Why China Has Not Caught Up Yet

Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage

Andrea Gilli and Mauro Gilli

Can adversaries of the United States easily imitate its most advanced weapon systems and thus erode its military-technological superiority? Do reverse engineering, industrial espionage, and, in particular, cyber espionage facilitate and accelerate this process? China's decades-long economic boom, military modernization program, massive reliance on cyber espionage, and assertive foreign policy have made these questions increasingly salient. Yet, almost everything known about this topic draws from the past. As we explain in this article, the conclusions that the existing literature has reached by studying prior eras have no applicability to the current day.

Scholarship in international relations theory generally assumes that rising states benefit from the "advantage of backwardness," as described by

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Alexander Gerschenkron.[1] By free riding on the research and technology of the most advanced countries, less developed states can allegedly close the military-technological gap with their rivals relatively easily and quickly.[2] More recent works maintain that globalization, the emergence of dual-use components, and advances in communications (including the opportunity for cyber espionage) have facilitated this process.[3] This literature is built on shaky theoretical foundations, and its claims lack empirical support.

The international relations literature largely ignores one of the most important changes to have occurred in the realm of weapons development since the second industrial revolution (1870–1914): the exponential increase in the complexity of military technology. We argue that this increase in complexity has promoted a change in the system of production that has made the imitation and replication of the performance of state-of-the-art weapon systems harder—so much so as to offset the diffusing effects of globalization and advances in communications. On the one hand, the increase in complexity has significantly raised the entry barriers for the production of advanced weapon systems: countries must now possess an extremely advanced industrial, scientific, and technological base in weapons production before they can copy foreign military technology. On the other hand, the knowledge to design, develop, and produce advanced weapon systems is less likely to diffuse, given its increasingly tacit and organizational nature. As a result, the advantage of backwardness has shrunk significantly, and know-how and experience in the production of advanced weapon systems have become an important source of power for those who master them. We employ two case studies to test this argument: Imperial Germany's rapid success in closing the technological gap with the British *Dreadnought* battleship, despite significant inhibiting factors; and China's struggle to imitate the U.S. F-22/A Raptor jet fighter, despite several facilitating conditions.

Our research contributes to key theoretical and policy debates. First, the

1. Alexander Gerschenkron, *Economic Backwardness in Historical Perspective: A Book of Essays* (Cambridge, Mass.: Belknap, 1962), pp. 5–30.
2. Kenneth N. Waltz, *Theory of International Politics* (New York: McGraw-Hill, 1979), pp. 74, 127; Robert Gilpin, *War and Change in World Politics* (Cambridge: Cambridge University Press, 1981), pp. 176–177; and Michael C. Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics* (Princeton, N.J.: Princeton University Press, 2010), p. 34.
3. Wayne Sandholtz et al., eds., *The Highest Stakes: The Economic Foundations of the Next Security System* (New York: Oxford University Press, 1991); Richard A. Bitzinger, "The Globalization of the Arms Industry: The Next Proliferation Challenge," *International Security*, Vol. 19, No. 2 (Fall 1994), pp. 170–198, doi.org/10.2307/2539199; and Emily O. Goldman and Richard B. Andres, "Systemic Effects of Military Innovation and Diffusion," *Security Studies*, Vol. 8, No. 4 (Summer 1999), pp. 79–125, doi.org/10.1080/09636419908429387.

ability to imitate state-of-the-art military hardware plays a central role in theories that seek to explain patterns of internal balancing and the rise and fall of great powers. Yet, the mainstream international relations literature has not investigated this process.[4] Because imitating military technology was relatively easy in the past, scholars and policymakers assume that it also is today, as frequent analogies between Wilhelmine Germany and contemporary China epitomize.[5] In this article, we investigate the conditions under which the imitation of state-of-the-art weapon systems such as attack submarines and combat aircraft is more or less likely to succeed.

Second, we develop the first systematic theoretical explanation of why U.S. superiority in military technology remains largely unrivaled almost thirty years after the end of the Cold War, despite globalization and the information and communication technology revolution. Some scholars have argued that developing modern weapon systems has become dramatically more demanding, which in turn has made internal balancing against the United States more difficult.[6] This literature, however, cannot explain why in the age of globalization and instant communications—with cyber espionage permitting the theft of massive amount of digital data—U.S. know-how in advanced weapon systems has not already diffused to other states. Other contributors to the debate on unipolarity have either pointed to the relative inferiority of Chinese military technology without providing a theoretical explanation, or they have argued that developing the military capabilities to challenge the status quo is, in the long run, a function of political will—an argument that cannot account for the failure of the Soviet Union to cope with U.S. military technology from the late 1970s onward.[7] We argue that in the transition from the second in-

4. For a summary of the literature, see Goldman and Andres, "Systemic Effects of Military Innovation and Diffusion."

5. See, for example, Jean-Christophe Defraigne, "Is China on the Verge of a Weltpolitik? A Comparison of the Current Shift in the Balance of Power between China and the West and the Shift between Great Britain and Wilhelmine Germany," in Bart Dessein, ed., *Interpreting China as a Regional and Global Power: Nationalism and Historical Consciousness in World Politics* (New York: Palgrave Macmillan, 2014), pp. 293–323.

6. Stephen G. Brooks, *Producing Security: Multinational Corporations, Globalization, and the Changing Calculus of Conflict* (Princeton, N.J.: Princeton University Press, 2006); Jonathan D. Caverley, "United States Hegemony and the New Economics of Defense," *Security Studies*, Vol. 16, No. 4 (October–December 2007), pp. 598–614, doi.org/10.1080/09636410701740825; Eugene Gholz, "Globalization, Systems Integration, and the Future of Great Power War," *Security Studies*, Vol. 16, No. 4 (October–December 2007), pp. 615–636, doi.org/10.1080/09636410701740908; and Stephen G. Brooks and William C. Wohlforth, "The Rise and Fall of the Great Powers in the Twenty-first Century: China's Rise and the Fate of America's Global Position," *International Security*, Vol. 40, No. 3 (Winter 2015/16), pp. 7–53, doi.org/10.1162/ISEC_a_00225.

7. See Michael Beckley, *Unrivaled: Why America Will Remain the World's Sole Superpower* (Ithaca,

dustrial revolution to the information age, the imitation of state-of-the-art military technology has become more difficult, so much so that today rising powers or even peer competitors cannot easily copy foreign weapon systems.[8] Our findings address existing concerns that China's use of cyber espionage and the increasing globalization of arms production will allow Beijing to rapidly close the military-technological gap with the United States.[9]

Third, the international relations literature accepts the claim that globalization and advances in communications have made the imitation of military technology easier; yet no one has empirically tested this proposition.[10] This failing is particularly concerning in light of the opportunities opened by cyber espionage—a practice that, according to many observers, could erode the U.S. advantage in military technology. Richard Clark, a former U.S. senior government official, believes that Chinese cyber espionage could result in the United States "hav[ing] all of [its] research and development stolen"; Gen. Keith Alexander, a former director of the National Security Agency, worries that cyber espionage could lead to "the greatest transfer of wealth in history."[11] With a few notable exceptions, however, international relations scholars have paid little attention to the advantages and limits of cyber espionage for copying foreign military technology.[12] Our research fills this gap and tests the conventional wisdom using the case of China, one of the states that has benefited the most from globalization and that has employed cyber espionage more extensively than any other country.

N.Y.: Cornell University Press, 2018), pp. 69–71; and Nuno P. Monteiro, *Theory of Unipolar Politics* (Cambridge: Cambridge University Press, 2014), p. 38.

8. For a discussion of late nineteenth- and early twentieth-century innovations with features no longer seen, see, for example, Vaclav Smil, *Creating the Twentieth Century: Technical Innovations of 1867–1914 and Their Lasting Impact* (New York: Oxford University Press, 2005); and Vaclav Smil, *Transforming the Twentieth Century: Technical Innovations and Their Consequences* (New York: Oxford University Press, 2006).

9. Tai Ming Cheung, ed., *The Chinese Defense Economy Takes Off: Sector by Sector Assessments and the Role of Military End Users* (San Diego: Institute on Global Conflict and Cooperation, University of California, 2013).

10. A previous work of ours in part addresses this topic. See Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Infrastructural, and Organizational Constraints," *Security Studies*, Vol. 25, No. 1 (Winter 2016), pp. 50–84, doi.org/10.1080/09636412.2016.1134189. More generally, however, few works have studied qualitative competition in military technology. An exception is Owen R. Coté Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, R.I.: Naval War College, 2009).

11. Ron Rosenbaum, "Richard Clarke on Who Was behind the Stuxnet Attack," *Smithsonian* magazine, April 2012, p. 12; and Gen. Keith Alexander, "Cybersecurity and American Power," keynote address, American Enterprise Institute, Washington, D.C., July 9, 2012.

12. Jon R. Lindsay, Tai Ming Cheung, and Derek S. Reveron, eds., *China and Cybersecurity: Espionage, Strategy, and Politics in the Digital Domain* (Oxford: Oxford University Press, 2015); and Robert

The remainder of the article proceeds as follows. First, we discuss the substantive and theoretical relevance of the outcome we aim to explain: the degree to which rising states are able to close the military-technological gap with their most advanced adversaries. Second, we examine why the increasing complexity of military technology accounts for the variation in outcome we observe over the past 150 years. In the third and fourth sections, we detail the causal mechanisms underpinning our theory. In the fifth section, we present the results of our empirical investigation: a comparison between Imperial Germany's imitation of big-gun battleships (1890–1916) and China's imitation of fifth-generation jet fighters (1991–2018). In the conclusion, we lay out implications of our findings for international relations theory and the future of U.S. primacy.

Military-Technological Superiority

Military-technological superiority is a central theme in both international politics and international relations theory. Yet, the discipline has not studied the conditions under which states can close the military-technological gap with their rivals.

MILITARY-TECHNOLOGICAL COMPETITION

States compete to develop, field, and maintain the most advanced military platforms possible.[13] When a country develops a new military technology, its competitors will devise countermeasures and counter-innovations to limit, and possibly eliminate, the advantage their enemy derives from its innovation. Counter-innovations such as anti-air defense systems force innovators to further improve the performance of their technology.[14] The history of military innovation is, in the end, the history of innovation, counter-innovation, and further innovation.[15]

Farley, "Intellectual Property, Cyber Espionage, and Military Diffusion," *Global Security and Intelligence Studies*, Vol. 1, No. 2 (Spring 2016), pp. 2–20, doi.org/10.18278/gsis.1.2.2.

13. Bernard Brodie and Fawn M. Brodie, *From the Crossbow to H-Bomb: The Evolution of the Weapons and Tactics of Warfare* (Bloomington: Indiana University Press, 1973), pp. 6, 137, 178; and Trevor N. Dupuy, *The Evolution of Weapons and Warfare* (New York: Da Capo, 1984), p. 199.

14. Andrea Gilli and Mauro Gilli, "The Dynamics of Military Innovations and Counter-Innovations," paper presented at the "Bridging the Straits" conference, Naval War College, Newport, Rhode Island, December 11–13, 2018.

15. Geoffrey Parker, *The Military Revolution: Military Innovation and the Rise of the West, 1500–1800* (New York: Cambridge University Press, 1996); and Kenneth Macksey, *Technology in War: The Impact of Science on Weapon Development and Modern Battle* (London: Guild, 1986), pp. 34–35.

Although countermeasures and counter-innovations can be very effective, they permit countries only to negate the benefits an enemy gains from its innovations.[16] When countries seek to remain or become regional or global powers, or when they aim to deploy certain capabilities, however, they have to acquire specific military platforms, such as aircraft carriers for long-range power projection, jet fighters for air superiority, or submarines for sea denial. Some countries lagging behind in these capabilities will try to copy others' military innovations and, ideally, to outperform them.[17] Under the right conditions, imitation will facilitate and accelerate the ability of some states to catch up technologically.[18] First, by free riding on the research and technology of innovators, imitators can save the resources they would otherwise need to invest to develop indigenously state-of-the-art technology.[19] Second, imitators can avoid making the mistakes of the innovators or, worse, embarking on technically unfeasible projects—a strong possibility when dealing with cutting-edge technologies.[20] Third, imitators can use their unused resources to improve existing technology and possibly outperform innovators.[21] In sum, imitators will derive an advantage when imitation is cheaper and faster than innovation.[22]

These conditions were present in the late nineteenth and early twentieth centuries, when rising powers such as Wilhelmine Germany, Imperial Japan,

16. See Andrea Gilli and Mauro Gilli, "The Spread of Military Innovations: Adoption Capacity Theory, Tactical Incentives, and the Case of Suicide Terrorism," *Security Studies*, Vol. 23, No. 3 (July–September 2014), pp. 513–547, doi.org/10.1080/09636412.2014.935233.
17. Martin van Creveld, *Technology and War: From 2000 B.C. to the Present* (New York: Touchstone, 1989), p. 229. Not coincidentally, the Soviet big-fleet program in the 1930s was driven by the slogan "Catch up and overtake." See Milan L. Hauner, "Stalin's Big-Fleet Program," *Naval War College Review*, Vol. 57, No. 2 (Spring 2004), p. 114, https://digital-commons.usnwc.edu/nwc-review/vol57/iss2/6.
18. See Yu-Ming Liou, Paul Musgrave, and J. Furman Daniel III, "The Imitation Game: Why Don't Rising Powers Innovate Their Militaries More?" *Washington Quarterly*, Vol. 38, No. 3 (Fall 2015), pp. 157–174, doi.org/10.1080/0163660X.2015.1099030.
19. Marvin B. Lieberman and Sigheru Asaba, "Why Do Firms Imitate Each Other?" *Academy of Management Review*, Vol. 31, No. 2 (April 2006), pp. 366–385, doi.org/10.2307/20159207; and Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore, Md.: Johns Hopkins University Press, 1990), pp. 7–8.
20. David J. Teece, "Capturing Value from Knowledge Assets: The New Economy, Markets for Know-How, and Intangible Assets," *California Management Review*, Vol. 40, No. 3 (Spring 1998), pp. 55–79, doi.org/10.2307/41165943.
21. Michael L. Tushman and Philip Anderson, "Technological Discontinuities and Organizational Environments," *Administrative Science Quarterly*, Vol. 31, No. 3 (September 1996), pp. 439–465, doi.org/10.2307/2392832.
22. Marvin B. Lieberman and David B. Montgomery, "First-Mover Advantages," *Strategic Management Journal*, Vol. 9, No. 5 (Summer 1988), pp. 41–58, https://www.jstor.org/stable/2486211; and Marvin B. Lieberman and David B. Montgomery, "First-Mover (Dis)Advantages: Retrospective and Link with the Resource-Based View," *Strategic Management Journal*, Vol. 19, No. 12 (December 1998), pp. 1111–1125, https://www.jstor.org/stable/3094199.

and the Soviet Union under Joseph Stalin could easily imitate foreign military technology and catch up with their rivals in a relatively short period of time.[23] Implicitly or explicitly, these and similar cases have informed the literature on the balance of power and on the rise and fall of great powers—a literature that largely has accepted the assumption that copying foreign military technology is relatively easy.[24]

LITERATURE REVIEW

The imitation of military technology plays a central but unappreciated role in the literature on international relations theory.[25] Internal balancing, for instance, often entails imitating foreign technology. Yet, international relations scholars have not investigated when and why efforts to imitate foreign weapon systems are successful.[26] Instead, they have assumed that states' intentions or incentives to imitate will ipso facto lead to success.[27]

According to Kenneth Waltz, for example, because of competition and socialization dynamics in international politics, the "weapons of the major contenders . . . come to . . . look much the same all over the world."[28] Similarly, Robert Gilpin argues that "there is a historical tendency for the military . . . techniques of the dominant state or empire to be diffused to other states in the system."[29] For P.W. Singer, "The problem for 'first movers' . . . is that they have to pay heavily" when developing military technology. In comparison, imitating countries "can 'free ride' on the early cost, copy what works and focus all their energy and resources solely on improving upon what the first mover does."[30] Interestingly, even some of the scholars who have questioned the liter-

23. Brooks and Wohlforth, "The Rise and Fall of the Great Powers in the Twenty-first Century," p. 9.
24. This is also true for the literature on offense-defense balance, which treats technology as a systemic variable. See Sean M. Lynn-Jones, "Offense-Defense Theory and Its Critics," *Security Studies*, Vol. 4, No. 4 (Summer 1995), pp. 660–691, in particular pp. 666–667, doi.org/10.1080/09636419509347600.
25. John A. Alic, "Managing U.S. Defense Acquisition," *Enterprise & Society*, Vol. 14, No. 2 (March 2013), p. 4, doi.org/10.1093/es/khs051; and Peter Dombrowski and Eugene Gholz, *Buying Military Transformation: Technological Innovation and the Defense Industry* (New York: Columbia University Press, 2006), pp. 12–14.
26. See Daniel H. Nexon, "The Balance of Power in the Balance," *World Politics*, Vol. 61, No. 2 (April 2009), pp. 330–359, in particular p. 351, doi.org/10.1017/S0043887109000124.
27. For an exception, see Alexander H. Montgomery, "Ringing in Proliferation: How to Dismantle an Atomic Bomb Network," *International Security*, Vol. 30, No. 2 (Fall 2005), pp. 153–187, doi.org/10.1162/016228805775124543.
28. Waltz, *Theory of International Politics*, pp. 74, 127.
29. Gilpin, *War and Change in World Politics*, pp. 176–177; see also pp. 1–3, 175–185, 227.
30. P.W. Singer, *Wired for War: The Robotics Revolution and Conflict in the 21st Century* (New York: Penguin, 2009), p. 239.

ature's conventional wisdom agree with the proposition that the imitation of military hardware is relatively easy. In the words of Emily Goldman, "Hardware is often easy to acquire."[31] Similarly, Michael Horowitz writes that "it is [not] difficult to copy . . . specific technologies."[32]

Many scholars further argue that globalization and information technologies have facilitated and accelerated the diffusion of technology in the military realm.[33] Joseph Nye observes that, in the age of globalization, "technology . . . eventually spreads and becomes available to adversaries."[34] Some scholars claim that countries with advanced commercial industrial and technological capabilities can exploit their industrial and scientific base to develop state-of-the-art military technology.[35] Other scholars have stressed that, since the early 1990s, commercial research and development (R&D) has supplanted military R&D as the main driver of innovation.[36] As a result, many advanced technologies are now accessible on the global market at moderate cost, including those required for producing first-class military capabilities.[37] For instance, Goldman and Richard Andres maintain that, in comparison to the industrial era, "revolutionary dual-use technologies, like computer and software capabilities," can be imitated more quickly and more easily, because they "are not capital intensive and do not require a huge industrial capacity to exploit."[38] Horowitz warns that because of increasing synergies with the commercial sector, "military technology . . . could become increasingly 'lootable,'" allowing "militaries [to] quickly reverse engineer systems built by other countries."[39]

31. Emily O. Goldman, "Introduction," in Goldman and Thomas G. Mahnken, eds., *The Information Revolution in Military Affairs in Asia* (New York: Palgrave Macmillan, 2004), p. 7.
32. Horowitz, *The Diffusion of Military Power*, pp. 27–28; see also p. 34.
33. Bitzinger, "The Globalization of the Arms Industry"; Dennis M. Gormley, "Dealing with the Threat of Cruise Missiles," Adelphi Paper, No. 339 (London: International Institute for Strategic Studies, 2001); and Christopher Layne, "This Time It's Real: The End of Unipolarity and the *Pax Americana*," *International Studies Quarterly*, Vol. 56, No. 1 (March 2012), pp. 203–213, doi.org/10.1111/j.1468-2478.2011.00704.x.
34. Joseph S. Nye Jr., *The Future of Power* (New York: PublicAffairs, 2011), p. 36.
35. Sandholtz et al., *The Highest Stakes*.
36. See John A. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Boston: Harvard Business School Press, 1992).
37. Aaron L. Friedberg, "The United States and the Cold War Arms Race," in Odd Arne Westad, ed., *Reviewing the Cold War: Approaches, Interpretations, Theory* (Portland, Ore.: Frank Cass, 2000), p. 215.
38. Goldman and Andres, "Systemic Effects of Military Innovation and Diffusion," p. 123; Bitzinger, "The Globalization of the Arms Industry"; and Robert O. Work and Shawn Brimley, *20YY: Preparing for War in the Robotic Age* (Washington, D.C.: Center for a New American Security, 2014).
39. Michael C. Horowitz, "Information-Age Economics and the Future of the East Asian Security Environment," in Avery Goldstein and Edward D. Mansfield, eds., *The Nexus of Economics, Security, and International Relations in East Asia* (Stanford, Calif.: Stanford University Press, 2012), p. 223.

PROBLEMS WITH INTERNATIONAL RELATIONS THEORY

There are three problems with the conventional wisdom in international relations theory regarding the ability of states to copy foreign military technology. First, if imitation is easy, why do states invest in military innovation at all? Why not simply wait for others to develop innovations and then copy them?[40] Second, the assumption that imitation is easy is at odds with the literatures in economic history, economics, history of technology, management, science and technology studies, and sociology, which have sought to explain why some innovators retain a first-mover advantage, what the sources of industrial leadership are, and why very advanced companies sometimes fail to replicate an innovation, even with full access to original blueprints and designs.[41] Third, imitating foreign technology also seems to be difficult in the commercial realm, where, according to international relations theory, it should be particularly easy. For instance, Google and Microsoft, two of the most advanced companies in the world, have struggled to cope with Apple's smartphone and tablet technology.[42] In the following section, we explain why these trends are even more pronounced in weapons production.[43]

Complexity and Military-Technological Superiority

Since the second industrial revolution, the complexity of military technology has increased exponentially. This dramatic increase has changed the nature of innovation and of imitation, making the latter much more difficult to implement.

COMPLEXITY AND THE INTEGRATION CHALLENGE

Complexity generates incompatibilities and vulnerabilities.[44] As complexity increases, the number and significance of incompatibilities and vulnerabili-

40. The same problem exists in economics. See Jess Benhabib and Mark M. Spiegel, "Human Capital and Technology Diffusion," in Philippe Anghion and Stephen N. Durlauf, eds., *Handbook of Economic Growth*, Vol. 1A (Amsterdam: Elsevier, 2005), p. 937, doi.org/10.1016/S1574-0684(05)01013-0.
41. Lieberman and Montgomery, "First-Mover Advantages"; Lieberman and Montgomery, "First-Mover (Dis)Advantages"; Alfred. D. Chandler Jr., *Inventing the Electronic Century: The Epic Story of Consumer Electronics and Computer Industries* (New York: Free Press, 2001); David C. Mowery and Richard R. Nelson, eds., *Sources of Industrial Leadership: Studies of Seven Industries* (New York: Cambridge University Press, 1999); and Harry M. Collins, "The TEA Set: Tacit Knowledge and Scientific Networks," *Science Studies*, Vol. 4, No. 2 (April 1974), pp. 165–185, doi.org/10.1177/030631277400400203.
42. Andrew McAfee and Erik Brynjolfsson, *Machine, Platform, Crowd: Harnessing Our Digital Future* (New York: W.W. Norton, 2017), p. 204.
43. Gilli and Gilli, "The Diffusion of Drone Warfare?" pp. 67–80.
44. Alic, "Managing U.S. Defense Acquisition"; Rebecca M. Henderson and Kim B. Clark, "Archi-

ties also increase—exponentially.[45] Anticipating, detecting, identifying, understanding, and addressing all possible technical problems when designing, developing, and manufacturing an advanced weapon system pose major challenges.[46] Addressing them without creating new problems is an even greater challenge.[47] More challenging still is the need for weapons producers to design platforms that can incorporate cutting-edge and yet-to-be-developed technologies, and to limit their vulnerability to subtle and effective enemy countermeasures and counter-systems.[48]

Three developments help account for the increase in the complexity of military technology since the second industrial revolution. First, the number of components in military platforms has risen dramatically: in the 1930s, a combat aircraft consisted of hundreds of components, a figure that surged into the tens of thousands in the 1950s and to 300,000 in the 2010s.[49] As the number of components expands, the number of potential incompatibilities and vulnerabilities increases geometrically. Ensuring the proper functioning and mutual compatibility of all the components and of the whole system thus becomes increasingly difficult.[50]

Second, advancements in electronics, engineering, and material sciences

tectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, Vol. 35, No. 1 (March 1990), pp. 9–30, doi.org/10.2307/2393549; Eugene Gholz, "Systems Integration in the U.S. Defense Industry," in Andrea Prencipe, Andrew Davies, and Michael Hobday, eds., *The Business of Systems Integration* (New York: Oxford University Press, 2003), pp. 279–306; Eugene Gholz, "Systems Integration for Complex Defense Projects," in Guy Ben-Ari and Pierre A. Chao, eds., *Organizing a Complex World: Developing Tomorrow's Defense and Net-Centric Systems* (Washington, D.C.: Center for Security and International Studies, 2009), pp. 50–65; and Mike Hobday, "Product Complexity, Innovation, and Industrial Organization," *Research Policy*, Vol. 26, No. 6 (February 1998), pp. 689–710, doi.org/10.1016/S0048-7333(97)00044-9.

45. The curse of dimensionality in statistics provides a useful analogy of the exponential increase resulting from the arithmetic growth of the number of parameters and constraints.

46. Harvey M. Sapolsky, "Inventing Systems Integration," in Prencipe, Davies, and Hobday, *The Business of Systems Integration*, pp. 15–34; and Stephen B. Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems," in Prencipe, Davies, and Hobday, *The Business of Systems Integration*, pp. 35–55.

47. See Marco Iansiti, *Technology Integration: Making Critical Choices in a Dynamic World* (Boston: Harvard Business Review Press, 1997), pp. 104–106, 133.

48. Alic, "Managing U.S. Defense Acquisition," pp. 16–19; and David J. Berteau, "Foreword," in Ben-Ari and Chao, *Organizing a Complex World*, pp. vii–viii.

49. Alan S. Milward, *War, Economy, and Society, 1939–1945* (Berkeley: University of California Press, 1977), p. 185; Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems," p. 40; and Jeremiah Gertler, "F-35 Joint Strike Fighter (JSF) Program" (Washington, D.C.: Congressional Research Service, April 29 2014).

50. Qing Wang and Nick von Tunzelmann, "Complexity and the Functions of the Firm: Breadth and Depth," *Policy Research*, Vol. 29, Nos. 7–8 (August 2000), pp. 805–818, doi.org/10.1016/S0048-7333(00)00106-2; and Carliss Y. Baldwin and Kim B. Clark, *Design Rules: The Power of Modularity*, Vol. 1 (Cambridge, Mass.: MIT Press, 2000), pp. 63–70.

have resulted in the components of major weapon systems becoming dramatically more sophisticated, leading military platforms to become "systems of systems."[51] Integrating large numbers of extremely advanced components, subsystems, and systems poses a daunting challenge. More sophisticated components have extremely low tolerances, which in turn require a degree of accuracy and precision in design, development, and manufacturing that was unthinkable a century ago.[52] For instance, aircraft engines in the 1900s and 1910s were "crude" mechanical devices that self-taught individuals could design, assemble, and install in their own repair shops.[53] In contrast, the production of today's aircraft engines is so technologically demanding that only a handful of producers around the world possess the necessary technical expertise.[54] Consider that in turbofan engines, a "close clearance between [a rotary] part and its surroundings can be critical. One-tenth of 1 millimeter [i.e., 0.00393 inch] variation in dimension can have a significant impact on system compatibility."[55] The same is true of materials, electronics, and software, where minor imprecisions can have dramatic consequences.[56] For example, in modern jet fighters, software controls everything, from the operation of radars to the supply of oxygen. The expansion of onboard software functions is reflected in the increase in the number of software code lines from 1,000 in the F-4 Phantom II (1958), to 1.7 million in the F-22 (2006), and to 5.6 million in the F-35 Joint Strike Fighter/Lightning II (2015).[57] Even a minor problem in those millions of lines of code could ground the aircraft or prove fatal.[58] This level of sophistication explains why software engineering is responsible for most of the delays and of the problems seen in advanced weapon systems.[59]

Third, modern weapon systems can now perform in extraordinarily de-

51. Eugene Gholz, "Systems Integration in the U.S. Defense Industry," p. 281.
52. Guy Ben-Ari and Matthew Zlatnik, "Introduction: Framing the Complexity Challenge," in Ben-Ari and Chao, *Organizing a Complex World*, p. 2.
53. Bill Gunston, *The Development of Piston Aero Engines: From the Wrights to Microlights: A Century of Evolution and Still a Power To Be Reckoned With* (Somerset, U.K.: Haynes, 1993), p. 105.
54. Vaclav Smil, *Prime Movers of Globalization: The History and Impact of Diesel Engines and Gas Turbines* (Cambridge, Mass: MIT Press, 2013), pp. 79–108.
55. Wedo Wang, *Reverse Engineering: Technology of Reinvention* (Boca Raton, Fla.: CRC, 2010), p. 266.
56. See Gholz, "Systems Integration for Complex Defense Projects," p. 50. See also Clarence L. "Kelly" Johnson with Maggie Smith, *Kelly: More than My Share of It All* (Washington, D.C.: Smithsonian Institute, 1985), p. 142.
57. Between the F-4 and the F-22, software has moved from controlling 8 percent to 80 percent of operations. Ali Mili and Fairouz Tchier, *Software Testing: Concepts and Operations* (Hoboken, N.J.: John Wiley and Sons, 2015), p. 6.
58. See Jeffrey J. Harris and G. Thomas Black, "F-22 Control Law Development and Flying Qualities," Conference Paper 96-3379 (Reston, Va.: American Institute of Aeronautics and Astronautics, July 1996), pp. 155–158.
59. Joe W. Heil, "Addressing the Challenges of Software Growth and Rapidly Evolving Software

manding environmental and operational conditions, thanks to improvements in all metrics (e.g., speed, altitude ceiling for aircraft, and collapse depth for submarines).[60] These improvements, however, have increased the likelihood of technical problems.[61] The more sophisticated a component is, the more likely minor environmental changes will affect its performance.[62] In addition, as technological advances permit weapon systems to operate in once unfamiliar environmental conditions, designers and engineers are forced to deal with previously unknown physical phenomena.[63]

CHANGE IN THE NATURE OF INNOVATION AND IMITATION

The increase in complexity and the resulting integration challenges have brought about a change in the very nature of innovation. In the late nineteenth and early twentieth centuries, innovation was primarily the product of conjecture, creativity, ingenuity, and intuition, as was the case with two of the most revolutionary military technologies of the twentieth century: submarines (1900) and aircraft (1903).[64] To move from intuition to military platforms, countries needed industrial facilities and managerial capabilities to supervise large production runs—what Alfred Chandler called "the Visible Hand" of industrial capitalism.[65] Because of the increase in complexity, however, innovation has progressively been the result of scientific and engineering research, as well as of accumulated experience in design, development, and manufacturing.[66] Consequently, arms producers working on the technological frontier have had to develop in-house technological knowledge bases, or systems integration capabilities—"the Visible Brain" as Keith Pavitt called it.[67] Consider the evolu-

Technologies," *Naval Engineers Journal*, Vol. 122, No. 4 (December 2010), pp. 45–58, doi.org/10.1111/j.1559-3584.2010.00279.x.

60. Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems."

61. Iansiti, *Technology Integration*, pp. 10–12, 110–116.

62. W. Brian Arthur, *The Nature of Technology: What It Is and How It Evolves* (New York: Free Press, 2009), pp. 45–67. See also Ben R. Rich and Leo Janos, *Skunk Works: A Personal Memoir of My Years at Lockheed* (New York: Little, Brown and Company, 1994), p. 82.

63. See David Miller and John Jordan, *Modern Submarine Warfare* (London: Salamander, 1987), pp. 44–45.

64. Alic, "Managing U.S. Defense Acquisition," pp. 1–36; and Barton C. Hacker, "The Machines of War: Western Military Technology, 1850–2000," *History and Technology*, Vol. 21, No. 3 (September 2005), pp. 255–300.

65. See Alfred D. Chandler Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass.: Belknap, 1977).

66. David C. Mowery and Nathan Rosenberg, *Technology and the Pursuit of Economic Growth* (New York: Cambridge University Press, 1989), p. 172.

67. Keith Pavitt, "Specialization and Systems Integration: Where Manufacture and Services Still Meet," in Prencipe, Davies, and Hobday, *The Business of Systems Integration*, p. 88.

tion of submarines: from "crude, slow and probably as dangerous to their crews as they were to any potential enemy" in the early twentieth century, they are now so complex that "the only comparison you could draw would be a space shuttle."[68]

The increase in complexity has also made imitation more challenging. For imitators to have an advantage vis-à-vis innovators, two conditions are necessary. First, the capabilities required to exploit foreign know-how and experience in the production of weapon systems must be relatively easy to develop or to acquire, so that the imitator can swiftly translate foreign designs and blueprints into a working military platform; that is, there must be relatively low entry barriers. Second, the know-how and experience of the innovating country must diffuse with relative ease and with relative rapidity to would-be imitators. The growth in complexity observed over the past century has made these two conditions increasingly difficult to meet.

During the second industrial revolution, imitating countries could exploit the know-how and experience of their most advanced peers to develop state-of-the-art military technology.[69] In fact, intuition and conjecture could be transferred from country to country with relative ease.[70] The main challenge these countries faced was to mobilize the necessary capital to launch production and to achieve the necessary economies of scale.[71] For industrialized countries, this challenge was not insurmountable.[72] Consider the naval rise of Imperial Japan. Because of its qualitatively modest domestic shipbuilding industry, in 1905 the Japanese navy mostly deployed British-made warships.[73] Yet, through a policy based on "copy, improve and innovate,"[74] involving the "purchase of specific foreign examples, the exhaustive analysis and testing of those models [and]

68. See, respectively, W.J.R. Gardner, *Anti-Submarine Warfare* (London: Brassey's, 1996), p. 4; and Hamish McDonald and Deborah Snow, "Submarines No Longer All At Sea," *Sydney Morning Herald*, July 9, 2012.
69. Holger H. Herwig, "The Battlefleet Revolution, 1885–1914," in MacGregor Knox and Williamson Murray, eds., *The Dynamics of Military Revolution, 1300–2050* (New York: Cambridge University Press, 2001), p. 126.
70. Paul Kennedy, *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000* (New York: Random House, 1987), p. 198.
71. William H. McNeill, *The Pursuit of Power: Technology, Armed Force, and Society since A.D. 1000* (Chicago, Ill.: University of Chicago Press, 1982), pp. 262–264.
72. Gerschenkron, *Economic Backwardness in Historical Perspective*, pp. 31–51.
73. See, respectively, John Roberts, "The Pre-Dreadnought Age, 1890–1905," in Robert Gardiner, ed., *Steam, Steel, and Shellfire: The Steam Warship, 1805–1905* (London: Conway Maritime, 1992), p. 123; and Mark R. Peattie, "Japanese Naval Construction, 1919–41," in Phillips Payson O'Brien, ed., *Technology and Naval Combat in the Twentieth Century and Beyond* (London: Frank Cass, 2001), p. 97.
74. Peattie, "Japanese Naval Construction, 1919–41," p. 97.

their subsequent improvement,"[75] by 1912–13, Japan was able to commission two super Dreadnoughts that surpassed their British counterparts in both speed and tonnage.[76] And by the 1920s, "the skills available at both naval and commercial dockyards made Japan capable of turning out a range of warships that in design and construction were equal or superior to those of any navy in the world."[77]

Over time, however, the increase in complexity of military technology has made the process of imitation much more difficult. Economies of scale and exorbitant capital investments still represent major barriers for most countries seeking to enter the defense sector. Yet, simply extracting and investing resources is no longer sufficient to close the technological gap with the most advanced countries. Lacking the necessary know-how for weapon systems production has, in fact, become a major obstacle for actors trying to imitate foreign technology—wealthy countries included.[78] Japan's experience in the 1980s and 1990s offers a useful comparison to the Imperial era discussed above. As Stephen Brooks notes, despite Japan's then primacy in high-technology and despite several decades of collaboration on weapons production with the United States, its F-2 fighter proved to be "a white elephant: no better than the F-16C [Japan built upon and] at least twice as expensive to produce."[79]

In the next two sections, we explain why the increase in complexity has steadily eroded the advantages of imitation that some countries once enjoyed.

Absorptive Capacity

The increase in technological complexity over the past 150 years has exponentially raised the requirements to assimilate and imitate foreign military technology, thus canceling the first necessary condition for states to enjoy the advantage of imitation—relatively low entry barriers for the imitation of state-of-the-art weapon systems.

75. Ibid., p. 94.
76. Spencer C. Tucker, *Handbook of 19th Century Naval Warfare* (Phoenix Mill, U.K.: Sutton, 2000), p. 225.
77. Peattie, "Japanese Naval Construction, 1919–41," p. 95.
78. Michael H. Best, "The Geography of Systems Integration," in Prencipe, Davies, and Hobday, *The Business of Systems Integration*, pp. 201–228.
79. Brooks, *Producing Security*, pp. 235–236. F-16s produced in Europe by license were consistently about 20 percent more expensive than those assembled in the United States. See Michael Rich et al., *Multinational Coproduction of Military Aerospace Systems* (Santa Monica, Calif.: RAND Corporation, 1981), pp. 79–120.

To free ride on the R&D of a foreign country, a country must be able "to identify, assimilate, and exploit knowledge from the environment."[80] But as scholarship from other disciplines shows, knowledge and experience are not public goods that can be easily and cheaply appropriated.[81] An imitator must possess an adequate absorptive capacity: material and nonmaterial capabilities such as laboratories, research centers, testing and production facilities, a skilled workforce, and a cumulative technological knowledge base (the stock of knowledge acquired through previous projects).[82] Without such absorptive capacity, the imitator will have to develop an advanced industrial, technological, and scientific base before it can copy foreign technologies. In the next two sections, we explain how the increase in complexity has created massive and highly specific requirements for those seeking to imitate advanced weapon systems.

FROM LIMITED TO MASSIVE ABSORPTIVE CAPACITY REQUIREMENTS

Whereas in the past, the requirements to imitate foreign military technology were limited, today, states need to master, to an unprecedented level, a much broader range of disciplines and activities.

LIMITED CAPACITY. In the aftermath of the second industrial revolution, the absorptive capacity required to imitate cutting-edge technologies was comparatively low for great powers. For industrialized countries, capital investments and sufficient economies of scale were essentially the only constraints, as entering weapons production required relatively little accumulated knowledge or experience.[83] During this period, "within many economic sectors, the knowledge required for moving out of the technological frontier was rather elementary scientific knowledge of a kind that had been available for a long time."[84] Even sectors such as metallurgy, which "placed a premium on basic chemical knowledge . . . drew primarily on elementary science when they drew on science at all."[85] This was also true for emerging fields such as avia-

80. Wesley M. Cohen and Daniel A. Levinthal, "Innovation and Learning: The Two Faces of R&D," *Economic Journal*, September 1989, pp. 569–570, doi.org/10.2307/2233763.
81. That knowledge is a public good was a popular conception among economists, stemming from Kenneth J. Arrow, "Economic Welfare and the Allocation of Resources for Invention," in *The Rate and Direction of Inventive Activity: Economic and Social Factors* (Princeton, N.J.: Princeton University Press, 1962).
82. Wesley M. Cohen and Daniel A. Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation," *Administrative Science Quarterly*, Vol. 35, No. 1 (March 1990), pp. 128–152, doi.org/10.2307/2393553.
83. Gerschenkron, *Economic Backwardness in Historical Perspective*, pp. 31–51.
84. See Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, p. 28
85. See ibid., p. 31.

tion, which owed "practically nothing to the relatively mature state of the science of fluid dynamics."[86] In addition, the number of disciplines required in a given field was limited. For example, aviation design well into the late 1930s essentially required knowledge about "efficient aerodynamic structure and hydraulic controls."[87] Similarly, until World War II, submarine development required only reliable and powerful diesel engines, welding of metals, and efficient designs.[88]

In these circumstances, it is clear why "the period before 1914 . . . was unlikely to produce asymmetrical [revolutions in military affairs] that conferred enduring advantages." Technology moved swiftly across borders, and great powers were able to exploit it with relative ease—to the point that it "was indeed often most convenient and cheapest to make use of another country's research and development."[89] For this reason, Germany in the 1930s could move from "possess[ing] no significant aircraft industry" to being "in the forefront of aviation technology" in just three years.[90]

MASSIVE CAPACITY. The increase in the complexity of weapon systems has exponentially raised the absorptive capacity requirements to assimilate foreign know-how and experience and to imitate foreign military platforms.[91] The stock of accumulated knowledge has, in fact, expanded to the point of becoming a "burden" for those seeking to assimilate it.[92] The number of disciplines involved has increased dramatically, going well beyond those necessary for weapon systems development, and reaching into new, unexplored fields related both to the environmental conditions where the platform is expected to operate and to interactions between human beings and technology (e.g., ergonomics, human physiology, and cognitive sciences).[93] Moreover, imitators

86. See John D. Anderson Jr., *The Airplane: A History of Its Technology* (Reston, Va.: American Institute of Aeronautics and Astronautics, 2002), p. 45.
87. Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems," p. 40.
88. See Eberhard Rössler, *The U-Boat: The Evolution and Technical History of German Submarines*, trans. Harold Erenberg (Annapolis: Naval Institute Press, 1981), p. 50.
89. Herwig, "The Battlefleet Revolution, 1885–1914," p. 126.
90. Richard J. Overy, *War and Economy in the Third Reich* (Oxford: Clarendon, 1994), p. 181.
91. Richard C. Levin et al., "Appropriating the Returns from Industrial Research and Development," Brookings Papers on Economic Activity, Vol. 1987, No. 3 (1987), pp. 783–831, doi.org/10.2307/2534454.
92. Benjamin F. Jones, "The Burden of Knowledge and the 'Death of the Renaissance Man': Is Innovation Getting Harder?" *Review of Economic Studies*, Vol. 76, No. 1 (January 2009), pp. 283–317, doi.org/10.1111/j.1467-937X.2008.00531.x.
93. See Patricia Hamburger, David Miskimens, and Scott Truver, "It Is Not Just Hardware and Software, Anymore! Human Systems Integration in U.S. Submarines," *Naval Engineers Journal*, Vol. 123, No. 4 (December 2011), pp. 41–50, doi.org/10.1111/j.1559-3584.2009.00198.x.

must master all of these disciplines, because the margins for error and imprecision have shrunk enormously. Infinitesimally small mistakes can have potentially catastrophic effects, given the low tolerances and vulnerability of many key components, as well as the demanding environmental and operational conditions in which military platforms are employed.[94]

The evolution of aircraft production illustrates this trend. Originally an empirical field, aircraft design in the 1920s and 1930s started to incorporate scientific discoveries from aerodynamics theory and engineering science as wooden strut-and-wire biplanes began giving way to streamlined all-metal monoplanes.[95] After World War II, the advent of rocket engines, radio communications, automatic guidance and control, and high-speed aerodynamics created new challenges. In response, aircraft manufacturers had to broaden and deepen their knowledge base to include fields such as weapons design, avionics, and material structures, as well as the training of aircrews, combat tactics, and, most importantly, human physiology and atmospheric sciences.[96] With supersonic speed and subsequent advances, the number and sophistication of disciplines required for aircraft development expanded to the point of being well ahead of scientific knowledge and understanding.[97] Work on the SR-71 Blackbird exemplifies these trends. Because of the friction resulting from flying at three times the speed of sound, the body of the Blackbird was exposed to temperatures above 600°F. To address the resulting problems, Lockheed had to develop "special fuels, structural materials, manufacturing tools and techniques, hydraulic fluid, fuel-tank sealants, paints, plastic, wiring and connecting plugs, as well as basic aircraft and engine design."[98] With the transition to fly-by-wire, the absorptive capacity requirements grew by an order of magnitude, as aircraft production expanded to a broad set of highly demanding fields such as electronics, computer science, and communications, with "software construction [being] the most difficult problem in engineering."[99] Moreover, given the nature of these disciplines, the margin for error has continued

94. Even minor problems can pose serious threats to military platforms given the presence of onboard ordnance and explosives, as well as the need to hide from enemy sensors. See, for example, Sherry Sontag and Christopher Drew with Annette Lawrence Drew, *Blind Man's Bluff: The Untold Story of American Submarine Espionage* (New York: PublicAffairs, 1998), pp. 109–120, 133–134.
95. Vernon Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development* (Oxford: Oxford University Press, 2006), p. 44.
96. See Stephen B. Johnson, *The Secret of Apollo: Systems Management in American and European Space Programs* (Baltimore, Md.: Johns Hopkins University Press, 2006), pp. 1–80.
97. Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, pp. 81–82; Alic et al., *Beyond Spinoff*, pp. 20–22; and Alic, "Managing U.S. Defense Acquisition," p. 17.
98. Johnson and Smith, *Kelly*, p. 137.
99. Winston Royce, "Current Problems," in Christine Anderson and Merlin Dorfman, eds., *Aero-*

to shrink: a minor glitch in the software or the exposure of the hardware to unforgiving conditions (e.g., extreme heat, cold, or humidity) can be fatal.[100] With the increase in autonomy in military aviation, the number of disciplines required for weapons production has expanded to "unmanned systems, human factors, psychology, cognitive science, communication, human-computer interaction, computer-supporter work groups and sociology."[101]

from generic to specific requirements

Since the second industrial revolution, the absorptive capacity required to imitate foreign technology has become so specific that countries can no longer exploit their civilian industries to catch up technologically in the military realm. This change has further raised the entry barriers for imitating advanced weapon systems.

generic requirements. In the second half of the nineteenth and early twentieth centuries, manufacturing benefited from unprecedented and possibly unique synergies and economies of scope.[102] The relatively low level of technological complexity imposed fairly loose requirements, permitting the adoption across different industries of the same machine tools, the same industrial processes, and the same know-how.[103] For instance, problems related to automobile production were "not fundamentally different from those which had already been developed for products such as bicycles and sewing machines."[104] As a result, "the skills acquired in producing sewing machines and bicycles greatly facilitated the production of the automobile."[105] With mass production, the opportunities for synergies and economies of scope among different industries expanded even further.[106] Automobile manufacturers during

space Software Engineering: A Collection of Concepts (Washington, D.C.: American Institute of Aeronautics and Astronautics, 1991), p. 6.

100. Johnson and Smith, *Kelly*, p. 143.

101. U.S. Department of Defense, "Task Force Report: The Role of Autonomy in DoD Systems" (Washington, D.C.: U.S. Department of Defense, July 2012), pp. 46–49.

102. Will Mitchell, "Whether and When? Probability and Timing of Incumbents' Entry into Emerging Industrial Subfields," *Administrative Science Quarterly*, Vol. 34, No. 2 (June 1989), pp. 208–230, doi.org/10.2307/2989896.

103. David A. Hounshell, *From the American System to Mass Production, 1800–1932: The Development of Manufacturing Technology in the United States* (Baltimore, Md.: Johns Hopkins University Press, 1985).

104. Nathan Rosenberg, *Perspectives on Technology* (New York: Cambridge University Press, 1976), pp. 18–19, 26; and Hounshell, *From the American System to Mass Production, 1800–1932*, pp. 218–223, 227.

105. Rosenberg, *Perspectives on Technology*, p. 30. See also Glenn R. Carroll et al., "The Fates of *De Novo* and *De Alio* Producers in the American Automobile Industry, 1885–1981," *Strategic Management Journal*, Vol. 17, No. S1 (Summer 1996), pp. 117–137, doi.org/10.1002/smj.4250171009.

106. Rosenberg, *Perspective on Technology*, pp. 9–31.

World War I could easily enter the business of aircraft and tank production by exploiting their existing industrial facilities and know-how.[107] Within a year of starting to produce aircraft engines, Rolls-Royce was delivering a very reliable and high-performing engine (the "Eagle"). Similarly, during the war, the company adapted its "Silver Ghost" chassis, the same used by King George, into an armored car that proved effective during the British campaign in the Middle Eastern desert.[108] Even during World War II, when the level of complexity of military technology was substantially higher than during World War I, the United States and the Soviet Union were able to convert their civilian manufacturing activities to military production at a pace and to a degree that would be unimaginable today.[109] As Richard Overy summarizes, "Manufacturing technically complex weapons . . . [such as] heavy bombers . . . with the methods used for Cadillacs . . . ultimately proved amenable."[110]

SPECIFIC REQUIREMENTS. Opportunities for synergies and economies of scope, however, have diminished dramatically.[111] Weapon systems increasingly rely on extremely advanced technologies, such as data fusion or stealth, that in many cases have no application in the commercial sector. At the same time, they operate under uniquely demanding environmental and operational conditions (e.g., flying at Mach 2). The resulting large number of subtle and challenging technical problems has led to an exponential increase in the required degree of accuracy.[112] Consequently, imitators can no longer exploit their existing technological and industrial capabilities to assimilate foreign military technology: the absorptive capacity requirements have become progressively more specific.[113] By "specific," we mean that the laboratories, research centers, testing and production facilities, skilled workforce, and the cumulative technological knowledge base developed for a particular type of production cannot be easily redeployed for assimilating and exploiting foreign know-how and experience in weapon systems.[114]

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107. Valerio Castronovo, *Fiat: una storia del capitalismo Italiano* (Fiat: a history of Italian capitalism) (Milan, Italy: Rizzoli, 2005), pp. 48–60.
108. Peter Botticelli, "Rolls-Royce and the Rise of High-Technology Industry," in Thomas K. McCraw, ed., *Creating Modern Capitalism: How Entrepreneurs, Companies, and Countries Triumphed in Three Industrial Revolutions* (Cambridge, Mass.: Harvard University Press, 1997), pp. 102–105.
109. Milward, *War, Economy, and Society, 1939–1945*, pp. 187–191.
110. Richard Overy, *Why the Allies Won* (New York: W.W. Norton, 1996), p. 195.
111. Ruttan, *Is War Necessary for Economic Growth*? p. 58.
112. Eric von Hippel, "Task Partitioning: An Innovation Process Variable," *Research Policy*, Vol. 19, No. 5 (October 1990), pp. 407–418, doi.org/10.1016/0048-7333(90)90049-C.
113. Edward W. Steinmueller, "Industry Structure and Government Policies in the U.S. and Japanese Integrated Circuit Industries," in John B. Shoven, ed., *Government Policies toward Industries in the U.S. and Japan* (New York: Cambridge University Press, 1988), p. 344.
114. William Walker, Mac Graham, and Bernard Harbor, "From Components to Integrated Sys-

For instance, the design of modern weapon systems requires advanced knowledge of enemies' counter-systems, tactics, and doctrines, as well as of the environmental conditions of operations.[115] When copying foreign technology, countries need this knowledge to translate foreign information into actual designs.[116] Design capabilities are also extremely important when seeking to integrate foreign component technologies into a competitive military platform. As John Alic writes, "Early design choices largely determine ultimate performance and costs." Once a design has been chosen, "no amount of analysis, modification, and refinement can salvage a deficient concept."[117] Understandably, commercial enterprises do not possess the necessary design capabilities for military production and cannot develop them overnight.[118] In submarine design, for example, "the most challenging competencies . . . require at least ten years of experience and a Ph.D."[119] Moreover, bringing a concept from prototype to finished product involves highly specific tasks and procedures that share little with other realms. For instance, to perform tests, interpret and understand the results, and identify and address the problems that will inevitably arise when developing new weapons, arms manufacturers need equipment, laboratories, test facilities, and specialized personnel with both domain-specific and product-specific expertise. These requirements include radars operating at different frequencies, supersonic wind tunnels, know-how in stealth coating, and test pilots with combat experience.[120] Consequently, defense and civilian industries have come to differ dramatically, to the point that even realms such as defense and commercial shipbuilding or aviation have limited opportunities for synergy.[121] Indeed, even military contractors cannot move easily from one area of weapons production to another, as "systems inte-

tems: Technological Diversity and Interactions between the Military and Civilian Sectors," in Philip Gummet and Judith Reppy, eds., *The Relations between Defense and Civil Technologies*, NATO ASI Series, Vol. 46 (Dordrecht: Springer Netherlands, 1988), pp. 17–37.

115. Dombrowski and Gholz, *Buying Military Transformation*, pp. 17–18; and Gholz, "Systems Integration for Complex Defense Projects," p. 54.

116. Shaker A. Zahra and Gerard George, "Absorptive Capacity: A Review, Reconceptualization, and Extension," *Academy of Management Review*, Vol. 27, No. 2 (April 2002), pp. 185–202, doi.org/10.2307/4134351.

117. Alic, "Managing U.S. Defense Acquisition," pp. 14–15.

118. Gholz, "Systems Integration for Complex Defense Projects," p. 54; and Brooks, *Producing Security*, pp. 235–238.

119. John F. Schank et al., *Sustaining U.S. Nuclear Submarine Design Capabilities* (Santa Monica, Calif.: RAND Corporation, 2007), pp. 92–94.

120. Keith Pavitt, "The Objective of Technology Policy," *Science and Public Policy*, Vol. 14, No. 4 (August 1987), pp. 182–188, doi.org/10.1093/spp/14.4.182.

121. John Birkler et al., *Differences between Military and Commercial Shipbuilding: Implications for the United Kingdom's Ministry of Defence* (Santa Monica, Calif.: RAND Corporation, 2005); and Eugene Gholz, "Eisenhower versus the Spin-Off Story: Did the Rise of the Military-Industrial Complex

gration contractors from the aerospace business may not truly understand the complex world of shipbuilding."[122]

One could argue that through reverse engineering, industrial espionage, or cyber espionage, an imitating country could skip the design and development stages and manufacture a foreign weapon system using its existing industrial base. This argument ignores a key constraint: the increase in complexity has also made manufacturing processes more specific and possibly unique. Because of the requirements that military platforms need to meet, today's production processes must achieve stringent levels of precision that are alien to most industries.[123] For instance, the low observability to radar of stealth aircraft will be compromised if "the heads of [just] three screws [are] not quite tight and extend . . . above the surface by less than an eighth of an inch."[124] In the words of the F-117 Nighthawk's program manager, "In building the stealth fighter, we had to tightrope walk between extreme care and Swiss-watch perfection to match the low radar observability of our original computerized shape."[125] In turn, developing, updating, and preserving this type of manufacturing skill calls for highly specific training, practices, and processes. In the shipbuilding industry, workers across all technical skills require "6–8 years to reach at least 90 percent of optimum productivity."[126]

The unique requirements of manufacturing weapon systems go well beyond skills and processes. Take, for example, machine tools. In the early twentieth century, as discussed earlier, disparate fields such as the automobile and sewing machine industries used the same machine tools. In contrast, since the end of World War II, the production of military aircraft engines has relied on machine tools with a degree of precision that no commercial company possesses or needs.[127] For its part, the U.S. Navy has developed propellers that dramatically reduce the acoustic signature of its submarines.[128] With help

Hurt or Help America's Commercial Aircraft Industry?" *Enterprise & Society*, Vol. 12, No. 1 (Spring 2011), pp. 46–95, doi.org/10.1093/es/khq134.

122. Dombrowski and Gholz, *Buying Military Transformation*, p. 58.

123. Rich and Janos, *Skunk Works*, pp. 76–78, 89–90. See also Howard Moon, *Soviet SST: The Technopolitics of the Tupolev-144* (New York: Orion, 1989), pp. 5–6.

124. Rich and Janos, *Skunk Works*, p. 69.

125. Alan Brown, quoted in ibid., p. 81.

126. See Hans Pung et al., *Sustaining Key Skills in the UK Naval Industry* (Santa Monica, Calif.: RAND Corporation, 2008), p. 35.

127. Tom Lilley et al., *Problems of Accelerating Aircraft Production during World War II: A Report* (Boston: Division of Research, Graduate School of Business Administration, Harvard University, 1947); and Roberto Mazzoleni, "Innovation in the Machine Tool Industry," in Mowery and Nelson, *Sources of Industrial Leadership*, p. 189.

128. Quietness has become the key parameter of competition in submarine warfare since the end of World War II. See Coté, *The Third Battle*, pp. 20–35.

from the John Walker spy ring, the Soviet Union obtained information about how to manufacture U.S. propellers.[129] Their production, however, required computer-controlled milling machines with a degree of accuracy that Soviet machines could not achieve.[130] In short, the Soviets could not rely on their existing capabilities to exploit the information they had obtained through industrial espionage.[131]

Technological Knowledge

The second condition for the advantage of imitation requires that imitating countries acquire, relatively easily and quickly, the technological knowledge of how to design, develop, and/or manufacture a given military platform, so that they can take advantage of the innovator's advances before the platform becomes obsolete.[132] The increase in the complexity of military technology, however, has made technological knowledge increasingly tacit and organizational in nature, which means that it does not diffuse to other countries either easily or quickly.

Regardless of how advanced a country's industrial, scientific, and technological base is, the production of new military platforms requires work at the design, development, and manufacturing stages aimed at anticipating, identifying, and addressing inherent idiosyncrasies. These idiosyncrasies stem from the challenges related to the integration of state-of-the-art components, subsystems, and systems, as well as from having the platform operate under previously unexplored environmental conditions. As the director of Lockheed's Skunk Works division, Chief Engineer Clarence "Kelly" Johnson, recalled when discussing the SR-71, "Everything about the aircraft had to be invented. Everything."[133] We argue that the technological knowledge related to the production of advanced military platforms such as the SR-71 does not

129. Ibid., p. 73.
130. Ibid., p. 69.
131. In the end, the Soviets managed to copy the propellers, but only after having acquired two pieces of equipment that had been subjected to an embargo: high-precision "nine-axes milling machinery tools" from the Japanese company Toshiba; and a computer device that could be used with them from a Norwegian defense company, Kongsberg. See ibid.; and Wende A. Wrubel, "The Toshiba-Kongsberg Incident: Shortcomings of Cocom, and Recommendations for Increased Effectiveness of Export Controls to the East Bloc," *American University Journal of International Law and Policy*, Vol. 4, No. 1 (Winter 1989), p. 254.
132. Fernando F. Suarez and Gianvito Lanzolla, "The Role of Environmental Dynamics in Building a First Mover Advantage Theory," *Academy of Management Review*, Vol. 32, No. 2 (2007), pp. 377–392, doi.org/10.5465/amr.2007.24349587.
133. Johnson and Smith, *Kelly*, p. 137.

diffuse easily, because such knowledge is embedded in the organizational memory of the defense company that produced it.

FROM CODIFIED TO TACIT KNOWLEDGE

Over the past century and a half, weapons production has changed dramatically, as indicated by the increase in the development time of weapon systems from a few months to several years and even decades.[134] As noted previously, in the late nineteenth and early twentieth centuries, innovations were the results of conjecture, creativity, ingenuity, and intuition (and sometimes of just plain luck or accidents).[135] This meant that the knowledge of how to produce a given technology was relatively simple; it could be written down in terms of principles and rules—it was codifiable. Codifiability permitted the spread of knowledge. Because of the growing complexity of weapons systems, however, innovations have become the product of extensive prototyping, testing, experimentation, and refinement: as a result of this change, knowledge related to a given weapon system has become increasingly less codifiable—it has become tacit. As former Secretary of Defense Ashton Carter and coauthors have noted, "Tacit knowledge is a route for maintaining a technological edge in military systems: what cannot be written down can hardly be stolen."[136]

CODIFIABLE KNOWLEDGE. During the immediate aftermath of the second industrial revolution, the knowledge behind most innovations was relatively simple: their logic and functioning were directly observable and understandable.[137] As such, an innovation generally carried within itself the very know-how related to its production process.[138] The simplicity of such know-how, in turn, allowed for the innovation's codification, and hence promoted its diffusion. This is what happened, for example, in manufacturing.

In the mid-nineteenth century, the implicit knowledge of skilled craftsmen was partially codified, allowing semi-skilled workers to perform the manual tasks associated with the emergence of mechanized, standardized manufacturing of interchangeable parts.[139] This trend was later reinforced with the devel-

134. Alic, "Managing U.S. Defense Acquisition," p. 3. See also Laurence K. Loftin Jr., *Quest for Performance: The Evolution of Modern Aircraft* (Washington, D.C.: NASA Scientific and Technical Information Branch, 1985), p. 7.
135. Hacker, "The Machines of War," p. 257.
136. Alic et al., *Beyond Spinoff*, p. 33.
137. Teece, "Capturing Value from Knowledge Assets," p. 64; Arthur, *The Nature of Technology*, pp. 45–67; and Alic, "Managing U.S. Defense Acquisition," pp. 1–36.
138. This, for example, is how the Soviet Union acquired the technological knowledge necessary to produce long-range heavy bombers after World War II. Yefim Gordon and Vladimir Rigmant, *Tupolev Tu-4: Soviet Superfortress* (Hinckley, U.K.: Midland, 2002).
139. Yasunori Baba, Shoichi Kuroda, and Hiroshi Yoshiki, "Diffusion of the Systemic Approach in

opment of the assembly line, which relied on the simplicity of the processes involved, and thus "the worker's implicit knowledge had to be made explicit."[140] Implicit knowledge was "gathered and analyzed" to permit the fragmentation of work into a multitude of extremely simple tasks.[141] Beginning in the 1910s, the organizational and technical principles of the assembly line and mass production were codified in articles and books.[142] The Ford Motor Company, the pioneer of the assembly line, also contributed to the codification of such knowledge when it decided to "have any part of its commercial, managerial or mechanical practice given full and unrestricted publicity in print."[143] Ford's transparency facilitated the diffusion of mass production processes to other industries.[144]

A similar trend occurred with the emergence of modern science in the late nineteenth and early twentieth centuries, as scientists began to understand, explain, systematize, and codify the body of knowledge developed by practitioners and on which many industrial processes were based.[145] As a result of the progress of modern science and of its diffusion, implicit knowledge was translated into explicit knowledge, thus reducing and, in many cases, negating the advantages enjoyed by early innovators.[146]

TACIT KNOWLEDGE. Because of the increase in the complexity of military technology, the technological knowledge of how to design, develop, and produce a given weapon system has become increasingly tacit. Tacit knowledge cannot be codified.[147] It entails knowledge derived mostly from experience and hence is retained by people and organizations: for this reason, it does not diffuse either easily or quickly.[148] Indeed, "the most effective way of [transferring tacit knowledge], despite telephone, video and other remote methods, is

Japan: Gauge and Industrial Standards," in Akira Goto and Hiroyuki Odagiri, eds., *Innovation in Japan* (New York: Oxford University Press, 1997), pp. 40–42.
140. Shoshana Zuboff, *In the Age of the Smart Machine: The Future of Work and Power* (New York: Basic Books, 1988), pp. 41–44.
141. Ibid., p. 44.
142. Hounshell, *From the American System to Mass Production, 1800–1932*, pp. 258–260.
143. Quoted in ibid., p. 260.
144. Ibid., pp. 260–261.
145. Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (New York: Oxford University Press, 1990), pp. 113–148.
146. Joel Mokyr, "The Contribution of Economic History to the Study of Innovation and Technical Change, 1750–1914," in Bronwyn H. Hall and Nathan Rosenberg, eds., *Handbook of the Economics of Innovation*, Vol. 1 (New York: Elsevier, 2010), pp. 25–43.
147. Donald MacKenzie and Graham Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," *American Journal of Sociology*, Vol. 101, No. 1 (July 1995), p. 63, doi.org/10.1086/230699.
148. Friedrich A. Hayek, "The Use of Knowledge in Society," *American Economic Review*, Vol. 35, No. 4 (September 1945), pp. 519–530, https://www.jstor.org/stable/1809376; and Michael Polanyi,

face-to-face interaction."[149] To replicate a given weapon system, an imitator needs direct access to the innovator's tacit knowledge—that is, access to the very people who worked on the system.[150] Otherwise, it will struggle to figure out what each part does, the requirements it is intended to meet, how to produce it, and how it is connected to other components—in other words, its design, development, and production know-how.[151] Moreover, disassembling a military platform into smaller components to observe and understand its functioning has become significantly more challenging. Today many weapon systems, such as jet fighters, "comprise highly integrated subsystems that are extremely difficult (if not impossible) to decompose into independent modules."[152] The introduction of electronics has reinforced this trend, as the functioning of software is governed not by observable physical laws (in contrast, for example, to aerodynamics), but by the software's internal correctness and its perfect integration with the weapon system's hardware.[153]

Three factors explain why design, development, and production know-how have become largely tacit. First, today designers, engineers, managers, and specialized workers face an infinite number of decisions, each entailing inherent trade-offs: from the choice among alternative designs; to the choice among different components, their materials, and their technical properties; to choices about manufacturing techniques and procedures.[154] Identifying the most appropriate choices and solutions relies heavily on experience, judgment calls, and educated guesses—all of which are, by definition, tacit.[155] As Marco Iansiti notes, "An employee with thirty years' experience in manufacturing will prob-

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Personal Knowledge: Towards a Post-Critical Philosophy (Chicago, Ill.: University of Chicago Press, 1958).

149. Wolfgang Keller, "International Technology Diffusion," *Journal of Economic Literature*, Vol. 42, No. 3 (September 2004), p. 756, doi.org/10.1257/0022051042177685.

150. See Collins, "The TEA Set," pp. 165–185; and MacKenzie and Spinardi, "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons," pp. 44–99.

151. Wesley M. Cohen and Richard C. Levin, "Empirical Studies of Innovation and Market Structure," in Richard Schmalensee and Robert Willig, eds., *Handbook of Industrial Organization*, Vol. 2 (Amsterdam: North Holland, 2007), p. 1093.

152. Charles H. Fine, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage* (Reading, Mass.: Perseus, 1998), p. 141.

153. Dennis D. Doe, "Current Practices," in Anderson and Dorfman, *Aerospace Software Engineering*, p. 164; and James E. Tomayko, *Computers Take Flight: A History of NASA's Pioneering Digital Fly-By-Wire Project* (Washington, D.C.: National Aeronautics and Space Administration, 2000), pp. 24–25, 30.

154. Alic, "Managing U.S. Defense Acquisition," p. 15; and Gholz, "Systems Integration for Complex Defense Projects," p. 53.

155. John A. Alic, "Computer-Assisted Everything? Tools and Techniques for Design and Production," *Technological Forecasting and Social Change*, Vol. 44, No. 4 (December 1993), p. 365, doi.org/10.1016/0040-1625(93)90041-5.

ably recognize that one design detail will be easier to manufacture than another, but she or he might not be able to articulate exactly why."[156] In fact, many choices are shaped by a subtle knowledge and understanding of existing capabilities, suppliers, and technical properties (e.g., ease of production or maintenance as well the availability of components); by idiosyncratic cultural, environmental, or operational needs; or by contingent factors within the development process (some problems can be solved without redesigning the whole platform).[157] It follows that some of these choices might not be intuitive or rational. Hence, they might be hard to understand by people who have not directly participated in the process that led to them.[158]

Second, identifying appropriate choices and solutions entails extensive experimentation, manipulation, prototyping, testing, and refinement (including a lot of tinkering) with constant back-and-forth among teams of designers, engineers, managers, and specialized workers. This process allows those involved in the production of a given weapon system to explore different options and potential solutions for the many kinds of problems encountered in such work and thus to understand what works and what does not.[159] Because such knowledge is developed in a disorganized as opposed to systematized way, writing it down in terms of general rules and principles is extremely difficult, if not impossible.[160] Consequently, the very act of developing this knowledge cannot be separated from the knowledge itself, because it reflects the personal experiences of those involved in each stage of production.[161]

Third, even if a country had access to all the blueprints and designs of a given weapon system, many crucial aspects would still be lacking, because "the best efforts to describe complex technologies . . . cannot capture all of the details that engineers and technicians understand."[162] In modern weapon sys-

156. Iansiti, *Technology Integration*, p. 11. See also Bruce Kogut and Udo Zander, "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology," *Organization Science*, Vol. 3, No. 3 (August 1992), pp. 383–397, doi.org/10.1287/orsc.3.3.383.
157. Iansiti, *Technology Integration*, pp. 104–106, 133; and Gholz, "Systems Integration for Complex Defense Projects," pp. 52–53.
158. Graham Spinardi, Robin Williams, and Ian Graham, "Technical Data Interchange in the Eurofighter Project," *Science and Public Policy*, Vol. 22, No. 1 (February 1995), p. 29, doi.org/10.1093/spp/22.1.29.
159. Stefano Brusoni, Andrea Prencipe, and Keith Pavitt, "Knowledge Specialization, Organizational Coupling, and the Boundaries of the Firm: Why Do Firms Know More Than They Make?" *Administrative Science Quarterly*, Vol. 46, No. 4 (December 2001), pp. 597–621, doi.org/10.2307/3094825.
160. Kathryn Henderson, "Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering," *Science, Technology, & Human Values*, Vol. 16, No. 4 (Autumn 1991), pp. 449–450, doi.org/10.1177/016224399101600402.
161. Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, pp. 81–82.
162. Gholz, "Systems Integration for Complex Defense Projects," p. 53.

tems, relatively small details, such as the specific weight of fasteners or the chemical composition of rubber valves, can create huge operational challenges, possibly compromising the reliability and even survival of the platform.[163] For this reason, just one of the many possible problems that weapons development entails can slow down and possibly even prevent a country from replicating a foreign weapon system, even when it has full access to blueprints and designs.[164] For example, in the 1990s and in 2005, the U.S. Navy failed repeatedly to reproduce its material to refurbish its nuclear warheads—codenamed "Fogbanks"—because there were "few records of the process when the material was made in the 1980s and almost all the staff with expertise on production had retired or left the agency."[165] The Navy eventually succeeded, but only after ten years of extensive work and an expenditure of more than $90 million.[166] From this experience, the U.S. Government Accountability Office concluded that "assumptions such as 'we did it before so we can do it again' are often wrong."[167]

FROM INDIVIDUAL TO ORGANIZATIONAL KNOWLEDGE

As a result of the increase in technological complexity, single individuals can no longer master all the knowledge and activities required for weapon development.[168] Such know-how and experience have become the product of the collective effort of designers, engineers, managers, and specialized workers with different backgrounds. As such, know-how and experience diffuse very slowly, because organizations are far less mobile than people.[169]

INDIVIDUAL KNOWLEDGE. During the second industrial revolution, lone inventors such as Alexander Bell, Thomas Edison, Nikola Tesla, and George Westinghouse brought scientific and technological knowledge forward.[170] They understood and put into practice principles that, in some cases, now

163. See Wang, *Reverse Engineering*, pp. 266–268.
164. Jon R. Lindsay and Tai Ming Cheung, "From Exploitation to Innovation: Acquisition, Absorption, and Application," in Lindsay, Cheung, and Reveron, *China and Cybersecurity*, p. 56.
165. U.S. Government Accountability Office (GAO), *Nuclear Weapons: NNSA and DOD Need to More Effectively Manage the Stockpile Life Extension Program* (Washington, D.C.: GAO, March 2009), p. 16.
166. Jonathan V. Last, "The Fog of War: Forgetting What We Once Knew," *Weekly Standard*, May 18, 2009, pp. 10–11.
167. GAO, *Nuclear Weapons*, p. 15.
168. Frederick Tell, "Integrating Electrical Power Systems: From Individual to Organizational Capabilities," in Prencipe, Davies, and Hobday, *The Business of Systems Integration*, p. 71. See also Herbert A. Simon, "Bounded Rationality and Organizational Learning," *Organization Science*, Vol. 2, No. 1 (February 1991), pp. 125–134, https://www.jstor.org/stable/2634943.
169. Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, pp. 73–74.
170. Tell, "Integrating Electrical Power Systems," p. 60; and Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, pp. 15–16, 59–60.

seem rather elementary but that until then nobody had been able to identify.[171] By 1933, when the legendary aircraft designer "Kelly" Johnson proved that one of the most advanced civilian aircraft of that time was aerodynamically inefficient, the chief engineer of Lockheed expressed surprise upon learning "how simple the solution [Johnson provided] really was."[172] Moreover, in many cases, the person who designed a new technology was also responsible for developing it or for specifying the principles for its production. As Alic puts it, "Design and manufacturing could be linked in one person's head."[173] Inventors could also transmit their knowledge to their apprentices, to their students, or even to another country in the event they decided to migrate, as Tesla did.[174]

ORGANIZATIONAL KNOWLEDGE. Because of the increase in complexity, lone inventors have increasingly lost relevance.[175] "By the eve of the Depression," G. Pascal Zackary writes in his biography of Vannevar Bush, "the lone inventor was fading into myth."[176] Laboratories and research centers were becoming the "locus of invention." Bush himself came to chair one of the most important of these centers during World War II, the Office for Scientific Research and Development.[177] Since then, designing, developing, and manufacturing advanced weapon systems has become a collective effort involving hundreds and possibly thousands of highly educated and skilled individuals with backgrounds in different fields and with decades of experience.[178] These individuals generally possess knowledge about extremely important but very small details regarding these systems. Even the most talented aircraft designer will not be able to develop the software necessary for today's fighters or to provide instructions on its development.[179] Consider, again, "Kelly" Johnson, director of Lockheed's Skunk Works division from its inception until 1975. Johnson took a leading role in designing some of the most advanced aircraft ever developed, including the P-38 Lightning, the U-2 Dragon Lady, and the aforementioned SR-71. His amazing knowledge and understanding of aircraft design

171. See Hacker, "The Machines of War," p. 257.
172. Johnson and Smith, *Kelly*, p. 24.
173. See Alic, "Computer-Assisted Everything?" p. 364.
174. Richard R. Nelson and Gavin Wright, "The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, Vol. 30, No. 4 (December 1992), p. 1944, https://www.jstor.org/stable/2727970.
175. Alic, "Computer-Assisted Everything?" p. 364.
176. G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (Cambridge, Mass.: MIT Press, 1999), p. 17.
177. Ibid.
178. Mowery and Rosenberg, *Technology and the Pursuit of Economic Growth*, pp. 73–74.
179. Rich and Janos, *Skunk Works*, pp. 30–31, 46, 204.

continue to be celebrated widely in the aviation community.[180] Yet, when fly-by-wire and stealth emerged in the 1970s, even his extraordinary expertise would be put to the test. Johnson believed that the new stealth aircraft that Skunk Works was developing (the future F-117) would never fly because of its aerodynamically inefficient shape.[181] Johnson was right: without fly-by-wire, "Hopeless Diamond," as the aircraft was nicknamed, "would have been hopeless indeed."[182] Without flight control software that carried out automatic microsecond flight adjustments, the F-117 "could not even taxi straight."[183] This software was the product of more than twenty years of hard work by dozens of people on computer-assisted flight control, which then had to be adapted to the specificities of the F-117.[184]

Today, know-how about weapon systems production is embedded in the collective memories and experience of defense organizations, which severely inhibits its diffusion.[185] The F-117 was designed by a team of fifty engineers, and still more engineers were necessary to develop and refine the end product.[186] That number has increased dramatically, with more than 6,000 engineers working on the F-35 project.[187] With numbers this large, if an engineer or a designer decides to migrate or defect, or even if she is kidnapped, she will at best be able to provide only a fraction of the knowledge needed.[188]

One might argue that the emergence over the past sixty years of computer-assisted design, engineering, and manufacturing, as well as of finite element analysis and computational fluid dynamics, can compensate for the impossibility for individuals to retain and put to use all the knowledge necessary for the development of modern weapon systems.[189] But as Alic notes, this argument "underestimate[s] the difficulties of mastering the new technologies."[190]

180. Leo P. Geary, "Foreword," in Johnson and Smith, *Kelly*, p. viii; and Rich and Janos, *Skunk Works*, p. 129.
181. Rich and Janos, *Skunk Works*, pp. 32, 108.
182. Ibid., pp. 30–31.
183. Ibid., p. 46.
184. Ibid., pp. 46, 95; and Tomayko, *Computers Take Flight*, pp. 43, 47, 53–54.
185. Daniel Ross, James P. Womack, and Daniel T. Jones, *The Machine That Changed the World: The Story of Lean Production* (New York: Harper Perennial, 1991), pp. 249, 283–285.
186. For example, the development of the XP-80 jet fighter prototype (1940s) required 120 people (23 of whom were engineers) and 143 days. For the JetStar corporate transport, the number of engineers increased to 37. For the U-2 Dragon Lady, it increased to 50, and for the SR-71 Blackbird to 135. Johnson and Smith, *Kelly*, pp. 161–162.
187. Marcus Weisgerber, "U.S. F-35 Chief Reorganizing Program Office," *Defense News*, March 13, 2013, https://fortunascorner.wordpress.com/2013/03/13/u-s-f-35-chief-reorganizing-program-office/.
188. Stefan Wuchty, Benjamin F. Jones, and Brian Uzzi, "The Increasing Dominance of Teams in Production of Knowledge," *Science*, May 18, 2007, pp. 1036–1039, doi.org/10.1126/science.1136099.
189. Alic, "Computer-Assisted Everything?" p. 364.
190. Ibid.

In fact, "design decisions will continue to be based on judgment, experience, intuition and rough calculations."[191] The lesson is that computers cannot help with conceptualization.[192] Moreover, given the infinite number of alternative designs, "there are too many permutations to be explored with even the most powerful computer-based methods [so], designers rely, as they always have, on tacit know-how and experience-based judgment."[193] Computer assistance ultimately "requires experts who understand a particular method's domain of application and can interpret the often ambiguous results of complicated mathematical models."[194] The development of the F/A-18 Hornet jet fighter is revealing in this respect.[195] Computer assistance "failed to predict" a problem the aircraft experienced "and provided little help in finding a solution."[196] To address this problem, the prime contractor had to carry out extensive ground and in-flight testing.[197] In the end, "designers had no choice but to fall back on informal procedural knowledge, some of it tacit."[198] Available evidence suggests that the same limitations apply to artificial intelligence and machine learning, as they cannot substitute for human creativity and intuition, but only complement them.[199]

Empirical Investigation

In this section, we employ two cases to test our theory. First, we explain the rationale behind our case selection. Second, we examine Imperial Germany's naval rearmament in the context of its naval rivalry with Great Britain from 1890 to 1916. Third, we consider China's aerospace modernization program in the context of its competition with the United States from 1991 to 2018.

RESEARCH DESIGN

The cases of Imperial Germany and contemporary China allow us to put our theory to a hard test and existing international relations theories to an easy

191. Ibid., p. 365.
192. See Ajay Agrawal, Joshua Gans, and Avi Goldfarb, *Prediction Machines: The Simple Economics of Artificial Intelligence* (Boston: Harvard Business Review Press, 2018), p. 13.
193. Alic, "Managing U.S. Defense Acquisition," p. 15.
194. Alic, "Computer-Assisted Everything?" p. 368.
195. John A. Alic, "Technical Knowledge and Experiential Learning: What People Know and Can Do," *Technology Analysis & Strategic Management*, Vol. 20, No. 4 (July 2008), p. 434, doi.org/10.1080/09537320802141403.
196. Ibid.
197. Ibid.
198. Ibid.
199. Paul R. Daugherty and H. James Wilson, *Human Machine: Reimagining Work in the Age of AI* (Boston: Harvard Business School Press, 2018), p. 76.

test. In other words, if the conventional wisdom fails here, we should be skeptical of its validity under less favorable circumstances. Conversely, if our empirical investigation supports our argument, we should be confident about its success under more favorable conditions.

SIMILARITIES. Imperial Germany and contemporary China represent rising powers with assertive and possibly expansionist geopolitical ambitions.[200] Both countries launched large-scale military buildups with the goal of developing state-of-the-art weapon systems.[201] And in both cases, the rise of commercial enterprises producing dual-use technologies not only drove the overall economic growth of both countries, but also contributed to their military modernization.[202]

DIFFERENCES. The two cases exhibit important differences, however, that according to international relations theory should have made China's imitation of U.S. fifth-generation fighters significantly easier than Imperial Germany's imitation of the *Dreadnought*, Britain's all-big-gun battleship. First, although the rise of both countries took place during two unrivaled eras of globalization, China has been operating in a much more open world economy from which it could derive higher inflows of foreign direct investment (FDI) and unrivaled access to foreign technology.[203] Second, Imperial Germany's impressive 88 percent economic growth from 1890 to 1916 pales in comparison to China's 3,092 percent economic growth from 1991 to 2017.[204] Third, whereas German defense spending doubled in the 1890–1916 period, China's military expenditure grew by 920 percent, from $23 billion in 1991 (U.S. 2015) to

200. Rolf Hobson, *Imperialism at Sea: Naval Strategic Thought, the Ideology of Sea Power, and the Tirpitz Plan, 1875–1914* (Leiden, Netherlands: Brill, 2002); and Thomas J. Christensen, *The China Challenge: Shaping the Choices of a Rising Power* (New York: W.W. Norton, 2015).

201. Volker R. Berghahn, *Der Tirpitz-Plan: Genesis und Verfall einer innernpolitischen Krisenstrategie* (The Tirpitz plan: genesis and decline of an internal political crisis strategy) (Düsseldorf, Germany: Droste Verlag, 1971); and Eric Heginbotham et al., *The U.S.-China Military Scorecard: Forces, Geography, and the Evolving Balance of Power, 1996–2017* (Santa Monica, Calif.: RAND Corporation, 2015).

202. The companies that promoted the commercial and military rise of Imperial Germany and contemporary China are Krupp and Thyssen (metallurgy), Siemens (electric systems), BASF (chemical), and Daimler-Benz (cars) for Germany; and Lenovo (computers), Sunway TaihuLight (supercomputers), Huawei (smartphones), and Alibaba (online retail) for China. See Gary E. Weir, *Building the Kaiser's Navy*, pp. 43–44; and Leigh Ann Ragland, Joe McReynolds, and Debra Geary, "China's Defense Electronics and Information Technology Industry," in Cheung, ed., *The Chinese Defense Economy Takes Off*, pp. 45–58.

203. Piya Mahtaney, *India, China, and Globalization: The Emerging Superpowers and the Future of Economic Development* (New York: Palgrave Macmillan, 2007), pp. 82–169; and Ted C. Fishman, *China, Inc.: How the Rise of the Next Superpower Challenges America and the World* (New York: Simon and Schuster, 2006).

204. Authors' calculation based on Paul Bairoch, "Europe's Gross National Product: 1800–1975," *Journal of European Economic History*, Vol. 5, No. 2 (Fall 1976), pp. 281, 295. World Bank data, available at https://data.worldbank.org.

$228 billion in 2017.[205] Third, the German naval buildup relied on the support of the domestic coalition of "Iron and Rye." Once *Dreadnought* was launched and the Anglo-German naval arms race rapidly accelerated, the German navy had to compromise on battleship costs and capabilities to preserve domestic support.[206] Conversely, China has so far faced little internal opposition to its military modernization program.[207] Fourth, as a land power, Germany could not invest all its resources in naval modernization.[208] Indeed, as Nicholas Wolz notes, nothing "illustrates better the insignificance of the [German] naval forces than the fact that until 1888, supreme command of the [German navy] . . . lay in the hands of army officers."[209] As war with France and Russia became more likely, naval budgets were cut.[210] Conversely, since the collapse of the Soviet Union, China has not faced a serious land threat.[211] Thus, the government in Beijing could focus its investments primarily on the high-technology modernization of both its air force and navy.[212]

INDEPENDENT VARIABLES. Most important, the cases of Imperial Germany and China display two key differences in our variables of interest: absorptive capacity and access to foreign technological knowledge. When Germany and China launched their military buildups, each had relatively low absorptive capacity: Germany was lagging behind in pre-Dreadnought battleships, and China could produce only old Soviet aircraft designs.[213] Yet, in comparison to Germany, China benefited extensively from FDI, R&D joint ventures, and

205. Volker R. Berghahn, *Imperial Germany, 1871–1914: Economy, Society, Culture, and Politics* (New York: Berghahn, 2005); and Stockholm International Peace Research Institute (SIPRI), "Military Expenditure by Country" (Stockholm: SIPRI, 2015), https://www.sipri.org/databases/milex.
206. Norman Friedman, *Fighting the Great War at Sea: Strategy, Tactics, and Technology* (Barnsley, U.K.: Seaforth, 2014), pp. 73–101, 195–213; and Gary E. Weir, *Building the Kaiser's Navy: The Imperial Navy Office and German Industry in the Tirpitz Era, 1890–1919* (Annapolis: Naval Institute Press, 1992), pp. 33–34.
207. Christensen, *The China Challenge*, pp. 37–62, 169–287.
208. Holger H. Herwig, *"Luxury" Fleet: The Imperial German Navy, 1888–1918* (London: George Allen and Unwin, 1980).
209. Nicholas Wolz, *From Imperial Splendor to Internment: The German Navy in the First World War* (Barnsley, U.K.: Seaforth, 2015), p. 2.
210. Herwig, *"Luxury" Fleet*, pp. 54–69; and Philip Pugh, *The Cost of Seapower: The Influence of Money on Naval Affairs from 1815 to the Present Day* (London: Conoway Maritime, 1986), pp. 43, 152–183.
211. Evan Braden Montgomery, "Competitive Strategies against Continental Powers: The Geopolitics of Sino-Indian-American Relations," *Journal of Strategic Studies*, Vol. 36, No. 1 (February 2013), pp. 76–100, doi.org/10.1080/01402390.2012.736383.
212. Dennis J. Blasko, "PLA Force Structure: A 20-year Retrospective," in James C. Mulvenon and Andrew N.D. Yang, eds., *Seeking Truth from Facts: A Retrospective on Chinese Military Studies in the Post-Mao Era* (Santa Monica, Calif.: RAND Corporation, 2001), pp. 51–86.
213. Kenneth W. Allen, Glenn Krumel, and Jonathan D. Pollack, *China's Air Force Enters the 21st Century* (Santa Monica, Calif.: RAND Corporation, 1995), p. 141.

mergers and acquisitions with Western companies, which significantly enhanced its absorptive capacity while allowing it to launch its stealth aircraft program. Moreover, unlike the German case, China has had massive access to foreign technology and know-how, especially given its extensive reliance on cyber and industrial espionage and opportunities to reverse engineer technologies purchased from abroad.[214] In other words, China represents a particularly easy case for testing the argument that globalization and cyber espionage have facilitated the imitation of foreign military technology.[215] The empirical record, however, demonstrates that copying state-of-the-art weapon systems has become only more difficult. In the span of just three to five years, Imperial Germany succeeded in copying the most advanced battleship of its time—the *Dreadnought*—the product of experience and know-how accumulated by Britain over the previous five decades.[216] In contrast, China faced massive struggles in imitating U.S. fifth-generation jet fighters: twenty years after its launch, China's stealth aircraft still suffers from shortfalls that make it inferior to its U.S. counterpart.[217]

WILHELMINE GERMANY AND THE ALL-BIG-GUN BATTLESHIP, 1890–1916

In 1906, at the apex of the Anglo-German naval rivalry, the Royal Navy commissioned *Dreadnought*, an all-big-gun battleship that delivered higher speed, more stability, better armor protection, and, possibly more important, the firepower of two to three pre-Dreadnought battleships.[218] As such, *Dreadnought* made all existing battleships suddenly obsolete, thus canceling the capital investments that Britain's competitors had made during the past decade, including those of Imperial Germany.[219] Dreadnought battleships incorporated newly available component technologies and translated into practice British Adm. Jackie Fisher's maxim to "hit first, hit hard, and keep hitting."[220] First, Dreadnought battleships employed turbines rather than boilers:

214. Evan S. Medeiros et al., *A New Direction for China's Defense Industry* (Santa Monica, Calif.: RAND Corporation, 2005).
215. See Phillip C. Saunders and Joshua K. Wiseman, "Buy, Build, or Steal: China's Quest for Advanced Military Aviation Technologies," China Strategic Perspectives, No. 4 (Washington, D.C.: Institute for National Strategic Studies, National Defense University Press, December 2011), p. 48.
216. See Brodie and Brodie, *From Crossbow to H-Bomb*, p. 162.
217. Dave Majumdar, "China's New J-20 Stealth Fighter Has Officially Entered Service," *National Interest*, September 27, 2017, https://nationalinterest.org/blog/the-buzz/chinas-new-j-20-stealth-fighter-has-officially-entered-22529.
218. Herwig, "The Battlefleet Revolution, 1885–1914," p. 120.
219. Macksey, *Technology in War*, p. 57.
220. Barry Gough, *Churchill and Fisher: The Titans at the Admiralty Who Fought the First World War* (Toronto: James Lorimer, 2017), p. 3.

their lower weight, increased horsepower, and superior fuel efficiency resulted in greater speed (from 12 knots to a high of around 20 knots) without compromising range.[221] Second, because of developments in mechanics, electrical systems, and metallurgy, Dreadnought battleships carried longer-range quick-firing guns that, thanks to the first fire-control systems, extended the range of naval combat from a few thousand yards in 1905 to 12,000–20,000 yards in 1916.[222] Third, progress in metallurgy enabled the production of lighter but more resistant armor that, combined with developments in naval science, led to a doubling of battleship tonnage (from 15,000 to 30,000 tons).[223]

ABSORPTIVE CAPACITY. For Germany, the challenge appeared daunting; now it had to confront "by far the strongest shipbuilding industry in the world" with unrivaled experience in warship production.[224] In comparison, Germany's absorptive capacity in naval shipbuilding was relatively low in 1906. Until 1876, Germany was still purchasing most of its warships from Britain, and well into the 1880s, it still had no significant defense shipbuilding capability.[225] With the launch, in 1890, of its imperialist foreign policy (*Weltpolitik*), and the resulting increase in budget allocations to the navy, Germany began to learn important lessons both in weapons procurement and in warship design.[226] Yet, on the eve of the Dreadnought revolution, Germany had only slightly more than a decade of experience in warship production, and its industry was still struggling to produce advanced battleships, which were significantly inferior to their British counterparts.[227]

Second, Germany had a late start in reproducing Britain's *Dreadnought* design and several component technologies. This is because the very factors driving Germany's naval rise—domestic politics and bureaucratic ambitions—paradoxically were also responsible for slowing down, and possibly even harming, its naval modernization.[228] On the one hand, civil-military relations

221. David K. Brown, *Warrior to Dreadnought: Warship Development, 1860–1905* (London: Chatham, 1997), pp. 180–187, 189–191.
222. Norman Friedman, *Battleship: Design and Development, 1905–1945* (New York: Mayflower, 1978), pp. 98–104.
223. See John Beeler, *Birth of the Battleships: British Capital Ship Design, 1870–1881* (Annapolis: Naval Institute Press, 2001).
224. Friedman, *Fighting the Great War at Sea*, p. 44; and Pugh, *The Cost of Seapower*, pp. 139–151.
225. Aidan Dodson, *The Kaiser's Battlefleet: German Capital Ships, 1871–1918* (Annapolis: Naval Institute Press, 2016), pp. 23–24.
226. Robert Gardiner, ed., *Conway's: All the World's Fighting Ships, 1860–1905* (Annapolis: Naval Institute Press, 1985), p. 32.
227. Dodson, *The Kaiser's Battlefleet*, pp. 25, 40, and, more generally, pp. 23–71.
228. Friedman, *Fighting the Great War at Sea*, pp. 73–101, 195–213; and Weir, *Building the Kaiser's Navy*, pp. 33–34.

were unstable: Kaiser Wilhelm II, the great sponsor of German naval rearmament, constantly intervened in navy policy, inadvertently delaying "warship design and construction."[229] On the other hand, Adm. Alfred von Tirpitz, appointed to lead the German Imperial Navy and fulfill the emperor's aspirations, was strenuously opposed to any increase in the capabilities of German battleships, because their additional costs risked undermining the domestic coalition supporting his naval plans.[230] As a result, the German Imperial Navy systematically ignored incoming intelligence about the development of *Dreadnought* and halted research in the technological domains underlying the new battleship's design, including turbines, fire-control systems, and long-range guns.[231] For instance, German naval yards continued to develop obsolete designs until late 1905, even though they had been aware since 1903 of the emerging all-big-gun battleship concept.[232] Similarly, until 1910 the German Imperial Navy designed its fire-control system for short-range naval engagements (around 6,000 yards).[233] Still, on the eve of World War I, no one in the German Imperial Navy "had thought it possible to fight effectively at a range of over . . . 16,250 yards."[234]

As a result, German investments in fire-control equipment initially remained limited, and the device Germany adopted in 1897 to measure bearing and bearing rate (the StandGerät) was much "clumsier" than its British counterpart (the Dumaresq).[235] Analogous considerations applied to German naval firepower: Tirpitz had long preferred "smaller-caliber guns firing relatively lightweight high-velocity shells." These shells, however, were ineffective at

229. Friedman, *Fighting the Great War at Sea*, p. 195; and Norman Friedman, *Naval Weapons of World War One: Guns, Torpedoes, Mines, and ASW Weapons of All Nations, An Illustrated History* (Barnsley, U.K.: Seaforth, 2011), pp. 121–123.
230. See Holger H. Herwig, "Imperial Germany," in Ernest R. May, ed., *Knowing One's Enemies: Intelligence Assessment before the Two World Wars* (Princeton, N.J.: Princeton University Press, 1986), pp. 62–97.
231. Weir, *Building the Kaiser's Navy*, pp. 30, 33, 47.
232. The two best examples are an open-access article anticipating the all-big-gun battleship design and reports from the German naval attaché in London. See, respectively, Vittorio Cuniberti, "An Ideal Battleship for the British Fleet," in Fred T. Jane, ed., *All The World's Fighting Ships* (London: Samson and Low, 1903), pp. 407–409; and Friedman, *Fighting the Great War at Sea*, p. 197. The idea was discussed, however, in 1901 "by navy gunnery experts in the *US Naval Institute Proceedings*" a magazine avidly read by members of the German Imperial Navy. See Tucker, *Handbook of 19th Century Naval Warfare*, p. 219.
233. Friedman, *Fighting the Great War at Sea*, p. 80; and Wolz, *From Imperial Splendor to Internment*, pp. 98–118.
234. John Brooks, *Dreadnought Gunnery and the Battle of Jutland: The Question of Fire Control* (Abingdon, U.K.: Routledge, 2006), p. 218.
235. Norman Friedman, *Naval Firepower: Battleship Guns and Gunnery in the Dreadnought Era* (Barnsley, U.K.: Seaforth, 2008), pp. 158–163.

longer ranges, because they "lost velocity more quickly than heavier ones" and thus were unfit for the engagements that took place during World War I.[236] Finally, and paradoxically, Tirpitz's defense industrial strategy explicitly obstructed domestic research on turbines, thus failing to promote the development of an indigenous industry in this domain.[237]

ACCESS TO FOREIGN TECHNOLOGY AND KNOW-HOW. The German Imperial Navy had relatively limited access to British *Dreadnought*-related technologies and technological knowledge—and, when it did, it did not use them.[238] Even though German naval yards had previous access to the all-big-gun battleship design, they did not immediately employ this information to improve either the warship designs they were working on or their design capabilities.[239] In the case of turbines, after having obstructed research in this realm, Tirpitz realized that German industry was lagging. Although he managed to have a British company establish a turbine production plant on German soil, he did not promote the transfer of technological know-how to German companies.[240]

OUTCOME. In line with our theory, within a few years, Germany was able to pose a serious challenge to Britain's naval dominance.[241] It made remarkable improvements in ship design and construction as well as in other key component technologies and, in some realms, it even managed to outperform the new British all-big-gun battleships.[242]

First, the German turbine industry caught up quickly, enabling the navy's battleships to match Britain's in terms of speed: by 1910–11, even the German companies that did not cooperate with foreign partners succeeded in indigenously producing modern turbines, which, in some cases, proved superior to their British counterparts.[243]

Second, with respect to light-but-resistant armor steel plates for fire protection, German technology outperformed British technology, as the thinner, and hence lighter, 6-inch armor plating produced by Krupp foundries in Germany "was approximately as effective as" the 8-inch steel armor plating manufactured by the Harvey United Steel Company in Britain.[244] German gun

236. Friedman, *Naval Firepower*, p. 158.
237. See ibid.; and Friedman, *Fighting the Great War at Sea*, pp. 188–213.
238. Friedman, *Fighting the Great War at Sea*, p. 197.
239. Weir, *Building the Kaiser's Navy*, pp. 30, 33, 47; and Friedman, *Fighting the Great War at Sea*, pp. 122–123.
240. Weir, *Building the Kaiser's Navy*, pp. 29, 96–98.
241. Ibid., pp. 86–91.
242. Robert Gardiner, ed., *Conway's: All the World's Fighting Ships, 1906–1921* (Annapolis: Naval Institute Press, 1985), p. 145.
243. Gary E. Weir, "Tirpitz and Technology," *Naval History*, Vol. 4, No. 1 (Winter 1990), p. 41.
244. Gardiner, *Conway's: All the World's Fighting Ships, 1860–1905*, p. 36.

technology also caught up quickly: the transition to larger calibers proved unproblematic, and according to some accounts, by the start of World War I Germany possessed the most advanced naval guns in the world.[245] Behind Germany's success was its capacity to transfer Krupp's know-how in steel plating to warship building and to exploit the superiority of its chemical industry for the development of more advanced propellant charges. In fact, Germany's shells enjoyed "greater penetrative power" than the Royal Navy's.[246]

Third, Germany succeeded in leveraging its domestic civilian industry to catch up quickly in the realm of fire-control equipment, which it had initially neglected.[247] After the introduction of the British *Dreadnought*, the German navy recognized the inadequacy of its own long-range gunnery capabilities, and therefore started working on a rangefinder (the EU/SV-Anzeiger) more advanced than the StandGerät, which it had acquired in 1897.[248] To assess its new system, the navy acquired a rangefinder from a British company that, by mid-1907, "had recaptured the lead in fire-control instruments," and whose equipment (the Mark II) was considered the best available at the time.[249] The tests revealed similar performances between the British and German systems.[250] From 1908 until World War I, the Royal Navy continued upgrading its fire-control systems (introducing Mark III and Mark IV equipment), but Germany managed to keep pace. By the eve of the 1915 Battle of Dogger Bank, not only was the German fire-control system "similar in principle" to those of British warships,[251] but "at 20,000 yards," it was also "as accurate as the [British] 9-foot coincidence rangefinders at 15,000–16,000 yards,"[252] while its "spotting procedures could straddle more quickly."[253] In other words, Germany managed to get a lead in fire-control systems.[254]

Combat performance during the most important naval engagement of World War I, the 1916 Battle of Jutland, further supports our conclusions.[255]

245. Friedman, *Naval Weapons of World War One*, p. 127.
246. Gardiner, *Conway's: All the World's Fighting Ships, 1906–1921*, p. 145.
247. See, respectively, Friedman, *Fighting the Great War at Sea*, p. 123; and Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p. 4.
248. Friedman, *Naval Firepower*, pp. 158–163; and Friedman, *Fighting the Great War at Sea*, p. 197.
249. Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p. 44.
250. Friedman, *Naval Weapons of World War One*, pp. 23–26; Brooks, *Dreadnought Gunnery and the Battle of Jutland*, pp. 78–210; and Friedman, *Naval Firepower*, pp. 68–81, 160.
251. Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p. 502.
252. This is the Zeiss 3-meter system produced by Siemens & Halske. See Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p. 216.
253. Ibid., p. 218.
254. Arthur Hezlet, *Electronics and Sea Power* (New York: Stein and Day, 1975), p. 121.
255. For the most recent and exhaustive scholarly investigation, see Brooks, *Dreadnought Gunnery and the Battle of Jutland*.

Despite some material and operational disadvantages that affected the mobility of German warships,[256] the two fleets performed very similarly in terms of accuracy: "117 British hits (2.45 percent) versus 83 German hits (2.3 percent)," thus suggesting that in terms of overall technology the two fleets were generally on par.[257] Interestingly, "German fire started excellently, but got worse as the day wore on, whereas British gunnery improved over time."[258] This indicates that the two sides enjoyed similar technology, but that over the duration of the battle, the Royal Navy could leverage its superior drilling, tactics, and experience.

In sum, despite all the countervailing pressures discussed earlier,[259] Germany managed in just a few years to imitate British Dreadnought battleships and to develop "superior North Sea fighting ships to their British contemporaries."[260] German ships had in fact "better range-finding equipment, superior fire-control, and improved compartmentalization . . . and better shells."[261] Moreover, German equipment "functioned excellently" during the war,[262] because some of its key components were "apparently better and more plentiful than in Great Britain."[263]

China and fifth-generation fighter aircraft, 1991–2018

The United States commissioned its fifth-generation stealth fighter, the F-22/A Raptor, in 2005. Like *Dreadnought*, the F-22 had no match when it was fielded, specifically because of its "first-look, first-shoot, first-kill" capabilities.[264] To begin, the application of stealth technology reduces by several orders of magnitude the observability of the F-22 to enemy sensors.[265] In addition, with its supercruising thrust-vectoring engines, the F-22 can achieve fuel-efficient supersonic speed and high maneuverability, enhancing its perfor-

256. Ibid., p. 473; Wolz, *From Imperial Splendor to Internment*, pp. 98–118; and Friedman, *Fighting the Great War at Sea*, pp. 104–187.
257. Friedman, *Naval Firepower*, p. 166.
258. Ibid.
259. Friedman, *Fighting the Great War at Sea*, pp. 73–101, 195–213; and Weir, *Building the Kaiser's Navy*, pp. 33–34.
260. See Friedman, *Fighting the Great War at Sea*, pp. 189–213. See also Gardiner, *Conway's: All the World's Fighting Ships, 1906–1921*, p. 145.
261. Tucker, *Handbook of 19th Century Naval Warfare*, p. 229.
262. Brooks, *Dreadnaught Gunnery and the Battle of Jutland*, p. 504.
263. The quotation refers to synchros, whose availability also enabled different design choices. See Friedman, *Naval Weapons of World War One*, p. 123.
264. See Ronald W. Brower, "Lockheed F-22 Raptor," in Cary R. Spitzer, ed., *The Avionics Handbook* (Williamsburg, Va.: CRC, 2001).
265. Doug Richardson, *Stealth: Deception, Evasion, and Concealment in the Air* (New York: Orion, 1989), pp. 24–57.

mance against enemy fighters.[266] Finally, the F-22 possesses superior and longer-range situational awareness thanks to its advanced onboard computer systems, software, and data-fusion capabilities: these attributes enable the collection, rapid processing, and exploitation of large amounts of different types of data that ultimately increase the F-22's battlefield performance.[267]

ABSORPTIVE CAPACITY. When in the late 1990s China started work to develop a fifth-generation fighter, its absorptive capacity in the military aviation domain was relatively limited.[268] China could assemble modern foreign weapon systems, but its experience with combat aircraft production was restricted to Soviet designs from the 1950s and 1960s.[269] The reasons for China's delay in combat aircraft production include economic backwardness, a command economy, and its international isolation, as well as some particular political choices, such as limiting the amount of attention paid to military aviation during the Cold War, especially when compared to missiles or warships.[270] China did not start from scratch, however. During the 1970s and 1980s, the Chinese defense industry worked on several programs, accruing some experience in military aviation.[271] Moreover, since the 1970s and in particular since the 1990s, China's industrial base has benefited tremendously from FDI, R&D joint ventures, and mergers and acquisitions with Western aerospace companies.[272] Most of the world's major jet engine producers, airline manufacturers, and companies specializing in avionics and aerospace component technologies have established a presence in China.[273] Chinese companies have also purchased machinery to "manufacture sophisticated weapon systems and related components."[274]

266. "Supercruise" means achieving supersonic speed without relying on afterburners. Afterburners increase the thrust of the engines by injecting fuel into the gas exhaust. This procedure significantly increases fuel consumption. Moreover, afterburners also expose the aircraft to enemy infrared search and track systems because of the enhanced heat.
267. Brower, "Lockheed F-22 Raptor."
268. Medeiros et al., *A New Direction for China's Defense Industry*; and Allen, Krumel, and Pollack, *China's Air Force Enters the 21st Century*, pp. 160–166.
269. Allen, Krumel, and Pollack, *China's Air Force Enters the 21st Century*, p. 159.
270. Shen Pin-Luenin, "China's Aviation Industry: Past, Present, and Future," in Richard P. Hallion, Roger Cliff, and Phillip C. Saunders, eds., *The Chinese Air Force: Evolving Concepts, Roles, and Capabilities* (Washington, D.C.: National University Press, 2012), pp. 251, 266–268.
271. These are the F-8 Finback, the F-8–2, the B-7/FB-7, and the K-8/L-8. See Allen, Krumel, and Pollack, *China's Air Force Enters the 21st Century*, pp. 150–153.
272. Roger Cliff et al., *Ready for Takeoff: China's Advancing Aerospace Industry* (Santa Monica, Calif.: RAND Corporation, 2011), pp. 35–87; and Chad J.R. Ohlandt et al., *Chinese Investment in U.S. Aviation* (Santa Monica, Calif.: RAND Corporation, 2017).
273. Cliff et al., *Ready for Takeoff*, pp. 35–88.
274. Ibid., p. 37.

ACCESS TO FOREIGN TECHNOLOGICAL KNOWLEDGE. Unlike Imperial Germany and its efforts to imitate the Dreadnought battleship, China has benefited from massive access to foreign technological knowledge in its attempt to imitate U.S. advanced jet fighters.

China has engaged more extensively in cyber espionage than any other country.[275] In 2007, 2009, and 2011, Chinese hackers entered the servers of the Pentagon and gained access to some fifty terabytes of data containing the designs and blueprints of U.S. stealth fighters, as well as other critical information.[276] China has also relied extensively on traditional industrial espionage, including the recruitment of former engineers and scientists who worked for Western aerospace organizations.[277] Together, industrial and cyber espionage have given China extensive access to American know-how. Moreover, China managed to obtain an F-117 that crashed in Serbia in 1999, allowing it to inspect, analyze, and possibly reverse engineer the aircraft's stealth features.[278]

Further, since the 1960s, China has benefited from significant transfers of technology from more advanced countries.[279] In the 1970s, it had access to turbofan engines developed by Rolls-Royce.[280] In the 1980s, Israel provided extensive "weapon-making know-how" useful in the design, fire control, avionics, and radar capabilities of China's fourth-generation aircraft.[281] Through Pakistan, China gained access to U.S. F-16 Fighting Falcon jet fighters.[282] After the end of the Cold War, China signed an agreement with Pakistan

275. William C. Hannas, James Mulvenon, and Anna B. Puglisi, *Chinese Industrial Espionage: Technology Acquisition and Military Modernization* (New York: Routledge, 2013).
276. David Axe, "Was China's Stealth Tech Made in America?" *Wired*, January 24, 2011.
277. Entities that have been victims of Chinese industrial espionage include Boeing, Pratt & Whitney, Rockwell, Rolls-Royce, and Wright-Patterson Air Base. Office of the National Counterintelligence Executive, *Foreign Spies Stealing US Economic Secrets in Cyberspace: Annual Report to Congress on Foreign Economic Collection and Industrial Espionage, 2009–11* (Washington, D.C.: U.S. Government Publishing Office 2011), p. 2; Stephen Chen, "America's Hidden Role in Chinese Weapons Research," *South China Morning Post*, March 29, 2017; and Stephen Chen, "China in Talks for Sale of Jet Engine Technology to Germany," *South China Morning Post*, January 18, 2018.
278. David Eimer, "China's Stealth Fighter 'Based on U.S. Technology'" *Telegraph*, January 23, 2011. It is important to emphasize that the theoretical explanation of how to reduce the radar cross section of an object has been known since 1962, when a Soviet physicist published an article in a scientific journal. Moreover, since the 1980s, several publications have provided technical insights behind stealth technology—most prominently, the lecture notes of Allen Fuhs of the U.S. Naval Postgraduate School and a textbook by Eugene Knott, John Schaeffer, and Michael Tuley of the Georgia Institute of Technology. See Rich and Janos, *Skunk Works*, pp. 19–20; and Richardson, *Stealth*, pp. 11–12.
279. Bates Gill, "Chinese Military-Technical Development: The Record for Western Assessment, 1979–1999," in Mulvenon and Yang, *Seeking Truth from Facts*, pp. 141–172; and Allen, Krumel, and Pollack, *China's Air Force Enters the 21st Century*, p. 155.
280. Medeiros et al., *A New Direction for China's Defense Industry*, p. 170.
281. Allen, Krumel, and Pollack, *China's Air Force Enters the 21st Century*, p. 155.
282. Saunders and Wiseman, "Buy, Build, or Steal," p. 10.

to coproduce Pakistan's fourth-generation fighter, itself the result of a coproduction project with the American Grumman Aerospace Corporation (the F-7P Sabre II "Super 7");[283] it also reached a licensing agreement with Russia for the production of its fourth-generation aircraft (the Sukhoi Su-27).[284] Russian experts have also provided Chinese workers and engineers "with the know-how to assemble Su-27 fighter aircraft using imported materials and equipment," and have trained them to "domestically manufacture key materials."[285] China has also been purchasing engines, radars, and other systems and subsystems from abroad in order to analyze and possibly replicate them.[286]

OUTCOME. Nevertheless, China's aerospace industry has struggled enormously to imitate U.S. technology. In 2017, China commissioned the J-20 Black Eagle, a step that many analysts viewed as the end of the U.S. monopoly on fifth-generation fighters.[287] Yet, serious doubts persist about whether the performance of the J-20 comes even close to that of the F-22. In fact, anonymous Chinese sources have admitted that China rushed the J-20 into service in response to increasing tensions in the South China Sea, despite capability gaps that make it inferior to the F-22.[288]

First, because of design similarities between the U.S. F-22 and the Chinese J-20, many observers have concluded that China has been able to quickly replicate U.S. technology.[289] A closer examination suggests otherwise. The J-20 displays several design flaws and non-stealthy features on the sides and in the rear of the fighter that dramatically increase its detectability to both radar and thermal sensors.[290] These limitations would represent a critical liability in air-to-air engagements with U.S. fifth-generation jet fighters.[291] Moreover, the J-20

283. Allen, Krumel and Pollack, *China's Air Force Enters the 21st Century*, p. 149.
284. Ibid., p. 156.
285. Medeiros et al., *A New Direction for China's Defense Industry*, p. 27.
286. Siemon T. Wezeman, "Impact of Shifts in Arms Trade and Exercises on South Asia and Europe," in Lora Saalman, ed., *China-Russia Relations and Regional Dynamics: From Pivots to Peripheral Diplomacy* (Stockholm: SIPRI, 2017), pp. 85–88.
287. See, for example, Jeffrey Lin and P.W. Singer, "China's Stealth Fighter May Be Getting a New Engine," *Eastern Arsenal* blog, *Popular Science*, September 8, 2017; and *Economist*, "No Longer Just Catch-Up: China Will Soon Have Air Power Rivalling the West's," February 15, 2018.
288. See Minnie Chan, "China's J-20 Stealth Fighter Joins the People's Liberation Army Air Force," *South China Morning Post*, March 10, 2017; and Minnie Chan, "Why China's First Stealth Fighter Was Rushed into Service with Inferior Engines," *South China Morning Post*, February 10, 2018.
289. Eloise Lee and Robert Johnson, "China's J-20 and the American F-22 Raptor—You Are Not Seeing Double," *Business Insider*, June 4, 2012; and Jeffrey Lin and P.W. Singer, China's J-20 Stealth Fighter Jet Has Officially Entered Service, *Eastern Arsenal* blog, *Popular Science*, February 18, 2018, https://www.popsci.com/chinas-j-20-stealth-fighter-officially-enters-service.
290. Michael J. Pelosi and Carlo Kopp, "A Preliminary Assessment of Specular Radar Cross Section Performance in the Chengdu J-20 Prototype," *Air Power Australia Analysis*, July 4, 2011, http://www.ausairpower.net/APA-2011-03.html.
291. Some observers have downplayed these problems by arguing that the J-20 is allegedly not intended to be an air-superiority fighter. This conclusion is unwarranted. For a summary and a

displays two small wing projections (canards) forward of the main wings. Generally intended to help the longitudinal equilibrium, and static and dynamic stability, of an aircraft, the canards also increase its frontal radar cross section, thus limiting its overall capabilities.[292] From an industrial perspective, that the J-20 carries canards suggests poor design.[293] As noted, little can be done about poor designs, which, once adopted, can be improved only marginally.[294] These flaws and features convey a more important message: China has been unable to fully copy U.S. stealth designs and technology. Instead, it has had to engage in extensive experimentation, prototyping, and refinement, inevitably encountering problems in the process.[295]

Second, China has faced enormous challenges in developing one of the most important systems of modern jet fighters—powerful and reliable thrust-vectoring turbofan engines capable of supercruise. According to experts, this failing represents probably "the most glaring weakness of China's aviation industry."[296] For this reason, China has so far relied on compromises. For its early prototypes, from 2010 to 2017, it relied on Russian underpowered engines that provide neither supercruise nor thrust-vectoring capabilities and that left a visible trail.[297] Subsequently, China decided to commission the J-20 into service by mounting indigenous but older and underpowered engines that also lack supercruise and thrust-vectoring capabilities.[298] This solution was intended to be temporary while work on the engines originally intended for the J-20 continued. These more advanced engines have experienced "critical problems," however, including an explosion during a ground test in 2015.[299] According to an anonymous source, as of 2018, "engineers ha[d] failed

rebuttal of this argument, see Rick Joe, "J-20: Striker or Interceptor," *PLA Real Talk* blog, December 27, 2015, http://plarealtalk.com/2015/12/27/j-20-striker-interceptor/.

292. By adding edges to the design of an aircraft, canards increase the reflection of radar beams, and hence the radar cross section. Pelosi and Kopp, "A Preliminary Assessment of Specular Radar Cross Section Performance in the Chengdu J-20 Prototype."

293. Richard Aboulafia, "Monthly Newsletter" (Fairfax, Va.: Richard Aboulafia personal website, October 2012), http://www.richardaboulafia.com/shownote.asp?id=366.

294. David Axe, "Seven Secret Ways America's Stealth Armada Stays Off the Radar," *Wired*, December 13, 2012.

295. Since the J-20 first appeared in late 2010, observers have noted several changes (primarily in the fuselage, tailbooms, vertical tails, and canards), suggesting that China has relied on trial and error to fix possible design problems. Bill Sweetman, "J-20 Stealth Fighter Design Balances Speed and Agility," *Aviation Week & Space Technology*, November 10, 2014, p. 57.

296. Medeiros et al., *A New Direction for China's Defense Industry*, p. 169.

297. The engine is the NPO Saturn AL-31. The exhaust inevitably compromises the aircraft's low observability. See Andrew Erickson and Gabe Collins, "The 'Long Pole in the Tent': China's Military Jet Engines," *Diplomat*, December 9, 2012; and Bill Sweetman, "China's Radar and Missile Work Means More Than Fighters," *Aviation Week & Space Technology*, December 1, 2014, p. 16.

298. The engine is the Shenyang WS-10.

299. Anonymous military sources, cited in Chan, "Why China's First Stealth Fighter Was Rushed into Service with Inferior Engines." The name of this engine is Xian WS-15.

to find the key reason for the[se] problems,"[300] and apparently "there [was] no fundamental solution to overcome [them]."[301] In November 2018, China switched back to Russian engines for three of the four J-20s that performed at the biannual Airshow China in Zhuhai—an event China uses to showcase its aerospace accomplishments. This decision suggests that the "temporary" indigenous engines are not deemed very reliable.[302]

China's struggle to indigenously develop aircraft engines thus throws into question the growing belief among observers that China has closed the military-technological gap with the United States with respect to fifth-generation fighters.[303] Possibly more important, it also illustrates that the advantages of imitation that China has enjoyed have inevitably been limited. As mentioned earlier, several factors significantly facilitated China's efforts to develop turbofan engines; and from 2010 to 2015, it spent some $22 billion to develop an indigenous engine for its combat aircraft.[304] Yet, as of 2019, it continues to struggle.[305] According to an executive with a Chinese engine manufacturer, "The road to success is filled with setbacks and failures," and far from being able to take a shortcut, China has experienced the same problems of "each of the world's engine powers."[306] It is unknown how Chinese engines will perform and when they will be operational.[307] According to defense industry experts Tai Ming Cheung, Thomas Mahnken, and Andrew Ross, they "lag one to two generations behind leading international competitors, and the near-term prospects of narrowing this gap are poor."[308] In fact, the engine China is developing might not be sufficiently powerful to make the J-20 a "viable . . . air combat fighter."[309]

300. Anonymous military source, cited in Minnie Chan, "China Reveals J-20 Stealth Fighter's Missile Carrying Capability at Zhuhai Air Show," *South China Morning Post*, November 14, 2018.
301. Anonymous military source, cited in Chan, "Why China's First Stealth Fighter Was Rushed into Service with Inferior Engines."
302. Minnie Chan, "China's New J-20 Stealth Fighter Engine a No-Show at Zhuhai Air Show after It Fails Reliability Tests," *South China Morning Post*, November 7, 2018.
303. The J-20 does not possess supercruise capabilities, so it is not a fifth-generation fighter.
304. Minnie Chan, "China Powers Up Military Jet Engine Tech to Wean Itself Off Russian Imports," *South China Morning Post*, December 12, 2016. The amount is 168 billion yuan, equivalent to $21–$24 billion.
305. Chan, "Why China's First Stealth Fighter Was Rushed into Service with Inferior Engines." See also Chan, "China Reveals J-20 Stealth Fighter's Missile Carrying Capability."
306. Quoted in Greg Waldrom, "China's J-20 Set to Receive Indigenous Engine," *Flight Global*, March 13, 2017.
307. According some experts, this will happen soon. See, for example, Lin and Singer, "China's Stealth Fighter May Be Getting a New Engine."
308. Tai Ming Cheung, Thomas G. Mahnken, and Andrew L. Ross, "Frameworks for Analyzing Chinese Defense and Military Innovation," in Cheung, ed., *Forging China's Military Might: A New Framework for Assessing Innovation* (Baltimore, Md.: Johns Hopkins University Press, 2014), p. 35.
309. Carlo Kopp, "An Initial Assessment of China's J-20 Stealth Fighter," *China Brief*, May 6, 2011, p. 10.

Third, military experts agree that China is also lagging in another key realm of fifth-generation fighters—avionics.[310] China's difficulties in this realm stem from the fact that aerospace sensors and software development currently pose some of the most daunting engineering challenges.[311] Software problems, in fact, are very difficult to anticipate: testing and refining must continue until the software is perfected, given that when the aerospace software fails, it fails "catastrophically."[312] Because China has thus far been unable to copy U.S. aircraft design and engines, there is little reason to believe that it has been more successful in this much more challenging realm. An additional consideration supports this assessment. The complexity of modern aerospace software is unprecedented.[313] Flight control software has become exponentially more complex, eliminating trade-offs in design—for example, between observability to radar and aerodynamic efficiency. In other words, complexity has moved from hardware to software.[314] In addition, software has taken over an increasing number of more complex functions—most prominently, automatic long-range enemy detection, geolocation, high-confidence identification, and accurate target tracking.[315] Little information is available on Chinese radar operation and data-fusion capabilities, but we can use available evidence on Chinese flight control as a proxy. This proxy is valid, because developing flight control software is far less demanding than software for radar operation and data fusion.[316] According to Chinese media, the J-20 still faces problems with its flight control software. There is thus little reason to believe that China has been able to develop the most challenging part of the J-20s' onboard software.[317]

Fourth, the difficulties that China has encountered with the development of less advanced fourth-generation fighters further corroborate our argument. Despite the significant transfer of technology and support that China has received from Russia, Israel, and various European countries, its industry has struggled in this domain.[318] For instance, in 2004 China suddenly broke a

310. Cheung, Mahnken, and Ross, "Frameworks for Analyzing Chinese Defense and Military Innovation," p. 35.
311. Royce, "Current Problems," p. 6.
312. Ibid., pp. 8–11.
313. See Mili and Tchier, *Software Testing*, p. 6.
314. For example, the low radar cross section of the F-117 was attainable by compromising its aerodynamics—a problem that was addressed by software. See Rich and Janos, *Skunk Works*, pp. 30–32, 46, 108.
315. Steve A. Fino, *Tiger Check: Automating the U.S. Air Force Fighter Pilot in Air-to-Air Combat, 1950–1980* (Baltimore, Md.: Johns Hopkins University Press, 2017).
316. Ninety percent of the 1.7 million lines of the F-22's code is "devoted" to radar operation and data fusion. See Mili and Tchier, *Software Testing*, p. 6.
317. Chan, "China's J-20 Stealth Fighter Joins the People's Liberation Army Air Force."
318. Medeiros et al., *A New Direction for China's Defense Industry*, p. 162.

licensing agreement with Russia on the Sukhoi Su-27, with the aim of exploiting the experience it had already gained to produce independently an indigenous version, the Shenyang J-11.[319] The production process did not go smoothly, however. For example, at "one point the [Chinese engines] were reportedly requiring overhauls every thirty hours of flight time, compared to four hundred hours for . . . the Su-27."[320] Similarly, according to U.S. sources, some variants of this aircraft have been "in big trouble," as technical malfunctions have led to several crash landings.[321] Additionally, in 2016 China bought twenty-four new, heavily upgraded derivatives of the very aircraft it had copied from Russia (the Sukhoi Su-35).[322] Although we do not know the reasons for this purchase, it is further indicative of China's inability to produce a copy of this aircraft—or even a more advanced one such as fifth-generation jet fighters.[323] China has experienced similar problems with its carrier-based fighter aircraft, the Shenyang J-15 Flying Shark, a reverse-engineered version of a Russian fighter (the Sukhoi Su-33) that is more than thirty years old and that China purchased from Ukraine.[324] Because of the thrust constraints of its engine, the J-15 can take off from an aircraft carrier ski-jump with only half a fuel load or with only four missiles, thus limiting either its range or its capabilities.[325] Even the Chinese media criticized it as a "flopping fish."[326] Because of recurrent fatal accidents and crashes, China recently decided to look for a replacement for this aircraft.[327]

Fifth, China has derived only limited cost and time advantages from its imitation efforts. According to Gabe Collins and Andrew Erickson, it is "reasonable to assume the J-20 has a unit cost of somewhere from US$100-to-$120 million . . . By contrast, the F-22 costs around US$143 million per

319. Sebastien Roblin, "China Stole This Fighter from Russia—And It's Coming to the South China Sea," *National Interest*, July 24, 2016.
320. Ibid.
321. David Axe, "China's Testing Woes Remind That Developing Carrier Planes Is Hard," *Wired*, March 21, 2013.
322. International Institute for Strategic Studies, *The Military Balance, 2015* (London: Routledge, 2015), p. 215.
323. Some observers even speculate that China bought these aircraft in order to copy, among other things, its thrust-vectoring engine. See, for example, Bradley Perrett, "China Has 11 Flanker Versions, with More Possible," *Aviation Week & Space Technology*, February 17, 2017, p. 50.
324. Dillon Zhou, "China J-15 Fighter Jet: Chinese Officials Defend New Fighter As Chinese Original, but Questions Remain," *Mic*, December 16, 2012.
325. David Cenciotti, "No Match for a U.S. Hornet: 'China's Navy J-15 More a Flopping Fish than a Flying Shark' Chinese Media Say," *Aviationist* blog, September 30, 2013, https://theaviationist.com/2013/09/30/j-15-critics/.
326. Ibid.
327. Dave Majumdar, "China's Aircraft Carriers Have a Big Problem: Fatally Flawed Fighter Planes," *National Interest*, July 5, 2018.

plane."[328] These estimates show that China has derived a cost advantage of just 14 to 20 percent, which is hardly impressive given that China is the country that has relied most extensively on both industrial and cyber espionage, and that has benefited massively from the transfer of technology through FDI, mergers and acquisitions, and the purchase of foreign components. Such a cost advantage is even less impressive given that the F-22 is now twelve years old, that the J-20 has significant deficiencies, and that its costs will inevitably increase further as China attempts to fix its problems and improve its performance. The latter point is critical, because "the final 10 percent striving towards maximum perfection costs 40% of the total expenditure on most projects."[329] The same is true with regard to time. The F-22 became operational in 2005—about twenty years after the project started.[330] Launched in the late 1990s and tested in 2010, the J-20 was officially commissioned in the fall of 2017.[331] Still, it is not yet fully operational and remains inferior to the F-22 on several dimensions: in other words, after more than twenty years, China has not yet closed the gap with the United States.[332]

A skeptical reader might wonder whether a more advanced country would have accomplished better results than China in imitating the F-22. The hardest case for our theory would be if the imitating country had the same aerospace capabilities as the United States and if it had access to all the technological knowledge related to the F-22. This case exists. In 2011, the U.S. government interrupted production of the F-22. In 2017, the U.S. Air Force commissioned a study to understand how much it would cost to restart production. In other words, the United States wanted to know what it would take to copy its own technology from just six years before. The findings are sobering: the same country that created the F-22 would have to spend $10 billion to restart the production of its fifth-generation fighter—equivalent to 25 percent of the total procurement cost for 194 aircraft.[333]

328. Gabe Collins and Andrew Erickson, "China's New Project 718/J-20 Fighter: Development Outlook and Strategic Implications," *China SignPost*, January 17, 2011.
329. Rich and Janos, *Skunk Works*, p. 325.
330. See Jay Miller, *Lockheed Martin's Skunk Works: The Official History* (Leicester, U.K.: Midland, 1995), p. 175; and Dennis R. Jenkins and Tony R. Landis, *Experimental and Prototype U.S. Air Force Jet Fighters* (North Branch, Minn.: Specialty Press, 2008), p. 234.
331. Richardson, *Stealth*, p. 93.
332. The advantages China derived from imitation also look quite modest in comparison to the first U.S. stealth fighter, F-117: it entered service in 1987; its development took six years; and it cost $155 million. See David C. Aronstein and Albert C. Piccirillo, *Have Blue and the F-117A: Evolution of the Stealth Fighter* (Reston, Va.: American Institute of Aeronautics and Astronautics, 1997), p. 267.
333. United States Air Force, *F-22A Production Restart Assessment* (Washington, D.C.: United States Air Force, February 2017).

In sum, over the past twenty years, China has made impressive accomplishments in modernizing its aerospace industry. Given the extent to which it has benefited from globalization and cyber espionage, however, the evidence casts serious doubt on the claim that these two factors have brought about a revolutionary transformation that makes the imitation of foreign weapon systems much easier than it used to be.[334]

Conclusion

In his seminal article "Command of the Commons," Barry Posen argued that the unrivaled military-technological superiority of the United States gives it a key advantage over other countries.[335] According to the literature in international relations theory, however, such advantages should be temporary, especially in an era of globalization, real-time communications, and dual-use technologies: knowledge allegedly diffuses quickly, thus undermining one of the sources of U.S. hegemony—superiority in military technology. In this article, we have provided a theoretical explanation for why, three decades after the fall of the Berlin Wall and more than fifteen years after the publication of Posen's article, U.S. weapon systems largely remain unrivaled.

We have argued that the dramatic increase in the complexity of military technology observed over the twentieth century has significantly shrunk the advantage of backwardness described by Gerschenkron. On the one hand, the requirements for imitating modern weapon systems have become harder to meet. On the other, the technological knowledge of how to design, develop, and produce modern weapon systems has become less likely to diffuse. As a result, compared to the pre–World War I period, today imitating foreign weapon systems is more difficult. Countries cannot simply free ride on the research and development of the most advanced states: they first have to develop the industrial, scientific, and technological capabilities required for becoming first-tier weapons manufacturers; then, they must go through extensive trial and error to address the multitude of extremely small but challenging problems that weapons development entails.

The evidence we presented shows that in comparison to the early twentieth century, when Germany could quickly catch up with Great Britain in all-big-gun battleships, in recent years China has faced enormous hurdles in closing

334. Saunders and Wiseman, "Buy, Build, or Steal," p. 48.
335. Barry R. Posen, "Command of the Commons: The Military Foundation of U.S. Hegemony," *International Security*, Vol. 28, No. 1 (Summer 2003), p. 10, doi.org/10.1162/016228803322427965.

the military-technological gap both with the United States in fifth-generation aircraft and even with Russia in fourth-generation jet fighters. China has struggled to achieve success despite its massive cyber theft activities, the benefits it has derived from globalization, its acquisition of foreign companies and technology, and an unprecedented inflow of foreign direct investments.

With this research, we provide a unified theory that helps explain why the imitation of advanced weapon systems has become more difficult with the transition from the industrial to the information age. Our theory holds also in other cases. For example, it helps account for the Soviet Union's incapacity to catch up with the United States in the later phases of the Cold War.[336] Our theory thus challenges the view among international relations scholars that catching up technologically is about will—which, for states, ultimately means mobilizing the necessary capital. Although warranted in the past, this view is no longer valid, because simply pouring money into a project cannot generate the necessary defense industrial base and experience with the technology being pursued.[337]

More important, by explaining the enduring military-technological superiority the United States currently enjoys, our research contributes to one of the most significant debates in the field of international relations theory: the potential for the United States to maintain its unrivaled power. Many observers and practitioners believe that U.S. primacy in military technology is coming to an end, because of the diffusion of cheap counter-systems and because of opportunities to exploit both dual-use technologies and cyber espionage to free ride on more advanced countries' research. Chinese military strategists themselves "subscribe to the arguments [of] Alexander Gerschenkron" about the advantage of imitation, and their technology and industrial policies have tried as much as possible to rely on the acquisition, assimilation, and replication of foreign technology.[338] Our theory indicates that under the current technological paradigm, the entry barriers for modern military platforms will remain massive, even for the most advanced countries. Meanwhile, the tacit and organizational know-how related to the production of modern weapon systems will force aspiring great powers to engage in extensive and expensive experimenta-

336. See Stephen G. Brooks and William C. Wohlforth, "Power, Globalization, and the End of the Cold War: Reevaluating a Landmark Case for Ideas," *International Security*, Vol. 25, No. 3 (Winter 2000/01), pp. 5–53, doi.org/10.1162/016228800560516.
337. See Mark R. Brawley, "The Political Economy of Balance of Power Theory," in T.V. Paul, James Wirtz, and Michel Fortmann, eds., *Balance of Power: Theory and Practice in the 21st Century* (Palo Alto, Calif.: Stanford University Press, 2004), p. 80.
338. Tai Ming Cheung, *Fortifying China: The Struggle to Build a Modern Defense Economy* (Ithaca, N.Y.: Cornell University Press, 2008), p. 243.

tion and testing before they can deliver state-of-the-art technology. We are not claiming that China or other countries are destined to fail in their attempts to close the military-technological gap with the United States. Rather, we argue that rising great powers cannot easily copy foreign technology and thus catch up militarily at a fraction of the cost and at a fraction of the time of their competitors.

Indirectly, our research also addresses existing concerns about future counter-systems that China could deploy to contest the Western Pacific. Although some of these systems are comparatively cheap and unsophisticated (e.g., missiles), key platforms such as submarines and jet fighters are extremely complex, while other emerging technologies such as remotely piloted and autonomous vehicles are becoming increasingly sophisticated and costly, and are expected "to converge rapidly with those of manned aircraft."[339] Similarly, exploiting emerging technologies (e.g., robotics or artificial intelligence) for military purposes will not be easy: to integrate them into their weapon systems, countries will have to invest massively in a broad range of disciplines and gain experience through trial and error. The key question for the future is whether the fourth industrial revolution will bring about a paradigmatic transformation in production, and if so, how this transformation will change the dynamics of innovation and imitation. Given that "as the capabilities of autonomy increase . . . considerable system complexity will be created as the software and hardware is expanded,"[340] our research suggests that the difficulty of imitation will continue to increase. Further research should focus on this topic.[341]

339. Ministry of Defence, "Joint Doctrine Note 2/22: The U.K. Approach to Unmanned Aircraft Systems" (Shrivenham, U.K.: British Ministry of Defence, March 30, 2011), pp. 1–2.
340. Office of the Chief Scientist, *Autonomous Horizons: System Autonomy in the Air Force—A Path to the Future*, Vol. 1: *Human-Autonomy Teaming* (Washington, D.C.: United States Air Force, 2015), p. 6.
341. Andrea Gilli and Mauro Gilli, "Seapower and the Second Machine Age: The Robotics Revolution and the U.S. Command of the Commons," paper presented at the International Studies Association annual convention, Baltimore, Maryland, February 22–25, 2017.