Concretely, we evaluate whether military electrification was consistent with the three theorized features of GMTs.

Figure 2: The Military Electrification GPT Tree (early applications)



GMT FEATURE 1: BROAD IMPACT PATHWAY

The versatility of military electrification eclipsed the constricted predictions of contemporary observers. As advances in electricity were emerging, experts and popular commentators alike envisioned that their main impact on military effectiveness would manifest through a narrow

[39] The supplementary appendix provides extensive citations for the dates in this figure.

pathway: war-winning weapons.[40] Engines would deliver electric shocks "of infinite variety" on the battlefield, one publication hypothesized in 1889;[41] electric rays of destruction would work "revolutionary effects on the art of modern warfare," predicted another in 1896;[42] the Gatling gun's inventor claimed that a powerful electrical weapon would bring peace to the world.[43] A 1911 edition of *Technical World* magazine painted a particularly vivid picture of what electric-powered warfare would look like in 1950:

> "The old War God hurling his thunderbolts will seem impotent beside man wielding the forces of nature for weapons. Magazines exploded without warning by darting, invisible, all-penetrating currents of electricity . . . Guns, explosives, and projectiles will sink into the past, even as have the bow and arrow, giving place to howling elements clashing under man's direction."[44]

The electric rays of destruction never materialized. Instead, electrification transformed militaries through many subtle, diffuse channels. The main applications spanned lighting (e.g., searchlights that helped to guard harbors and forts against surprise night attacks),[45] power (e.g., electric firing of guns),[46] and communications (e.g., telephones and wireless telegraphy).[47] As Marvin argues, "Actual as opposed to fantasy developments in electrical warfare were mostly in the realm of communications rather than destructive weaponry."[48]

Indeed, electrical communications became a new arena for conflict. Described by Rosen as "one of the most significant military technological innovations of the modern era," electronic

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40 Brown, "Annihilating Time and Space," 148; Marvin, Carolyn. *When Old Technologies Were New: Thinking About Electric Communication in the Late Nineteenth Century*. Oxford University Press, 1990, 145.
41 *"Electric Shells in Warfare!" Electrical Review, February 16, 1889*, 4.
42 Marvin, *When Old Technologies Were New*, 146.
43 *"Electricity in Warfare." Western Electrician (Chicago), April 18, 1891*, 221.
44 La Baueme, E.I. "Visions of 1950." *Technical World (Chicago*, December 1911), 439; quoted in Marvin, *When Old Technologies Were New,* 144.
45 Hezlet, *The Electron and Sea Power*, 21; Fiske, B. A. "Electricity in Warfare." *Journal of the Franklin Institute* 121, no. 2 (February 1, 1886): 81–93, 86; Marvin, *When Old Technologies Were New*, 145.
46 Hezlet, *The Electron and Sea Power*, 82.
47 Headrick, *The Invisible Weapon*; Marvin, *When Old Technologies Were New*, 145.
48 Marvin, *When Old Technologies Were New*, 144; see also Brown, "Annihilating Time and Space," 165.

warfare was first demonstrated in the Russo-Japanese conflict of 1904.[49] During WWI, British radio intelligence was effective in tracking German communications at sea. Many assessed this capability as "the most important single factor in the defeat of the U-boats in 1914-1918."[50] Arguably the most powerful demonstration of electricity's mark on WWI was the British penetration of German diplomatic codes, which facilitated the leakage of the Zimmerman telegram.[51]

Eventually, electrical applications in communications, lighting, transportation, and weapons control converged in complete electrical systems. On naval ships, electrical systems incorporated dynamos that supplied energy, searchlights that guarded the ship from surprise attacks, electric-powered velocimeters that calculated the positions of enemy ships, and electric technology that transmitted the commander's communications.[52] To underscore this point, electricity was central to the dreadnought, a new type of battleship often deemed the key military innovation of this time period.[53] Electrical communications and range finders supported centralized fire control, which facilitated long-range shooting with heavy gunnery — the crucial advance from pre-dreadnought ships to dreadnoughts.[54] Wireless telegraphy also supported coordination between dreadnoughts and the overall battlefleet.[55]

Ultimately, we should extend some grace to those who foretold of electrical weapons of mass destruction. After all, the broad impact pathway of electricity made it difficult to envisage how it would shape military power. An American ordnance engineer, a frontline user of electrical applications, put it best in an 1892 article, "Great as was the usefulness of electricity during the

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[49] The Russian military jammed the radio transmissions on Japanese battleships. Price, Alfred. *The History of US Electronic Warfare. Volume 1- "The Years of Innovation-Beginnings to 1946* (The Association of Old Crows, 1984), 3-6; Rosen, *Winning the Next War*, 190.
[50] Hezlet, *The Electron and Sea Power*, 143.
[51] Headrick, *The Invisible Weapon*, 170.
[52] Fiske, "Electricity in Warfare," 90; "The Kansas City Electric Light Convention." *The Electrical World,* February 22, 1890, 125. Cited in Marvin 1990, 145n113.
[53] Gilli and Gilli, "Why China Has Not Caught Up Yet"; Horowitz, *The Diffusion of Military Power*.
[54] Lautenschläger, Karl. "Technology and the Evolution of Naval Warfare." *International Security* 8, no. 2 (1983): 3–51, 19.
[55] Horowitz, *The Diffusion of Military Power*, 139.

period of the Civil War…there was probably *no one at that era whose imagination was sufficiently elastic* to dream of electricity ever acquiring the compass it possesses at the present time."[56]

GMT FEATURE 2: INDUSTRIAL PRODUCTIVITY SPILLOVERS

In addition to spurring a variety of military innovations, a GPT should also influence military effectiveness by boosting industrial productivity. It is well-documented that electrification resulted in a productivity surge in the U.S. and other advanced economies.[57] Crucially, electrification enabled mass production, as the adoption of electric unit drive in factories resulted in standardized workflows and plant capacity expansion.[58] By WWI, the "capacity of civilian firms to manufacture large numbers of standardized weapons became increasingly central to the conduct of industrialized warfare."[59] Recognizing that the U.S. needed to realize "the greatest possible production of needed war materials of the kind peculiarly dependent upon a cheap and dependable supply of electricity," the War Industries Board restricted civilian uses of electricity in key industrial centers.[60]

This connection between the electrification of manufacturing and military production only intensified in WWII. Electricity was one of the highest targeting priorities for Allied strategic bombing efforts because of its impact upon a wide range of German industrial activities.[61] Historians attribute the outcome of the war to a large extent on the Allied capabilities in mass production.[62]

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56 Parkhurst, C.D. "Electricity and the Art of War." *Journal of the United States Artillery* 1, no. 4 (1892): 315–63, 359. Emphasis ours.
57 Crafts, Nicholas. "The Solow Productivity Paradox in Historical Perspective." SSRN Scholarly Paper. Rochester, NY: Social Science Research Network, January 1, 2002.; David, "The Computer and the Dynamo." Timmer, Marcel P., Joost Veenstra, and Pieter J. Woltjer. "The Yankees of Europe? A New View on Technology and Productivity in German Manufacturing in the Early Twentieth Century." *The Journal of Economic History* 76, no. 3 (September 2016): 874–908, 880-881.
58 Devine, "From Shafts to Wires."
59 McNeill, William H. *The Pursuit of Power: Technology, Armed Force, and Society since A.D. 1000* (Chicago: University of Chicago Press, 1982), 330-331; Zeitlin, Jonathan. "Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States, and Germany, 1939-1945." *Technology and Culture* 36, no. 1 (1995): 46–79, 47.
60 Keller, Charles. *The Power Situation during the War* (Washington, DC: Government Printing Office, 1921).
61 Kuehl, Daniel T. "Airpower vs. Electricity: Electric Power as a Target for Strategic Air Operations." *Journal of Strategic Studies* 18, no. 1 (March 1, 1995): 237–66, 239.
62 Kennedy, Paul M. *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000* (New York: Random House, 1987), 244, 248-249; McNeill, *The Pursuit of Power*, 355, 358-59; Zeitlin, "Flexibility and Mass Production at War," 47.

American industry produced more than 250,000 planes during WWII, which exceeded the output of Britain and Germany combined.[63] Smil concludes, "the rapid mobilization of America's economic might, which was energized by a 46% increase in the total use of fuels and primary electricity between 1939 and 1944, was instrumental in winning the war against Japan and Germany."[64]

GMT FEATURE 3: DELAYED EFFECTS

In the economic realm, scholars hold up the diffusion of electricity as an example of the lag between the emergence of a GPT and its impact on national productivity. Measured by percentage of total installed horsepower in manufacturing industries, adoption of unit drive, and estimates of electricity's contributions to GDP growth, American electrification did not take off until the 1920s.[65] This was a full four decades after major advances like the dynamo and incandescent light bulb.

Do we find a similarly delayed timeline for military electrification? Though it is more difficult to track the effects of electricity on military effectiveness, we can trace how and when complementary innovations in different military branches were first introduced as military capabilities, first used in warfare, and fully adopted as a standard military capability (Table 1).[66] Combined with the previous technology tree, this mapping exercise of two electrical military innovations shows that even early movers did not achieve widespread adoption of key innovations until right before WWI. Among later adopters, widespread adoption did not take place until the interwar period or after WWII. In fact, some of the most significant military applications of electricity, including radars, did not emerge until the 1940s.[67]

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[63] Smil, Vaclav. "War and Energy." In *Encyclopedia of Energy*, 6:363–71. Elsevier, 2004, 367.
[64] Smil, "War and Energy," 368.
[65] Crafts, "The Solow Productivity Paradox in Historical Perspective"; Devine, "From Shafts to Wires."
[66] The supplementary appendix provides extensive citations for the dates in this table.
[67] Developed based on principles first seeded by Hertz's 1888 discovery of the reflective properties of electromagnetic waves, radar systems came to play a pivotal role in WWII. Rosen, *Winning the Next War*, 198.

Table 1: Delayed Impact of Electrical Military Innovations				
	Wireless telegraphy (radio)		**Electric firing of guns**	
Complementary innovation	Hertz's demonstration of radio waves (1888)		AC induction motor (1886)	
Application Sector	Navy (early)	Air Force (late)	Navy (early)	Army (late)
First Introduction as Military Capability	British fleet equipped with wireless telegraph (1900)	Planes equipped with radio at end of WWI (1916-1918)	Electric firing introduced in British navy (early 1870s)	GE develops electric-powered miniguns (1950s)
First Application in War	Russo-Japanese War (1904-1905)	WWI (but very ineffective)	World War I (1914-1918)	Vietnam War (1960s)
Widespread Adoption	British Royal Navy has "patchy global network" that supported radio communication (1914)	Germany equips air force with complete set of radio equipment (1938)	Half of British battlefleet had director firing (by 1914)	U.S. procured 10,000 miniguns during Vietnam War (1960s)

It took time for militaries to upgrade their skill base and make organizational adjustments for electrification. Due to limitations in their ability to train and attract electrical engineers, even leading militaries relied on volunteer technical reserves to maintain and develop their electrical infrastructure through WWI.[68] Like manufacturers reluctant to overhaul their factory layouts to optimize electricity usage, militaries were slow to adopt electrical applications that demanded structural changes. For instance, although the opportunity existed as early as 1899, the U.S. Navy did not fully integrate radio communications until fifteen years later, due to opposition by senior naval officers who saw the radio as a direct threat to their authority onboard ships.[69]

[68] Brown, "Annihilating Time and Space," 110; Fiske, B.A. *From Midshipman to Rear-Admiral* (Century Company, 1919), 130, 239. Britain established a unit devoted to the maintenance and repair of electrical equipment, the Royal Electrical and Mechanical Engineers, in 1942.
[69] Douglas, Susan J. "Technological Innovation and Organizational Change : The Navy's Adoption of Radio, 1899 - 1919." In *Military Enterprise and Technological Change : Perspectives on the American Experience*, edited by Merritt Roe Smith, 117–73. Cambridge, MA: MIT Press, 1985.

COMPARISON TO SUBMARINES AS A NON-GPT

Not all technologies interact with military systems in the same way. Along all three features of GMTs, the evolution of submarines in military affairs differed from military electrification.[70] First, advances in underwater submersion technology affected military effectiveness through a much narrower pathway, largely in the application of submarines as weapons platforms.[71] During the late 19th century and early 20th century, underwater submersion technology had very few civilian applications, resulting in limited effects on industrial productivity. Lastly, there was a relatively short delay between the introduction of the first modern submarines, which occurred around the turn of the 20th century, and their impact on military effectiveness, which was apparent in the years before WWI.[72]

ELECTRIFICATION GAPS ACROSS MILITARIES

The pervasive applicability of GPTs across many sectors, combined with the fact that the civilian realm offers a broader range of applications than the military realm, means that the military will grow more dependent on the civilian sector as GPTs develop. By comparison, military applications of some dual-use technologies also rely on the civilian sector, but the civilian and military development trajectories of many dual-use technologies, such as aircraft parts, now greatly diverge.[73] Industrial dependency, therefore, should prove especially relevant for GPTs.

This was the case with electricity. The amount of money invested in research and development within electrical engineering departments and electric companies across the United

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[70] Since the focus of our empirical analysis is on military electrification, we only briefly survey the impact of submarines on military affairs. For an extended discussion of submarines as a non-GMT, see the supplementary appendix.
[71] The only other substantial application was in reconnaissance. Hezlet, *The Electron and Sea Power*, 133.
[72] The *Holland*, introduced by the U.S. Navy in 1900, is generally considered the first modern submarine. By 1913, all the leading navies had substantial submarine fleets. Crisher, Brian Benjamin, and Mark Souva. "Power at Sea: A Naval Power Dataset, 1865–2011." *International Interactions* 40, no. 4 (August 8, 2014): 602–29.
[73] Alic, John A., Lewis M. Branscomb, and Harvey Brooks. *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston, MA: Harvard Business Press, 1992).

States was “many times greater than that invested in all [the U.S.’s] ships put together.”[74] It was difficult for the military to retain electricians because of the breadth of opportunities in private industry. In the years before WWI, an electrician-sergeant in the U.S. army earned about $40 per month; a civilian electrician with similar competencies earned about $100 per month.[75]

One of the clearest demonstrations of military electrification’s dependence on the civilian electric industry is the U.S. military’s switch from direct current (DC) to alternating current (AC) standards in coastal defense fortifications. Prior to 1898, all U.S. military electrification projects preferred the use of DC, even though civilian industry was transitioning to AC systems.[76] Over time, as expenses of maintaining separate DC power systems for military posts accumulated, U.S. policy adjusted “towards a goal of accommodation with civilian commercial utilities.”[77] Ultimately, in adapting AC standards, the U.S. recognized that widespread military electrification would only be possible if the army permitted the integration of AC systems, which were dominant in commercial electrification.[78]

To test our proposition about the non-leveling effects of GPTs, we evaluate whether industrial dependency accounted for differences between the British and Russian militaries in their adoption of electrical military innovations. The British demonstrated an effective system of wireless military communications and electric fire control in WWI.[79] At the time, Russia was a first rank power and perceived to be growing rapidly in military strength. However, its military was a technological laggard with respect to electrification. According to one comparison of the signal communication systems of the British and Russian militaries at the onset of WWI, Britain and

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[74] Fiske, B.A., “Electricity in Naval Life,” *Proceedings of the United States Naval Institute* (Vol. 22/2/78), 1896.
[75] Brown, “Annihilating Time and Space,” 98. For a similar account from the U.S. Navy’s perspective, see Fiske, “Electricity in Naval Life.”
[76] Brown, “Annihilating Time and Space,” 36-37.
[77] Brown, “Annihilating Time and Space,” 59.
[78] Brown, “Annihilating Time and Space,” 64.
[79] Headrick, *The Invisible Weapon*, 143; Hezlet, *The Electron and Sea Power*, 82, 143.

Russia were at complete opposite ends of the spectrum.[80] If GMT theory holds, we should observe that the British military was more connected to a robust industrial electricity sector than the Russian military. To further isolate the effects of industrial dependency, we also examine developments in submarine technology, a non-GPT.

Compared to its Russian competitor, Britain's military could draw from a more robust civilian electricity sector. Measures of electricity production per capita from 1896 to 1940 depict the substantial gap in civilian electrification between these two countries (Figure 3). As earlier evidence about the U.S. experience showed, militaries needed to tap into civilian talent pools to adopt electrical advances. Accordingly, Britain's employment of signals intelligence during World War I "used the best technology and science and electrical engineers of the day."[81] Archival evidence from military service appeal tribunals during the First World War provide a more granular picture of British industrial dependency. Of those that appealed against conscription into the army based on the grounds that it was more conducive to national interests that they continue to engage in work, electrical occupations occupied a far larger share than other technologically progressive fields, including chemicals, steel, and submarines.[82]

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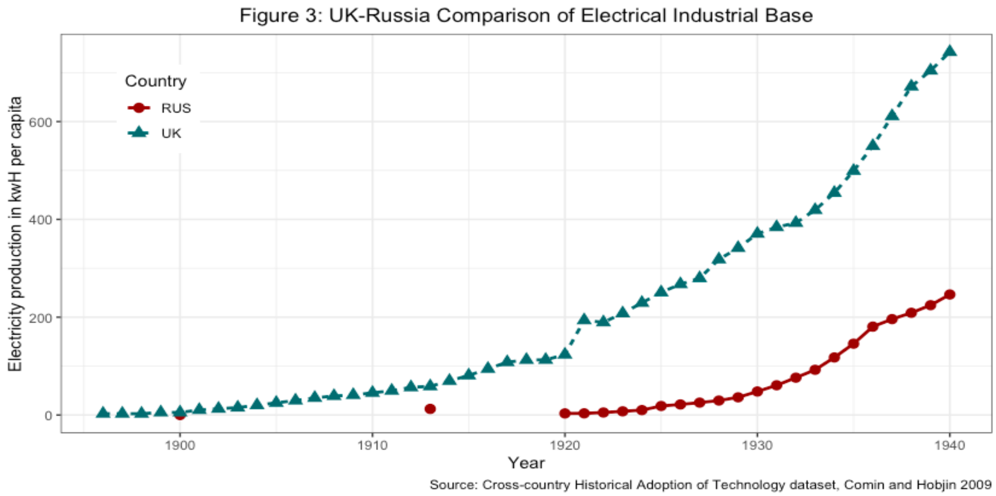
[80] Back, George, and George Thompson. "Military Communication." Encyclopedia Britannica, 1988.
[81] Ferris, John. "Airbandit: C3I and Strategic Air Defence during the First Battle of Britain, 1915-1918." In *Strategy & Intelligence: British Policy During the First World War*, edited by M. Dockrill, 23–66 (London: Hambledon Press, 1996), 29.
[82] This is based on case files of over 8,000 men who appealed at the Middlesex tribunal from 1916-1918. We provide further details in the supplementary appendix.



On the other hand, Russia was unable to electrify its military. This failure came to the fore at the Battle of Tannenberg between Russian and German forces at the onset of WWI, to dramatic effect. The Russian army suffered a massive defeat, and 100,000 men were captured. According to George I. Back, who served as the chief signal officer of the Mediterranean theater for the U.S. Army, and George Thompson, a military historian, Russia's setback at Tannenberg "was largely due to an almost total lack of signal communication."[83] Because the Russian military lacked both the electrical equipment and the requisite technical knowledge base for using these devices and encrypting electrical communications, the Germans had access to detailed Russian communications and marching orders.[84]

One key factor behind the Russian military's relative failure with adopting electricity was its weakly developed industrial base in electricity. The lack of a unified technical profession and skilled personnel functioned as bottlenecks on Russian military electrification.[85] With no leading electrical companies of their own, Russia's electrical engineering sector depended on foreign suppliers for

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[83] Back and Thompson, "Military Communication"; see also Headrick, *The Invisible Weapon*, 156.
[84] One of the two main Russian armies at Tannenberg only had twenty-five telephones and a handful of manual Morse Code machines. Jackson, Frederick E. "Tannenberg: The First Use of Signals Intelligence in Modern Warfare." Strategy Research Project. U.S. Army War College, 2002, 4.
[85] Coopersmith, Jonathan. "The Electrification of Russia, 1880-1926." In *The Electrification of Russia, 1880-1926*, edited by Jonathan Coopersmith, 99–120. Cornell University Press, 1992, 97-101.

critical components such as high voltage transformers and measuring instruments.[86] When imports were cut off amidst war, Russian industry could not independently manufacture this equipment, even with support from the Russian war industry committee.[87]

If civilian dependency holds, then even a strong, technologically savvy military cannot bring about a GMT on its own. Before WWI, the Russian military tried to promote electrification by whatever means necessary. It sponsored research and travel, trained scientists, subsidized domestic industry, gathered information about the latest developments in electric technology, and provided testbeds for materials and systems.[88] While the Russian military did achieve success in some limited, early applications of electricity, this success did not extend to overall electrification. Russian electric mine technology, for instance, was relatively advanced. Russian electric mines damaged two British ships in the Crimean War, and the Japanese sent a delegation to the Russian Mine School in 1877 to gain knowledge from Russian experts. However, this competent pool of workers was "one of the few such groups in Russia."[89] Unfortunately for the Russian military, taking full advantage of a GPT necessitates much more than skill competencies in a few application sectors; it requires access to an industrial base that can facilitate widespread GPT adoption.

What about other factors besides industrial dependency? For instance, Russia's general economic underdevelopment vis-à-vis Britain might explain this military electrification gap. Other considerations include differences in the two militaries' organizational and cultural attitudes toward emerging technologies. To control for alternative explanations, we examine trends in submarine

[86] Coopersmith, "The Electrification of Russia," 97-101; Graham, Loren. *Lonely Ideas: Can Russia Compete?* (Cambridge, MA: MIT Press, 2013), 28-29.
[87] Coopersmith, The Electrification of Russia," 104. For the effects of slow Russian military electrification in the Russo-Japanese War, see Lee, Bartholemew. "Wireless — Its Evolution from Mysterious Wonder to Weapon of War, 1902-1905." *AWA Review, California Historical Radio Society* 25 (2012), 25-28; Hezlet, Arthur Richard. *The Electron and Sea Power*. London: P. Davies, 1975, 42-49.
[88] Coopersmith, Jonathan. "The Role of the Military in the Electrification of Russia, 1870–1890." In *Science, Technology and the Military*, edited by E. Mendelsohn, Merritt Roe Smith, and P. Weingart, 291–305. Springer, 1988.
[89] Coopersmith, "The Role of the Military in the Electrification of Russia," 298.

technologies, which do not fulfill the characteristics of a GPT. If Russia was able to keep pace with Britain adopting submarines, then it is less likely that general economic, organizational, and cultural factors were driving differences in military electrification.

Indeed, the Russian navy was closer to parity with the British in terms of submarine capabilities than military electrification. Russia quickly realized the strategic potential of submarines as new combat platforms, and Russian submarines played an effective role during WWI. Before the outbreak of war, the Russian navy was equipped with 18 diesel-electric submarines,[90] of which the Bars and Morzh class submarines were on par with the best foreign counterparts. In the Baltic Sea, for example, British submarines sank fifteen merchant boats in total, while the Russian *Bars* class submarines sank eight in 1916-1917. [91] Russian submarines also delivered results in the Black Sea, sinking and capturing twenty-five ships.[92]

Unlike Russia's experience with military electrification, the Russian navy could achieve isolated areas of technical competence in submarine capabilities. For instance, Russia launched the world's first submarine mine-layer, the *Krab*, in 1912. Underwater minelaying was successful enough at restricting Turkish naval operations in the Black Sea to justify converting other submarines into minelayers.[93] Overall, the gap between Russian and British submarine capabilities was smaller than the corresponding disparity in military electrification.[95]

Since submarine technology was not a GPT, a military's connection to a robust industrial base should be less significant for explaining which militaries are differentially advantaged by

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90 Crisher and Souva, "Power at Sea."
91 Rowher, Jürgen. "Submarine Warfare, Allied Powers." In The European Powers in the First World War: An Encyclopedia, edited by Spencer Tucker, Laura Matysek Wood, and Justin D. Murphy. Taylor & Francis, 1999, 668.
92 Rowher, "Submarine Warfare, Allied Powers," 668.
93 Kipp, Jacob W. "Undersea Warfare in Russian and Soviet Naval Art, 1853-1941." Army Combined Arms Center Fort Leavenworth KS Soviet Army Studies Office, 1989, 25; Westwood, J. N. *Russian Naval Construction, 1905-45*. Springer, 1994, 114.
95 Kassell, Bernard. "Russia's Submarine Development (1850–1918)." *Journal of the American Society for Naval Engineers* 63, no. 4 (1951): 831–50, 846.

submarines. Like Russia's electrical base, Russia's civilian shipbuilding industry was weak, but this weakness was not as significant in determining the military effectiveness of Russian submarine capabilities.[96] Developing effective submarine capabilities required a relatively narrow talent base skilled in operating high-speed reciprocating machinery.[97] Russian submarine engineers were experienced, knowledgeable, and recognized for their skill even when the boats they were commanding lacked in quality.[98] Russia struggled more with electrification because of the demand for general upskilling drawing on a broad industrial base connected to electrical advances.[99]

IV. Conclusion and Implications for AI

In sum, the evidence from the electricity case is consistent with GMT theory. Like its economic impact pathway, electricity found widespread military applications only after a protracted period of gestation. In addition to directly boosting military effectiveness through a broad array of military innovations, electricity also indirectly transformed military power through stimulating industrial productivity. Recognizing the GMT associated with electricity is a prerequisite to evaluating how electricity shaped the balance of military power. Instead of leveling the military playing field, the electrification GMT advantaged militaries that were able to tap into a robust electrical industrial base.

Recognizing the limitations of a single case, this paper provides a promising building block in the study of GMTs. By uncovering how militaries adopted electricity, it provides the first

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[96] Hauner, Milan. "Stalin's Big-Fleet Program." *Naval War College Review* 57, no. 2 (2004): 87–120, 94.

[97] Nimitz, C. W. "Submarine Engines of the German Navy." *Journal of the American Society for Naval Engineers* 28, no. 2 (1916): 487–97, 487.

[98] After the war, the Soviet submarine school emerged as one of the world's leading centers of submarine warfare. Muraviev, Alexey. "'St Andrew against the Kaiser: Russia's Naval Strategy and Naval Operations in the Baltic and Black Sea Theatres 1914-17.'" In *The War at Sea Proceedings of the King-Hall Naval History Conference 2013: 1914-18*, 73–94, 2015, 86-87; Polmar, Norman, and Jurrien Noot. *Submarines of the Russian and Soviet Navies, 1718-1990* (Naval Institute Press, 1991), 28-29.

[99] In fact, one of the main shortcomings of Russian submarines was linked to the Russian military's weakness in electrification. WWI's onset exposed Russia's dependence on Germany for diesel-electric engines for stronger propulsion. Coopersmith, "The Electrification of Russia."

comprehensive explanation of how GPTs affect military power. This fills a large gap in the military innovation literature, which has not adequately explored some of the most significant technological advances throughout history. To further flesh out our paper's contribution, we conclude by mapping out how GMT theory challenges current discussions of how military affairs will be transformed by AI — often dubbed the "next GPT."[100]

To begin, it is necessary specify scope conditions when extending the implications of the electricity case to other possible GMTs. While AI and electricity are both GPTs, they differ along many other relevant characteristics. Autonomy, for instance, is a distinctive characteristic of some AI systems. Whether the lessons from history about the effects of electricity on military affairs can apply to current developments in AI depends not just on whether the technical properties of AI are comparable to those of electricity but also on the congruence between the nature of military competition and dynamics of the international system in the current period and those of the late 19th century. Still, our analysis can provide an initial guide for comprehending the impact of AI on military affairs, akin to how studies of electricity's effect on economic transformation framed scholarship on the impact of computers on productivity.[102]

First, speculation about how AI will transform military affairs places excessive emphasis on the narrow effects of weapon systems. Possibly influenced by popular images of killer robots, both policymakers and scholars focus on autonomous weapons as the primary military application of AI. U.S. defense intellectuals highlight how China could take advantage of AI-enabled hypersonic missile systems to leapfrog U.S. military power.[103] In its approach to AI, the Chinese military also tends to prioritize "trump card" or "assassin's mace" weapons that can counter U.S. capabilities.[104]

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[100] See, for example, Trajtenberg, Manuel. "AI as the next GPT: A Political-Economy Perspective." National Bureau of Economic Research, January 29, 2018..
[102] See, for example, David, "The Dynamo and the Computer."
[103] Work, Robert O., and Greg Grant. "Beating the Americans at Their Own Game." Center for a New American Security, June 6, 2019.
[104] Kania, "Battlefield Singularity," 33-34.

In contrast, a GMT approach emphasizes the accumulation of AI-enabled improvements across many military systems. This impact pathway will likely interact with weapons capabilities, as was the case with electricity and fire control. Overall, though, effects of AI advances will be more consequential in other military domains, including communications, decision support, intelligence, and logistics.[105] Moreover, the focus on AI weapons neglects the indirect effects of AI's potential to upgrade a nation's productive capabilities. AI applications that improve the efficiency and adaptability of manufacturing lines could have significant follow-on effects for military readiness.

Second, existing conjectures about the impact of AI on military affairs severely underestimate the timeframe for when substantial effects will occur. Recent influential articles on AI and national security converge on the next ten to twenty years as the timeframe for when AI will substantially transform military power.[106] This is reflective of a broader tendency to conflate rapid progress in a technological field, which is characteristic of GPTs, with rapid adoption across military applications, which is uncharacteristic of GPTs.

GMT theory suggests a different view. Economists have already begun to model implementation lags in the effects of AI on economic productivity.[107] A similar extended trajectory will apply in the military realm. The current wave of AI development started with breakthroughs in deep learning in the early 2010s, so if AI follows the same timeline as electricity, a prolonged period of gestation could extend until around the 2050s.[108] In addition, since the development of AI is still in its early stages, the foreseeability of its military applications is very limited. Twenty years after the introduction of the electricity dynamo, even the most astute observers of military transformation

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105 Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power"; Kania, "Battlefield Singularity."

106 Allen, Greg, and Taniel Chan. "Artificial Intelligence and National Security." Cambridge, MA: Belfer Center for Science and International Affairs, 61; Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power," 42. Payne, "Artificial Intelligence," 10.

107 Brynjolfsson et al., "Artificial Intelligence and the Modern Productivity Paradox."

108 Some evidence indicates the waiting time for a significant productivity boost from a new GPT has decreased over time. Crafts, "The Solow Productivity Paradox in Historical Perspective."

could not envision how that technology would transform military affairs. As only a decade has passed since critical breakthroughs in deep learning, any attempt to foreordain the ultimate military implications of AI should be met with deep skepticism. Our imaginations — to borrow language from the ordnance engineer quoted earlier — are not sufficiently elastic.

Lastly, GMT theory supplements existing thinking about international diffusion of military applications of AI and the effect of AI on the military balance of power. Some scholars argue that if military advances in AI continue to be closely linked to civilian applications, then military AI capabilities will rapidly diffuse to other countries.[109] Informed by a historical perspective of GMTs, we view "military AI technology" as not a singular technological innovation but part of a GPT trajectory, which encompasses a broad distribution of technological applications. Just like the organizational requirements for adopting wireless telegraphy were different from those required to adopt searchlights, the adoption capacity for different military applications of AI will vary.

To more fully account for how AI advances will differentially advantage certain militaries, more attention should go to factors that apply across the broad front of a GPT trajectory. We highlight the significance of a state's industrial capacity to provide AI infrastructure and skilled labor to militaries. Specifically, militaries able to draw from a wide skill base in AI will better exploit the AI-based GMT. Crucially, the talent base required for AI differs from the talent base required for other dual-use technologies like nuclear power. GMT theory suggests that military linkages to a wide base of AI engineering talent, rather than star researchers or cutting-edge technical capabilities, are crucial to adapting generalized models to a variety of specific military applications.[110] If leading

[109] Drezner, "Technological Change and International Relations"; Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power."
[110] Ryseff, James. "How to (Actually) Recruit Talent for the AI Challenge." *War on the Rocks* (blog), February 5, 2020.

militaries have stronger connections to their civilian GPT sector than challengers, then GMTs could reinforce existing military balances.[111]

The three great influences on naval warfare of the 20th century were the aircraft, the submarine, and electricity. We have shown that electricity is not like the others. It powered a GMT. In parallel characterization, Horowitz identifies three key technologies that could reshape the future of warfare in the 21st century: cyber, drones, and AI.[112] As plausibly the defining GPT of our century, AI is not like the others. After all, it's the new electricity.

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[111] For example, Russia's civilian sector "is so far behind other countries in its efforts to develop AI that its start-ups and researchers barely register." Weiss, Andrew S. "New Tools, Old Tricks: Emerging Technologies and Russia's Global Tool Kit." *Carnegie Endowment for International Peace* (blog), April 29, 2021. In the information technology domain, linkages between China's military and civilian sectors are weak. Cheung, Tai Ming. *Fortifying China: The Struggle to Build a Modern Defense Economy*. Cornell University Press, 2013.
[112] Horowitz, Michael. ""Do Emerging Military Technologies Matter for International Politics?" *Annual Review of Political Science* 23, no. 1 (2020): 385–400.