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The Appendix:

Additional Material to 'Why China Has Not Caught Up Yet'

This is the online appendix for the article Andrea Gilli and Mauro Gilli, "Why China Has Not Caught Up Yet: Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage", *International Security 43*, No. 3 (Winter 2018/19), pp. 141-189, https://doi.org/10.1162/ISEC_a_00337.

This appendix contains additional acknowledgements as well as the bibliographic and explanatory material for the article that, for space reasons, we could not include in the printed version.

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Bibliographic and Explanatory Material

The bibliographic and explanatory material presented below is organized numerically, with each number corresponding to the footnote in the printed article.

Footnote 3. See also John Zysman, "Power, Wealth, and Technology: Industrial Decline and American Security," working paper no. 38 (Berkeley, Calif.: Berkeley Roundtable on the International Economy, University of California, Berkeley, January 1990); and William C. Hannas, James Mulvenon, and Anna B. Puglisi, *Chinese Industrial Espionage: Technology Acquisition and Military Modernization* (New York: Routledge, 2013).

Footnote 4. See also Emily O. Goldman and Leslie C. Eliason, eds., *The Diffusion of Military Technology and Ideas* (Palo Alto, Calif.: Stanford University Press, 2003).

Footote 5. For such analogies, see also Robert Kagan, "What China Knows That We Don't: The Case for a New Strategy of Containment," *Weekly Standard,* January 20, 1997; Fareed Zakaria, "China: Appease or Contain? Speak Softly... and Carry a Veiled Threat," *The New York Times* (February 18, 1996) and and Jan van Tol, with Mark Gunzinger, Andrew Krepinevich, and Jim Thomas, *AirSea Battle: A Point of Departure Operational Concept* (Washington, DC: Center for Strategic and Budget Assessment, 2010), p. 4. For broader theoretical discussions, see for instance Alastair Iain Johnston, "Is China a Status Quo Power?" *International Security*, Vol. 27, No. 4 (Spring 2003), pp. 5–56; Steve Chan, "Exploring Puzzles in Power-Transition Theory: Implications for Sino-American Relations," *Security Studies* vol. 13, no. 3 (Spring 2004), pp. 103–141; Aaron L. Friedberg, "The Future of U.S.-China Relations: Is Conflict Inevitable?" *International Security*, Vol. 30, No. 2 (Fall 2005), pp. 7–45; and Christopher Layne, "The Waning of U.S. Hegemony—Myth or Reality? A Review Essay," *International Security*, Vol. 34, No. 1 (Summer 2009), pp. 147-172.

Footnote 8. See also Robert J. Gordon, *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War* (Princeton, N.J.: Princeton University Press, 2016); and Joel Mokyr, *Twenty-Five Centuries of Technological Change: An Historical Survey* (New York: Harwood, 1990), Joel Mokyr, *The Lever of the Riches: Technological Creativity and Economic Progress* (New York, NY: Oxford University Press, 1990); and Joel Mokyr, "The Second Industrial

Revolution, 1870-1914." in Valerio Castronovo, ed., *Storia dell'economia Mondiale* (Rome: Laterza publishing, 1999), pp. 219-245.

Footnote 9. See also Andrew Erickson and Gabe Collins, "Taking Off: Implications of China's Second Stealth Fighter Test Flight," *Wall Street Journal.* November 3, 2012; Sydney J. Freedberg Jr., "The End Of Advantage: Enemies May Catch Up With US Technology — Or Surpass It," *Aol Defense,* December 21, 2012; J. Randy Forbes and Elbridge Colby, "We're Losing Our Military Edge Over China. Here's How to Get It Back," *The National Interest,* March 27, 2014; and Jeffrey Lin and P.W. Singer, "Hypersonic Gliders, Scramjets, And Even Faster Things Coming To China's Military, *Popular Science-Eastern Arsenal Blog,* August 25, 2014.

Footnote 10. Another exception, but from a different field, is Carolina Castaldi, Roberto Fontana, and Alessandro Nuvolari, "'Chariots of Fire': The Evolution of Tank Technology, 1915–1945," *Journal of Evolutionary Economics*, Vol. 19, No. 4 (August 2009), pp. 545–566, doi: 10.1007/s00191-009-0141-0.

Footnote 16. More generally, on the employment of superior tactics to defy enemy's superior technology, see Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Battle* (Princeton, NJ: Princeton University Press, 2004).

Footnote 18. Across history, there have been cases of two or more countries independently but simultaneously developing the very same technology. This outcome is generally called parallel development. Jet engines provide an excellent example. See Sterling Michael Pavelec, *The Jet Race and the Second World War* (Annapolis, Md.: Naval Institute Press, 2007), pp. 17–63. In this article, however, we focus only on imitation attempts: in comparison to parallel development, imitation should logically make convergence among countries easier and quicker.

Footnote 19. Innovation entails working with technologies that are not yet understood and whose arrangement is not yet known. In contrast, imitation entails exploiting, to different degrees, the knowledge and understanding accumulated by the innovator.

Footnote 20. Technological development presents innovators with a broad range of research directions, but many of these avenues will not yield results. Thus, by trying to innovate, a country will not only bear the costs associated with research and development, but will also risk wasting precious time and resources.

Footnote 21. For an empirical case, see Emily O. Goldman Goldman, "Receptivity to Revolution: Carrier Air Power in Peace and War," in Goldman and Eliason (eds.), *The Diffusion.*

Footnote 22. See also Fernando F. Suarez and Gianvito Lanzolla, "The Role of Environmental Dynamics in Building a Theory of First-Mover Advantages," *Academy of Management Review*, Vol. 32, No. 2 (April 2007), pp. 377–392, doi:10.2307/20159307.

Footnote 25. This problem is so pervasive in the IR scholarship, that, in the words of John Alic, "few studies of military innovations pay even superficial attention to technological specifics." See Alic, "Managing U.S. Defense Acquisition," p. 4.

Footnote 26. For a discussion on imitation and internal balancing, see Joseph M. Parent and Sebastian Rosato, "Balancing in Neorealism," *International Security,* Vol. 40, No. 2 (Fall 2015), p. 53.

Footnote 31. In "Systemic Effects of Military Innovation and Diffusion," Goldman and Andres note that history "shows that the practices for the use of innovative technologies tend to spread more slowly than does the technology itself," p. 121. A similar assumption is also widely accepted among policymakers that the diffusion of technological knowledge from the military to civilian sectors "is [in fact] portrayed as easy, almost automatic." See John A. Alic et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Cambridge, Mass.: Harvard Business School Press, 1992), p. 25.

Footnote 32. In more recent works, Horowitz has emphasized the importance of technological and industrial challenges. See for example, Michael C. Horowitz, "Artificial Intelligence, International Competition, and the Balance of Power," *Texas National Security Review*, Vol. 1, No. 3 (May 2018), pp. 36-57.

Footnote 33. See also Aaron L. Friedberg, "The End of Autonomy: The United States after Five Decades," *Daedalus*, Vol., 120, No. 4. (Fall 1991), pp. 69–90, https://www.jstor.org/stable/20025404; and Aaron L. Friedberg, *A Contest for Supremacy: China, America, and the Struggle for Mastery in Asia* (New York: W.W. Norton, 2011), pp. 232–244.

Footnote 34. See also Raymond Vernon and Ethan B. Kapstein, "National Needs, Global Resources," *Daedalus*, Vol. 120, No. 4 (Fall 1991), pp. 1–22, https://www.jstor.org/stable/20025401.

Footnote 35. For a more extensive summary of the literature, see n. 3 in Stephen Biddle, "Past As Prologue: Assessing Theories of Future Warfare," *Security Studies*, Vol. 8, No. 1 (Autumn 1998), pp. 3–4, doi:10.1080/09636419808429365. See also Zysman, "Power, Wealth and Technology."

Footnote 41. See also Michele Boldrin and David K. Levine, *Against Intellectual Monopoly* (Cambridge, UK: Cambridge University Press, 2008).

Footnote 42. Tablets and smartphones, in fact, "are incredibly complicated devices that must be designed well and built reliably. The engineering expertise […] required [… is] so formidable that only a handful of companies in the world ever try." McAfee and Brynjolfsson, *Machine, Platform, Crowd*, p. 204. About Microsoft and Google's struggles, consider that in 2016, according to some observers, they had not been able to "come up with a tablet that works half as well as Apple's iPad." Matt Weinberger, "Microsoft and Google Are Learning How Hard It Is To Be Like Apple," *Business Insider* (January 25, 2016), https://www.businessinsider.com/microsoft-google-its-not-easy-being-apple-2016-1?r=US&IR=T. For a discussion on the problems encountered by Apple's competitors, see Sara Lepley, "A year after switching from the iPhone to the Google Pixel, I'm sad to admit it wasn't worth it," *Business Insider* (December 4, 2018), http://uk.businessinsider.com/why-switching-from-iphone-to-google-pixel-isnt-worth-it-2018-12?r=US&IR=T; Jeffrey Van Camp Gear, "The 11 Tablets Worth Buying Right Now," *Wired* (November 13, 2018), https://www.wired.com/gallery/the-best-tablets/; Cameron Faulkner, "How Google's Pixel Slate tablet compares to the Surface Pro 6 and iPad Pro" *The Verge* (October 3, 2018), https://www.theverge.com/tech/2018/10/3/17929946/microsoft-surface-pro-6-apple-ipad-pro-tablet-spec-comparison-storage-battery; Will Greenwald, "Microsoft Surface Go vs. Apple iPad: Inexpensive Tablets Compared," *PCMag* (July 10, 2018), https://www.pcmag.com/compare/362368/microsoft-surface-go-vs-apple-ipad-inexpensive-tablets-com; Andrew Orlowski, "Six things I learned from using the iPad Pro for Real Work," *The Register* February 14, 2018); https://www.theregister.co.uk/2018/02/14/ipad_pro_for_real_work/; Joshua Goldman, "iPad Pro vs. Surface Pro: 5 ways to choose," *Cnet* (June, 22, 2017), https://www.cnet.com/how-to/ipad-pro-vs-surface-pro-5-ways-to-choose/; and Lisa Eadicicco, "Apple iPad Pro vs. Microsoft Surface Pro: Which Tablet Is Right For You?", *Time Magazine* June 16, 2017), http://time.com/4820774/microsoft-surface-pro-vs-ipad-pro/. The experience of Intel, the largest semiconductor chip producer in the world provides further evidence in this regard, as it gave up on its plan to enter the smart phones market after having invested about $10 billion (with a b) in this technology – a performance that hardly suggest it could "free ride" on others. See Julie Bort, "Intel has finally admitted that it failed miserably in the mobile market," *Business Insider* (May 2, 2016), https://www.businessinsider.com.au/intel-kills-its-next-smartphone-and-tablet-chips-2016-5. A comparison between the two most representative technologies of the Second and Third Industrial Revolution, the car and the computer, is telling. In the early 20th century, car manufacturing was one of the most advanced fields of its time. However, producers could easily borrow know-how and technology from other industries, as we discuss later. This explains why car manufacturing spread extremely quickly to all major Western European countries and to the US and, by the Second World War, also to Central and Eastern Europe and to the Soviet Union. See Steven Parissien, *The Life of the Automobile: The Complete History of the Motor Car* (New York, NY: Thomas Dunne Books, 2014). Conversely, the computer industry shows, in the words of Alfred Chandler, "the difficulty in a high-technology industry of catching-up to the first mover." In fact, despite massive government funding and investments, European governments failed in their attempt to catch up with IBM in the 1960s and 1970s. See Chandler, *Inventing the Electronic Century*, p. 37. For a comparison across different industries, including the computer industry, see Mowery and Nelson (eds.), *Sources of Industrial Leadership*. See also "A maturing Apple still awaits the Apple-killer," *Financial Times* (January 8, 2017). Importantly, the challenge does not only concern hardware but also software. In fact, *contra* Goldman and Andres, software development seems to be even more daunting and observe even higher entry barriers than industrial production. On the one hand, this is due to its increasing, rather than decreasing marginal costs curve that, logically, strengthen first movers. For a broader discussion, see Carl Shapiro and Hal R. Varian, *Information Rules: A Strategic Guide to the Network Economy* (Cambridge, MA: Harvard Business School Press, 1999). On the other hand, integrating software and hardware poses severe difficulties, as it has been in fact the case for the competitors of the iPhone. On this, see

Joshua Gans, *The Disruption Dilemma* (Cambridge, MA: MIT Press, 2016), p. 46.

Footnote 43. Among the many possible examples, consider that despite the concerns for the "democratization" of defense production resulting from technological change and the ICT revolution, for instance, the merger between Sikorsky and Lockheed Martin evolved with them "emerging as leaders in autonomous helicopter flight with no close second." See Patrick Tucker, "Black Hawk Empty: Unmanned Helicopter Passes Key Test," *DefenseOne* (October 29, 2015). For a discussion of the commercial sector, see Richard R. Nelson and Gavin Wright, "The Rise and Fall of Technological Leadership: The Postwar Era in Historical Perspective," *Journal of Economic Literature*, Vol. 30, No. 4 (December 1992), pp. 1931–1964, https://www.jstor.org/stable/2727970; and Edward Steinfeld, "China's Shallow Integration: Network Production and the New Challenges for Late Industrialization," *World Development*, Vol. 32, No. 11 (November 2004), pp. 1984 –1985, doi: 10.1016/j.worlddev.2004.04.003.

Footnote 44. See also Jeffrey A. Drezner, "Competition and Innovation under Complexity," in Ben-Ari and Chao, *Organizing a Complex World*; and Marco Iansiti, "Managing 'Mega-Projects': Lessons for Future Combat Systems," in Ben-Ari and Chao, *Organizing a Complex World*; and Eugene Gholz, Andrew D. James and Thomas H. Speller, "The Second Face of Systems Integration: An Empirical Analysis of Supply Chains to Complex Product Systems," *Research Policy*, Vol. 47, No. 8 (October 2018), pp. 1478–1494, doi:10.1016/j.respol.2018.05.001; and Robert L. Paarlberg, "Knowledge as Power: Science, Military Dominance, and U.S. Security." *International Security* 29, no. 1 (Summer 2004), pp. 122-151. The article by Paarlberg has provided a very important source for our thinking. Unfortunately, we went over more than 50 draft before the article before the article was finally accepted, and some 15 to 20 iterations during the copy-editing stage. Somewhere, the citation to his work got lost. We regret that this happened.

Footnote 45. Given x number of state variables, in order to approximate each state in y grid points, the solution will require the evaluation of the function in yx. To get decent approximation, usually one can use y = 1000. With 2 states, the solution will require the evaluation of 1 million points. With 4 states, the solution will require 1 tera points. We would like to thank Antonio Mele for providing us with the example.

Footnote 47. An unanticipated problem can be addressed without re-designing the entire product if one properly understands all the properties of the components and how they interact.

Footnote 48. See also Charles H. Fine, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage* (Reading, Mass.: Perseus, 1998), pp. 119–124. This strategy, however, increases dramatically technological risks, as performance, incompatibilities and reliability are not known at the time of design.

Footnote 49. See also Andrea Prencipe, "Corporate Strategy and Systems Integration Capabilities: Managing Network in Complex Systems Industries," in Prencipe, Davies and Hobday (eds.), *The Business of Systems Integration*, p. 122.

Footnote 50. Game theory shows that the difficulties of achieving a cooperative equilibrium are directly related to the number of actors – even when pursuing common goals. The same logic applies to engineering principles: as the number of components increases, their integration becomes more challenging. See Herbert A. Simon, "The Architecture of Complexity," *Proceeding of the American Philosophical Society* vol. 106, n. 6 (December 1962), p. 467-482.

Footnote 51. Between 1850 and 2006, for example, computing has increased, depending on the measure, by a factor of 2 trillion to 76 trillion. William D. Nordhaus, "Two Centuries of Productivity Growth in Computing," *Journal of Economic History*, Vol. 67, No. 1 (March 2007), pp. 128–159, doi:10.1017/S0022050707000058. See also Murrae J. Bowden, "Moore's Law and the Technology S-Curve," *Current Issues in Technology and Management*, Vol. 8, No. 1 (Winter 2004).

Footnote 52. As Ben-Ari and Zlatnik put it, "even the smallest changes may initiate large variations in the resulting pattern of behavior and thereby affect strategic outcomes." In comparison, consider that during World War I, when Ford Motor Co. was invited to manufacture the British aircraft engine produced by Rolls-Royce, the problems Ford encounter were the very opposite. In their account, "the tolerances are far too wide for us. We make motors car far more accurately than this." 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. 116.

Footnote 53. The most obvious example is that of the Wright Brothers, who designed and produced themselves the engine for their Flyer. For full credit, it was Orville Wright who took responsibility for the engine. Wilbur focused on the propeller design and construction. See John D. Anderson Jr., *The Airplane: A History of Its Technology* (Reston, VA: American Institute of Aeronautics and Astronautics, 2002), p. 118.

Footnote 54. For a summary of the market of turbofans, see FlightGlobal, *Commercial Engines: Turbofan Focus 2015* (London, UK, FlightGlobal, 2015), pp. 9-11.

Footnote 55. For example, a jet high-pressure turbine blade needs to show, among others, "limited creep extension" as the latter "can affect the clearance between the blade tip and the turbine case and can cause engine stall, a serious safety concern in aviation." However, "the mechanisms of creep are very complicated" and hence difficult to predict and understand. See Wang, *Reverse Engineering*, p. 248. These aspects are important because, in the words of Wang, "For a single-engine fighter jet, the turbine engine has to operate properly at all times. Any other engine performance standard, even just with 0.1% probability to fail, is not acceptable." See Wang, *Reverse Engineering*, p. 256. See also Obaid Younossi, Mark V. Arena, Richard M. Moore, Mark A. Lorell, Joanna Mason, and John C. Graser, *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology* (Santa Monica, CA: RAND, 2002), pp. 16-20 and 126; Lee S. Langston, "Each Blade a Single Crystal," *American Scientist*, Vol. 103, No. 1 (Jan.-Feb. 2005), p. 30; and Lee S. Langston, "Gems of Turbine Efficiency," *Mechanical Engineering* Vol. 136, No. 09 (Sep. 2014), pp. 76-77. Designing, developing, and manufacturing a single system such as a jet engine poses significant problems. Developing such system, integrating it in a larger system of systems, and having the latter work successfully and deliver its maximum performance, is extremely challenging. The market of turbofan engines is in fact very concentrated: it is controlled in fact by "the big three", Pratt and Whitney, General Electric and Rolls Royce. Even a country like Russia, which has a long experience in this sector dating back to the post-World War II period, has faced several problems in keeping the technological gap with Western countries from increasing. According to Erickson and Collins, "Russian engines remain heavier, utilize less of the most sophisticated materials, suffer from higher fuel burn rates; have poorer acceleration, lower thrust-to-weight ratios, shorter lifespans, and less maintainability than the top U.S. and European-made jet engines; and also remain incapable of using the latest management technologies to best advantage." See Andrew Erickson and Gabe Collins, "The 'Long Pole in the Tent': China's Military Jet Engines," *The Diplomat* (December 09, 2012); and Andrea Prencipe, "Technological Competencies and Product's Evolutionary Dynamics: A Case Study from the Aero-engine Industry," *Research Policy* Vol. 25, No. 8 (January 1997), pp. 1261-1276; Smil, *Prime Movers of Globalization*, pp. 131-139.

Footnote 56. About the role of impurities in material development, consider that spotwelds on the wing panels of the RS-71 *Blackbird* "failed very early in their test life [if the panels were built] in the summer, but if they were built in the winter they lasted indefinitely." It was later discovered that this problem was caused by chlorine in the water, which the local water utility company added during the summer period in order to reduce algae. See Johnson with Smith, *Kelly*, p. 142. About improvements in material, see the discussion in Vaclav Smil, *Making the Modern World - Materials and Dematerialization* (Chichester, UK: John Wiley & Sons, 2014).

Footnote 58. In 2000, the United States had an average software defect rate of 5.9 to 7 defects per 1000 lines code. See Misty Davies and Lyle N. Long, "Special Issue on Software Challenges in Aerospace," *Journal of Aerospace Information Systems* Vol. 11, No. 10 (2014), pp. 607–609, doi: 10.2514/1.I010339. On how regulation of the oxygen caused problems for U.S. pilots (notably, hypoxia) see for example, Lara Seligman, "What's Wrong With The U.S. Navy's F/A-18s?," *Aviation Week & Space Technology*, February 14, 2018.

Footnote 59. For a more general discussion, see Government Accounting Office, *Stronger Management Practices Are Needed to Improve DOD's Software-Intensive Weapon Acquisitions* (Washington, DC: GAO, March 2004); Government Accounting Office, *Defense Acquisitions: Assessments of Selected Weapon Programs* (Washington, DC: GAO, March 2011).

Footnote 60. For example, surface cruising range for conventional submarines has increased from about 540 nautical miles in 1900 (US *B class*) to 8,100 in 1914 (German *U-63 class*), to 10,500 in 1937 (German *Type IX*) to 15,500 in 1944 (German *Type XXI*). During the same time, underwater range has increased because of improvements in electric batteries, the introduction of snorkel (in 1944) and finally the development of air-independent propulsion systems (1990s). From 21 nautical miles in 1900, underwater range increased to 60 miles in

1914, 87 in 1937, 340 in 1944 and 2,400 by 2014. The same is true for depth, which passed from 150ft in 1900 to 195 in 1914, 328 in 1937, 850 in 1944 and finally 3,000 in 2004. Also surface and submerged speed have increased, even though in this case the improvement has been much more limited: from 9 knots per hour on the surface in 1900 to 18 knots in 1944 (subsequently, surface speed lost importance for submarines); and from 8 knots per hour underwater in 1900 to 20 in 2004. Data collected from Roger Chesneau (ed.), *Conway's All the World's Fighting Ships, 1860-1905* (London, UK: Conway Maritime Press, 1979); Randal Gray (ed.), *Conway's All the World's Fighting Ships: 1906-1921* (London, UK: Conway Maritime Press, 1985); Roger Chesneau (ed.), *Conway's All the Worlds Fighting Ships 1922-1946* (London, UK: Conway Maritime Press, 1980), Norman Friedman (ed.) *Conway's All the World's Fighting Ships, 1947-1982, Part 1: The Western Powers* (London, UK: Conway Maritime Press, 1983); Robert Gardiner (ed.) *Conway's All the World's Fighting Ships 1947-1995* (Annapolis, MD: US Naval Institute Press, 1996); and Paul E. Fontenoy, *Submarines: An Illustrated History of Their Impact* (Santa Barbara, CA: ABC-CLIO, 2007).

Footnote 62. For instance, the endurance of the batteries of smartphones suddenly drops to few minutes and even to few seconds when exposed to below-freezing temperatures (32°F, 0°C). Ossi Jääskeläinen, "Sub-Zero Weather: Can Your Smartphone Stand The Cold?," *TechHive* (Feb 1, 2012). Modern combat aircraft rely on external sensors (pitot tubes) that provide the air management system with the aerodynamic data needed to make automatic microsecond adjustments needed for flight stability. The freezing temperatures at which these sensors are exposed make them particularly prone to malfunctioning, which in turn could lead the aircraft to go out of control within seconds. See Rich and Janos, *Skunk Works*, p. 82.

Footnote 63. In aerospace, the so-called "transonic gap" provides an illustrative example: aircraft designers in the 1930s did not know how drag, air density and possibly other key variables would change when approaching and breaking the sound barrier. John D. Anderson Jr., *The Airplane: A History of Its Technology* (Reston, VA: American Institute of Aeronautics and Astronautics, 2002), p. 308, and in general 298-334. In the submarine realm, developments after World War II provide an illustrative example. Improvements in anti-submarine warfare (ASW) technology promoted further increases in submarines capabilities – depth, range, speed and quietness. This posed a set of completely new problems related, among others, to hydrodynamics and how to control a fast submarine, structural and naval engineering, as well as oceanography and acoustics. Consider that with depth, the weight of the water above a given submerged object (hydrostatic pressure) increases by about 14.5 pounds per square inch every 33 feet. At significant depth, a minor vulnerability or defect in production could cause the collapse of the hull and hence the loss of the submarine. For this reason, the hull of the first operational nuclear-powered submarine of the U.S. Navy *Skipjack* was made of high-yield 80 steel – steel intended to withstand 80,000 pounds per squared inch. This is explained by the operational depth of *Skipjack* (its maximum depth was 700 feet), and by the inherent perils of cruising at sustained speed underwater: a minor downward slope caused by inadequate underwater controls or by unexpected underwater turbulence could suddenly expose the submarine to crushing pressure. Apparently, the loss of *USS Thresher* (designed to operate at 1,300 feet) was caused by underwater turbulence resulting by sharp salinity and temperature gradients that brought the submarine beyond its crushing depth. At which point, its welds failed. See respectively Jeffrey L. Rodengen, *Serving the Silent Service: The Legend of Electric Boat* (Ft. Lauderdale, FL: Write StuffSyndacate, Inc., 1994), p. 108; Capt. W. D. Roseborrough, "The Evolution of Modern U.S. Submarine From the End of World War II to 1964, *Naval Engineer Journal* vol. 112, no. 2 (March 2000), pp. 27-31; and Norman Friedman, *Submarine Design and Development* (Annapolis, MD: Naval Institute Press, 1984), pp. 82-83; Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington, MA: Lexington Books, 1987): pp. 131-54. See also Gary E. Weir, *An Ocean in Common: American Naval Officers, Scientists, and the Ocean Environment* (College Station, TX: Texas A&M University Press, 2001).

Footnote 64. See also Arthur, *The Nature of Technology*, pp. 45-67. The inventor of modern submarines, John Holland, understood that with lateral fins for depth control (hydroplanes) a submarine would not suffer the fore-and-aft instability that contemporary vessels experienced due to their reliance on vertical propellers. Similarly, Oliver and Wilbur Wright understood that controlling the airplane when airborne through a movable tail (flight controls) was more important than endowing it with a propulsion system powerful enough for taking off. See respectively Norman Friedman, *U.S. Submarines Through 1945: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 1995), p. 19; and Walter J. Boyne, *The Influence of Air Power Upon History* (Gretna, LA: Pelican Publishing Company, 2003), pp. 26–36. On the Wright brothers see also Anderson, *The Airplane*, p. 116. The model T produced by Ford was "the ultimate standardized machine. It was so simple in the extreme… It contained the barest minimum of moving parts. In contrast to today's complex cars, it could be repaired by almost anyone with a smattering of mechanical sense." Thomas K. McCraw and Richard S. Tedlow, "Henry Ford, Alfred Sloan, and the Three Phases of Marketing," in Thomas K. McCraw (ed.), *Creating Modern Capitalism: How Entrepreneurs, Companies and Countries Triumphed in Three Industrial Revolutions* (Cambridge, MA: Harvard University Press, 1997), pp. 273-274. An extreme example in this regard is provided by Hiram Maxim, better known for his "Maxim gun." In the late 1880s Maxim started working on flying machines, out of his "I can do anything" attitude. In 1908, he stated that that "[w]hat is required by experimenters in flying machines… is a treatise which they can understand, and which required no more delicate instruemnts than a carpenter's two foot rule and a grocer's scale." Anderson, *The Airplane*, p. 53.

Footnote 65. See also David C. Mowery, "The Relationship Between Contractual and Intrafirm Forms of Industrial Research in American Manufacturing, 1900-1940", *Explorations in Economic History* vol. 20, No. 4 (1983), pp. 351-374.

Footnote 66. David C. Mowery and Nathan Rosenberg, *Technology and The Pursuit of Economic Growth* (New York, NY: Cambridge University Press, 1989), p. 172. Between 1930 and 1970, for example, average annual development costs have risen by 20%. *Ibid.* Similarly, while for the B-52, the first American intercontinental jet-powered bomber, R&D "amounted to only 1.5% of total program expenditures", for the B-2 Spirit, the first stealth bomber, "more than half of the total [cost]… went for RDT&E [Research, Development, Test and Evaluation]." See Alic, "Managing U.S. Defense Acquisition," p. 10. As a result, for the period 1956-2005, development expenditures "rarely accounted for less than 80% of [Department of Defense] R&D." See David C. Mowery, "Military R&D and Innovation," in Bronwyn H. Hall and Nathan Rosenberg (eds.), *Handbook of the Economics of Innovation Volume 2* (New York, NY: Elsevier, 2010), pp. 1230.

Footnote 67. Keith Pavit, "Specialization and Systems Integration: Where Manufacture and Services Still Meet," in Prencipe, Davies and Hobday (eds.), p. 88. See also Stephen B. Johnson, "Three Approaches to Big Technology: Operations Research, Systems Engineering, and Project Management," *Technology and Culture,* Vol. 38, No. 4 (October 1997), pp. 891–919, doi: 10.2307/3106953; Hobday, "Product Complexity;" Sapolsky, "Inventing Systems Integration;" and Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems." As a result of the increase in complexity, in order to outsource components and subsystems production, and then be able to design, develop and manufacture the whole system, systems integrators must know more than they do. Stefano Brusoni and Andrea Prencipe, "Unpacking the Black Box of Modularity: Technologies, Products and Organizations," *Industrial and Corporate Change*, Vol. 10, No. 1 (March 2001), pp. 179–205 and in particular p. 193, doi: 10.1093/icc/10.1.179; and Stefano Brusoni, Andrea Prencipe and Keith Pavitt, "Knowledge Specialization, Organizational Coupling and the Boundaries of the Firm: Why Firms Know More Than They Make?," *Administrative Science Quarterly*, Vol. 46, No. 4 (December 2001), pp. 597 –621, doi: 10.2307/3094825. See also Prencipe, Davies and Hobday (eds.), "Introduction," p. 4; and Prencipe, "Corporate Strategy," p. 122; Iansiti, *Technology Integration,* p. 12; Wang and Von Tunzelmann, "Complexity and the Functions of the Firm." For an overview of this transition, 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.

Footnote 68. In fact, "in many ways, we know more about the moon and the nearer planets than we do about our own oceans." Miller and Jordan, *Modern Submarine Warfare*, p. 44. The contrast between the invention of the submarine (fn. 64) and the development of sonar-evading technology is telling: the materials and the procedures required are demanding even for the most advanced countries and call for an extremely advanced understanding of sound and radio waves propagation in the ocean, including how depth, water pressure, salinity, heat and many other factors affect them. Miller and Jordan, *Modern Submarine Warfare*, pp. 44-49, 92; John Merrill and Lionel D. Wyld, *Meeting the Submarine Challenge: A Short History of the Naval Underwater Systems Center* (Washington, D.C.: Department of the Navy, 1997), pp. 18, 35-60. See also Thaddeus Bell, *Probing the Ocean for Submarines A History of the AN/SQS-26 Long-Range, Echo-Ranging Sonar* (Washington, DC: NAVSEA Newport Underwater Warfare Center Division, 2003), pp. 1-2, 11-14. The article cited in the footnote can be found at, Hyperlink to the article in the footnote: https://www.smh.com.au/national/submarines-no-longer-all-at-sea-20120708- 21pk3.html.

Footnote 69. For an historical discussion, see for example Rosenberg, *Perspective on Technology*, pp. 141-210; and Joel Mokyr, "The Contribution of Economic History to the

Study of Innovation and Technical Change: 1750-1914," in Bronwyn H. Hall and Nathan Rosenberg, *Handbook of The Economics of Innovation Volume 1* (New York, NY: Elsevier, 2010), pp. 11-51. See also Gilpin, *War and Change in World Politics*, pp. 176–177.

Footnote 71. See also Kennedy, *The Rise*, p. 198-203; and For a more general discussion, see Alfred D. Chandler Jr., *Scale and Scope* (Cambridge, Mass. The Belknap Press, 1990), pp. 1–46. See also Thomas K. McCraw, "American Capitalism", in McCraw (ed.) *Creating Modern Capitailsm*, p. 315.

Footnote 72. Gerschenkron, *Economic Backwardness*, pp. 31-51. This is the reason why German universal banks played such an important role in the economic development of Germany during this period. See Chandler, *Scale and Scope*. For a broader discussion of the capacity to mobilize resources, see Fareed Zakaria, *From Wealth to Power: The Unusual Origins of America's World Role* (Princeton: University Press, 1998); and Jeffrey W. Taliaferro, "State Building for Future Wars: Neoclassical Realism and the Resource-Extractive State," *Security Studies*, Vol. 15, N. 3 (Fall 2006), pp. 464-495.

Footnote 75. This included also invitation of foreign naval architects, such as Emile Bertin from France, as well as study and observation abroad (in British yards). See Peattie, "Japanese," p. 94.

Footnote 78. The case of South Korea's plan for an indigenous jet fighter provides an illustrative example in that the decision by the US not to provide systems integration knowledge required for the avionics has so far represented a key constrain in the advancement of the project. See Bradley Perrett, "South Korea's KF-X Set For Slow Progress In 2016," *Aviation Week and Space Technology* (September 24, 2015); and "KF-X Struggles With U.S. Technology Policy," *Aviation Week and Space Technology* (Oct 23, 2015).

Footnote 79. The poor performance of the Japanese program is even more striking in light of Kelly Johnson's claim that the F-16 came "at least ten years later […] at nearly three times the cost" of an aircraft that "was comparable in performance" developed by Lockheed. Johnson, *Kelly*, p. 116.

Footnote 81. See also Joseph A. Schumpeter, *Business Cycles Volume 1* (New York, NY: McGraw and Hill, 1939), p. 100. Both Arrow and Schumpeter later on changed their mind. See respectively Kenneth Arrow, "Classificatory Notes on the Production and Transmission of Technological Knowledge," *American Economic Review* vol. 59, No. 2 (May 1969), pp. 29-35; and Joseph A. Schumpeter, *Capitalism, Socialism and Democracy* (New York, NY: Harper and Row Publishers, 1976), pp. 133-134.

Footnote 82. Chemical and pharmaceutical firms, for example, invest in basic research in order to maintain the know-how and experience needed to take advantage of new discoveries and develop new drugs. See Nathan Rosenberg, "Why Do Firms Do Basic Research With Their Own Money?" *Research Policy* 19 (1990): 165-174, pp. 229-234; Moses Abramovitz, "Catching Up, Forging Ahead, and Falling Behind," *The Journal of Economic History* vol. 46, no. 2 (June, 1986), pp. 385-406; and David T. Coe, Elhanan Helpman, and Alexander W. Hoffmaister, "International R&D Spillovers and Institutions," *IMF Working Paper*, WP/08/104 (2008); and Benhabib and Spiegel, "Human Capital and Technology Diffusion." The difference between Egypt's incapacity to develop an indigenous jet fighter in the 1960s, and US capacity to imitate a Soviet helicopter in the 1980s, can be attributed, at least in part, to the difference in their "absorptive capacity". In the former case, Egypt "recruited hundreds of German experts and scientists," including Willy Messerschmitt, "the father of the deadly fighter planes of the Luftwaffe, the Nazi air force, during World War II." However, the project encountered financial and technical problems (and also political), and was finally cancelled. In the latter case, Pakistani intelligence, in the mid-1980s, captured a Soviet helicopter (the Mi-24D) and handed it intact to U.S, which in turn could analyze it and study it in depth. This opportunity, in turn, "saved the Pentagon millions of dollars in research and development costs, the Pentagon later reported." See respectively, Michael Bar-Zohar and Nissim Mishal, *Mossad: The Greatest missions of the Israeli Secret Service* (New York, NY: HarperCollins, 2012), p. 114; and Steve Coll, *Ghost Wars: The Secret History of the CIA, Afghanistan, and Bin Laden, From the Soviet Invasion to September 11* (New York, NY: Penguin Press 2004), p. 134.

Footnote 85. Mowery and Rosenberg add that, "[a]lthough a number of laboratories had been established by 1900, even well after that date industrial research laboratories were not yet performing activities that should be regarded as research. Rather, they were engaged in a variety of routine and elementary tasks such as the grading and testing of materials, assaying, quality control, and writing of specifications. These were the primary initial applications of science in the industrial context. Science, when it entered the industrial establishment, came to perform tasks that were elementary *from the point of view of their scientific content*." See Mowery and Rosenberg, *Technology*, pp. 29, 31. See also Nelson and Wright, "The Rise and Fall of Technological Leadership," p. 1838. The case of Thyssen is particularly interesting in this regard. From an "internal repair shop" that entered the machine-engineering operation, in the span of two decades, it "had become a huge success and a powerful rival to the most renowned machine-engineering firm in Germany, the Machinenfabrik Agsburg-Nurnberg (MAN)." Sean Fear, "August Thyssen and German Steel," in McCraw (ed.), *Creating*, pp. 188, 198.

Footnote 86. See also Vincenti, *What Engineers Know*, p. 4; and Laurence K. Loftin, Jr., *Quest for Performance: The Evolution of Modern Aircraft* (Washington, DC: NASA Scientific and Technical Information Branch, 1985), pp. 3, 7-9, 77-105. Loftin writes that "the results of [the National Advisory Committee for Aeronautics's] studies… did not begin to have a significant impact on aircraft design until the mid- to late 1920s… [In fact, a]ircraft design during World War I was more inventive, intuitive, and daring than anything else. Prototypes were frequently constructed from full-size chalk drawings laid out on the factory floor. The principles of aerodynamics that form so important a part of aircraft design today were relatively little understood by aircraft designers during the war." See respectively *ibid*, p. 7 and pp. 8-9.

Footnote 88. See also Gary E. Weir, *Building American Submarines, 1914-1940* (Washington, DC: Government Printing Office, 1991), pp. 31, 85; Norman Friedman, *U.S. Submarines Through 1945: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 1995), p. 191.

Footnote 91. On the challenges of imitating complex products, see also Cohen and Levin, "Empirical Studies," p. 1093; Edwin Mansfield, Mark Schwartz and Samuel Wagner, "Imitation Costs and Patents: An Empirical Study," *The Economic Journal* vol. 91, no. 364 (December 1981), pp. 907-918; Richard C. Levin, "Appropriability, R&D Spending, and Technological Performance," *American Economic Review* vol. 78, no. 2 (May 1988), pp. 424-28; Jan W. Rivkin, "Imitation of Complex Strategies," *Management Science* vol. 46, no. 6 (June 2000): 824-844; and Boldrin and Levine, *Against Intellectual Monopoly*.

Footnote 94. For instance, in the late 1960s, a Mark 37 torpedo "battery […] exploded in flames during a vibration test at the Naval Torpedo Station" because of the failure of a "tiny foil diaphragm" that was "worth pennies." Similarly, loss of the nuclear submarine USS *Scorpion* (SSN-589) was apparently due to the activation and subsequent overheating of torpedoes batteries caused by the vibrations experienced during underwater cruising. Sherry Sontag and Christopher Drew with Annette Lawrence Drew, *Blind Man's Bluff: The Untold Story of American Submarine Espionage* (New York, NY: Public Affairs, 1998), pp. 113, 109-120. In other cases, the challenges are even subtler. Relatively minor and subtle sources of noise, for example, are sufficient to make submarines acoustically detectable. When rotating, the propeller of a submarine produces a change in underwater pressure, which in turn can lead to the creation of bubbles (cavitation). While this might seem a relatively small problem, it is actually quite serious, as the noise resulting from the explosion of these bubbles can prove sufficient for a submarine to be detected. In fact, "[o]ne watt of acoustical energy coming out of the propeller of a submarine in the Strait of Gibraltar can be heard off the coast of Virginia." David E. Sanger, "A Bizarre Deal Diverts Vital Tools to Russians*, New York Times* (June 12, 1987), cited in 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, N. 24 (1989), pp. 254. The case of the mid-1960s Project 667a class of Soviet nuclear-powered ballistic missiles submarines (NATO classification "Yankee") is telling: although significantly quieter than its predecessor – the Project 658 class (NATO classification "Hotel") – it was still fairly easy to detect and to track by American anti-submarine platforms because it suffered from a "structural flaw" that resulted in additional noise when the submarine was turning leftward. Sontag et al, *Blind Man's Bluff*, pp. 133-134. Allegedly, because of such vulnerability, an American admiral referred to the Yankee class as a "tethered goat." See Coté, *The Third Battle*, p. 72. For a discussion of sounds propagation in the ocean and submarine competition on quietness, see Stefanick, Strategic *Antisubmarine Warfare*, pp. 1-32, 217-365; Austin Long and Brendan Rittenhouse Green, "Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy," *Journal Of Strategic Studies* Vol. 38, N. 1-2 (2015), pp. 38-73; Merrill and Wyld, *Meeting the Submarine Challenge*, 35-60; and Gary E. Weir, "The American Sound Surveillance System: Using the Ocean to Hunt Soviet Submarines, 1950-1961," *International Journal of Naval History*, Vol. 5, N. 2 (August 2006).

Footnote 95. See also Anderson, *The Airplane*, pp. 170-286.

Footnote 96. This transition is aimed at understanding how the platforms and their individual components would function when operating under different environmental conditions. See also Johnson, "Systems Integration and the Social Solutions of Technical Problems in Complex Systems," p. 40; Sapolsky, "Inventing," p. 19; and Johnson, "Three Approaches to Big Technology," pp. 894, 900. We observe the same trend with naval platforms, whose research since World War II has increasingly expanded, among others, to oceanography, oceanic topography, climate science, acoustics, marine biology, and many others. Merrill and Wyld, *Meeting the Submarine Challenge*, p. 18. See also William K. Klingaman, *APL-Fifty Years of Service to the Nation: A History of The Johns Hopkins University Applies Physics Laboratory* (Laurel: Maryland, The Johns Hopkins University Applies Physics Laboratory, 1993), pp. 210-211.

Footnote 97. See also Mowery and Rosenberg, *Technology*, pp. 81-82; and Alic, et al., *Beyond Spinoff*, p. 20-22.

Footnote 98. *Blackbird* could reach an altitude of 80,000ft. In the subsequent pages, Johnson describes some of the other problems, which stemmed from dealing with materials (such as titanium: "we had to invent a very large press that would shape titanium under very high temperatures – up to 1500°F and very high pressures") as well as with systems ("hydraulic, electrical, and others."). For example, for the hydraulic system of *Blackbird*, the hydraulic fluid had to be "able to operate at above 600°F" because of the heat generated by Mach 3.2. See Johnson, *Kelly*, p. 139-147. Similarly, when the Johns Hopkins University Applied Physics Laboratory Research Center was created, its "areas of concentrations were largely limited to spectroscopy, chemical kinetics, high-altitude research and wave physics." By the 1970s, the disciplines it mastered broadened to, among others, "plasma physics, map-matching technology for cruise missiles, flame structure, laser technology and unstable burning of solid fueled rockets." Klingaman, *APL*, p. 239.

Footnote 99. Among the many problems, consider that the introduction of fly-by-wire exposed aircraft to the risk of lightning-induced voltages and currents. See Carl S. Droste, Robert T. Zeitler and James L. Dabold, "Lightning Protection Program for the F-16 Fly-By-Wire System," *1979 IEEE International Symposium Electromagnetic Compatibility* (9-11 Oct 1979), pp. 1-7.

Footnote 100. The problems that the engineers of Skunk Works encountered when working on the electrical system of the *Blackbird* epitomize this issue. As recalled by Kelly Johnson, "we simply were not able to get the electrical system to work reliably under conditions of very high altitude, very high temperature, and very substantial vibration."[1] Given that the electrical system "controlled the autopilot, flight control system, navigation system, and with electrical transducers even the hydraulic system," its malfunctioning "threatened the success of the [whole] project." Johnson, *Kelly*, p. 143.

Footnote 101. See also Department of Defense, *Unmanned Systems Integrated Rroadmap, FY2011–2036* (Washington, D.C.: Department of Defense, October 2011), pp. 82–86.

Footnote 102. See also Constance E. Helfat and Marvin B. Lieberman, "The Birth of Capabilities: Market Entry and the Importance of Pre-history," *Industrial and Corporate Change* vol. 11, n. 4 (2002), pp. 725-760.

Footnote 103. Rosenberg has called this process "technological convergence." Precisely, he has argued that the application of the same machines to different sectors has played a key role in promoting the American System of interchangeable parts. See Rosenberg, *Perspective on Technology*, chapter 1. Firearms manufacturer Samuel Colt understood this aspect when he said, "there is nothing that cannot be produced by machinery." See Hounshell, *From the American System*, p. 19. For a broader discussion on the generic applicability of machine tools during this period, see Robert S. Woodbury, *History of the Milling Machine* (Cambridge, MA: MIT Press, 1960).

Footnote 104. Rosenberg has stressed that "[m]etal-using industries... were continually being confronted with similar kinds of problems which required solution and which, once solved, took their place in short order in the production of other metal-using products employing similar processes." See Rosenberg, *Perspective on Technology*, p. 18. See also Hounshell, *From the American System*, pp. 218-223, 227.

Footnote 105. See also Richard Nelson and Sydney Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Belknap Press, 1982), pp. 259-261. Orville and Wilbur Wright themselves had a shop where they manufactured bicycles. Anderson notes on this regard that "the Wright's talent in designing and building bicycles had a nontrivial impact on their later flying machine work." Anderson, *The Airplane*, p. 83.

Footnote 106. See also Hounshell, *From the American System*. Consider that just before World War I, with the purchase of a "troubled electrical machinery producer," the Thyssen Machine Company entered the heavy electric dynamos and in the span of few years went on to challenge the leadership of Siemens-Schukert's." See Fear, "August Thyssen and German Steel," p. 208.

Footnote 107. See also Peter Botticelli, "Rolls-Royce and the Rise of High-Technology Industry," in McCraw (ed.), *Creating*, pp. 102-105; Pascal Danjou, *Renault FT* (Paris, France: Editions du Barbotin, 2009), p. 6; and George C. Larson "The Wasp Engine's Great Leap Forward: The Only Aircraft Engine to be Designated an Historic Landmark, *Air & Space Magazine* (December 2017). This does mean that using expertise or facilities from the commercial sector was always easy. See for example David A. Hounshell, "Ford Eagle Boats and Mass Production during World War I," in Merritt Roe Smith (ed.), *Military Enterprise and Technological Change: Perspective on the American Experience* (Cambridge, MA: MIT Press, 1985), pp. 175-202.

Footnote 108. Similarly, advances in aircraft design in the 1930s resulting from wind tunnel testing and analysis proved to be helpful both for military and commercial aviation. See David C. Mowery and Nathan Rosenberg, "Technical Change in the Commercial Aircraft Industry," in David C. Mowery and Nathan Rosenberg (eds.), *Inside the Black Box: Technology and Economics: 1925-1975* (Cambridge: Cambridge University Press, 1982), pp. 163-177.

Footnote 109. See also Richard Overy, *Why The Allies Won* (New York, Norton & Co., 1996), chapter 6.

Footnote 110. This does not mean that using industrial facilities of the commercial sector was always easy. For example, the tolerances of aircraft engines were much smaller than machine tools for commercial production could yield, which in turn required significant adaptation. See for example Tom Lilley et al., *Problems of Accelerating Aircraft Production during World War II* (Boston: Division of Research, Harvard Business School, January 30, 1946), pp. 52-56. See also Alic "Managing", p. 13.

Footnote 112. See also Iansiti, *Technology Integration;* Sapolsky, "Inventing;" Johnson, "Systems Integration."

Footnote 113. See also Mowery, "Military R&D and Innovation," pp. 1220-1256. For a more general discussion, see Alic et al. *Beyond Spinoff.* For a discussion on complexity and specificity, see also Brusoni and Prencipe, "Unpacking the Black Box of Modularity," p. 203.

Footnote 115. During a 2002 exercise in Oman, the British main battle tank *Challenger II*, for instance, experienced clogging in its filters that ultimately led to a ground halt because of the peculiar characteristics of the fine dust sand. American main tank M1a1 *Abrams* were too heavy for most bridges in Albania on the eve of the Kosovo war while U.S. infantry vehicles like the IAV *Striker* were too vulnerable to land mines during the 2003 Iraq War. See respectively National Audit Office, "Ministry of Defence, Exercise Saif Sareea II," *Report by the Comptroller and Auditor General, HC 1097 Session 2001-2002* (London: The Stationery Office, 2002), p. 16; Alan Vick et al., *The Stryker Bridgade Combat Team: Rethiking Strategic Responsiveness and Assessing Deployment Options* (Santa Monica, CA: RAND Corporation, 2002), p. 120; Terrence Kelly et al., *The U.S. Combat and Tactical Wheeled Vehicle Fleets Issues and Suggestions for Congress* (Santa Monica, CA: RAND Corporation, 2011), pp. 52-54. As Alic and co-authors explain, "the craft experience or tacit know-how acquired in military projects is a poor guide for making design choices in commercial projects even when the purely technical knowledge involved is similar." See Alic, et al., *Beyond Spinoff*, p. 33.

Footnote 116. For an application of this distinction between the capacity to acquire and assimilate information and the capacity to transform and exploit it, see Tai Ming Cheung, "The Chinese Defense Economy's Long March from Imitation to Innovation," *Journal of Strategic Studies,* Vol. 34, No. 3 (June 2011), pp. 325–54, doi: 10.1080/01402390.2011.574976; and Jon Lindsay and Tai Ming Cheung, "From Exploitation to Innovation: Acquisition, Absorption, and Application," in Lindsay et al. (eds.), *China and Cybersecurity*, pp. 51-86.

Footnote 118. Conversely, as Nelson and Wright have pointed out that "American dominance of the frontiers of military technology… buys us little outside the military sphere." See Nelson and Wright, "The Rise and Fall," p. 1959-1960.

Footnote 119. These are Computational Fluid Dynamics Code Development and Turbulence Modeling. Other skills "require at least a master's degree and ten years of experience to develop." This is the case for "Computational Structural, Mechanics Engineering, Software Development and Maintenance, Computational Hull Design and Analysis, Computational Shock Analysis, Computational Structural Acoustics." As for others technical competences, “nearly 40 percent require at least five years of experience to develop. Other competencies take more than ten years of experience to develop or more than a bachelor’s degree—10 percent require both.” John F. Schank et al., *Sustaining U.S. Nuclear Submarine Design Capabilities*, pp. 92-94.

Footnote 120. See also Rosenberg and Mowery, *Technology*, pp. 58, 80-82; Partha Dasgupta and Paul A. David, “Information Disclosure and the Economics of Science and Technology,” in George R. Feiwel, *Arrow and the Ascent of Modern Economic Theory* (New York, NY: New York University Press, 1987), pp. 519-542. According to Mowery and Rosenberg, the increasing complexity of the activities undertaken by in-house laboratories has led the research and development to become “highly specific to a given form or [even] production process and cannot by produced by an organization not engaged in both production and research.” Mowery and Rosenberg, *Technology*, pp. 81-82. Practical examples are the McKinley Climatic Laboratory (Elgin Air Force Base), the Nevada Test and Training Range (Nellis Air Force Base) and the Avionics Laboratory (Wright- Patterson Air Force). See for example William F. Bahret, “The Beginnings of Stealth Technology,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 29, No 4 (October 1993), pp. 1377-1385.

Footnote 122. Dombrowski and Gholz’s book was published only in 2006, shortly after the LCS was launched. However, over the next decade, the program has observed an incredible amount of problems that seem to go beyond the normal “teething troubles” of weapons manufacturing. See for instance Government Accounting Office, *Littoral Combat Ship: Navy Complied with Regulations in Accepting Two Lead Ships, but Quality Problems Persisted after Delivery* (Washington, DC: Government Accounting Office, September 25, 2014).

Footnote 123. The case of the *Concorde*, the British-French turbojet powered passenger aircraft that could fly at Mach 2, is illuminating in this regard. While military platforms generally differ from commercial ones in several dimensions, the *Concorde* differed from other commercial airliners in only one, speed. Yet, this 1970s aircraft still posed tremendous problems for the Soviet aircraft industry: “Soviet technology or metallurgy was not up to the job of interpreting or reconstructing Western technology… The best that the USSR could produce… could not match the West’s skill in refinement, creature comforts, or applied electronics.” Moon, *Soviet SST*, pp. 5-6.

Footnote 125. As Brown continues: "… we couldn't allow even the tiniest imperfection in the fit of the landing gear door, for example, that could triple the airplane's radar cross section if it wasn't perfectly flush with the body… We were well aware that what we were doing was outside the scope of normal engineering experience. We were dealing with radar cross section lower by *thousands* not *hundreds* of order of magnitude." Alan Brown in Rich and Janos, *Skunk Works*, p. 81. Another program manager of the stealth project, Sherm Mullin, corroborates this description: "[t]he structure of the stealth fighter required mechanical tolerances way beyond those of any conventional military or commercial airplane. For example, in a commercial airplane if the skin is not exact, let's say here and there it is out by maybe ¼ inch in a 150-foot wingspan, that does not cause any particular problem." Quoted in Alfred Price, *War In The Fourth Dimension* (London, UK: Greenhill Books, 2001), p. 197.

Footnote 129. See also Robert W. Hunter with Lynn Dean Hunter, *Spy Hunter: Inside the FBI Investigation of the Walker Espionage Case* (Annapolis, Md.: Naval Institute Press, 1999), p. 203.

Footnote 131. The proper name of computer-controlled milling machines is numerical control (NC) milling machines or computer numerical control (CNC) milling machines. The rotation of the propeller creates bubbles. Their collapse generates noise. This phenomenon is called cavitation. Cavitation, intuitively, if a function of speed and depth; it occurs only within the first layer of the ocean. See Friedman, *Submarine Design and Development*, 82; Donald C. Daniel, *Anti-Submarine Warfare and Superpower Strategic Stability* (Chicago, IL: University of Illinois Press, 1986), 28-34; and Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington, MA: Lexington Books, 1987), 8-15.

Footnote 132. As technology matures, its underlying engineering and scientific principles tend to be understood more broadly and hence to diffuse.

Footnote 134. See also Loftin, *Quest for Performance*, p. 7.

Footnote 135. As Hacker explains, "[t]he paradox of military-technological change in the decades before the First World War can be stated simply: Sources of change remained chiefly empirical, but rates of change continued to accelerate. Vast as the accumulation of technical knowledge had become, it remained normally the product of hit-or-miss accident by craftsmen or tinkerers, laboriously augmented over many years, unevenly developed, and slow to spread." See Hacker, "The Machines of War," p. 257.

Footnote 136. It is important to stress that non-codified know-how has always existed. See for example Nathan Rosenberg, "Economic Development and the Transfer of Technology," *Technology and Culture,* Vol. 11, No. 4 (October 1970), pp. 550–575, doi: 10.2307/3102691.

Footnote 138. During the war, three American *B-29 Superfortress* emergency-landed on Soviet soil. The Soviets disassembled one *Superfortress* in order observe, analyze and copy "rivet-by-rivet" its components, while using the other two respectively as a model and for testing. The B-29 was an extraordinary aircraft in terms of performance. Yet, as Soviet aircraft designer Anatoly Tupolev noted after inspecting the *B-29:* "[t]his is a normal aircraft, I see nothing unusual in it." Gordon and Rigmant, *Tupolev Tu-4:*, Tu-4, p. 17. In fact, within two to four years the Soviets had their own heavy long-range bomber, the Tupolev Tu-4.

Footnote 139. See also Alexandra M. de Pleijt and Jacob L. Weisdorf, "Human Capital Formation From Occupations: The 'Deskilling Hypothesis' Revisited," *Centre for Global Economic History Working Paper* no. 14 (June 2014).

Footnote 140. See also Hounshell, *From the American System*, pp. 251-256 and Ruttan, *Is War Necessary*, p. 22.

Footnote 141. It is important to stress that during this period, it was possible to gather and codify the "complete knowledge" of the various tasks. Zuboff, *In the Age*, p. 44. See also Robin Cowan and Dominique Foray, "The Economics of Codification and the Diffusion of Knowledge," *Industrial and Corporate Change* Vol. 6, No. 3 (September 1997), pp. 595–622.

Footnote 144. See also Daniel Ross, James P. Womack, Daniel T. Jones, *The Machine That Changed the World: The Story of Lean Production* (New York, NY: Harper Perennial, 1991), p. 43.

Footnote 145. "Until the late nineteenth and early twentieth century, many sectors were in fact largely practical as the "technologist typically 'got there first'." Rosenberg and Mowery, *Technology*, p. 33. See also Ruttan, *Is War Necessary*, p. 44; and Anderson, *The Airplane*, pp. 298-308. As Mokyr has explained, "… in the past hundred and fifty years the majority of important inventions, from steel converters to cancer chemotherapy, from food canning to aspartane, have been used long before people understood why they worked, and thus systematic research in these areas was limited to ordered trial-and-error operations." Moreover, he continued, "… much technological progress in the years between 1830 and 1914 took the form of novel applications and refinements of existing knowledge." See

Mokyr, *Twenty-five Centuries*, p. 76, 84. See also Smil, *Creating the Twentieth Century*. In the case of submarines, for example, the principles of buoyancy had been known since Archimedes (250 B.C.) – it is called in fact Archimedes' principle. See Friedman, *Submarine Design and Development*, p. 17. Similarly, the working of internal combustion engines draws form the second law of thermodynamics, whose origin had been known since 1824 (the Carnot's Principle). See Mokyr, "The Contribution," p. 27. In an analogous way, some of the principles behind flying have been known for a long time: the observation of lift and drag can be dated back to Leonardo Da Vinci's work in 1513, and the velocity-squared law stem from the independent works of Edme Mariotte, Christian Huygens and Isaac Newton in the period 1673-1690. Even the transonic drag rise described in footnote 67 above "was first observed in the 18th century," long before transonic flight was could fathomed. See Anderson, *The Airplane*, pp. 12, 22-23. See also Anderson's discussion on the separation between practitioners and scientists throughout history and the subsequent convergence in the XX century, see pp. 6-8, 171, 175-176, 212, 240, 245, 267. On how these developments affected the aircraft industry, see Almarin Phillips, *Technology and Market Structure: A Study of the Aircraft Industry* (Lexington, VA: Lexington Books, 1971), chapter 5, 6 and 7.

Footnote 146. See also Nelson and Wright, "The Rise and Fall," p. 1958-1959.

Footnote 147. See also Harry M. Collins, "The TEA Set: Tacit Knowledge and Scientific Networks," *Science Studies,* Vol. 4, No. 2 (April 1974), p. 167, https://www.jstor.org/stable/284473; and also Ravi Patnayakuni and Cyntia P. Ruppel, "Managing the Complementarity of Knowledge Integration and Process Formalization for Systems Development Performance," *Journal of the Association for Information Systems*, Vol. 7, No. 8 (August 2006), pp. 545 –567, doi: 10.17705/1jais.00097.

Footnote 148. See also Kenneth J. Arrow, "Classificatory Notes on the Production and Transmission of Technological Knowledge," *American Economic Review*, Vol. 59, No. 2 (May 1969), pp.29–35, https://www.jstor.org/stable/1823650; Eric von Hippel, "Sticky Information' and The Locus of Problem Solving: Implications for Innovation," *Management Science,* Vol. 40, No. 4 (April 1994), pp. 429-439, doi: 10.1287/mnsc.40.4.429; Pavit, "Specialization and Systems Integration;" Edward W. Steinmueller, "The Role of Technical Standards in Coordinating the Division of Labor in Complex Systems Industries," in Prencipe, Davies and Hobday (eds.), *The Business of Systems Integration*, pp. 113-151.

Footnote 149. See also Polanyi, *Personal Knowledge*, p. 53.

Footnote 150. A particularly illustrative example is the failure of replicating the Transversely Excited Atmospheric Pressure CO2 laser – more commonly known as TEA laser by North American and British military research centers and universities laboratories that had full access to the published research of the innovators. The obstacle they found was the lack of access to the innovators' tacit knowledge. See Collins, "The TEA Set," pp. 165-185. See also Dany Bahar, Ricardo Hausmann and Cesar Hidalgo, "Neighbors and the Evolution of the Comparative Advantage of Nations: Evidence of International Knowledge Diffusion?" *CID Working Paper No. 235* (July 2013). As Dosi and Nelson have put it, "[t]he bottom line is that even when there is... an informationally codifiable template, the actual process of reproduction involves significant efforts, costs, and degrees of uncertainty about the ultimate success." See Giovanni Dosi and Richard R. Nelson, "Technical Change and Industrial Dynamics as Evolutionary Processes," Bronwyn H. Hall and Nathan Rosenberg (eds.), *Handbook of the Economics of Innovation Volume 2* (New York, NY: Elsevier, 2010), p. 58.

Footnote 151. As Cohen and Levin point out, for some highly complex civilian products like turbofan engines or commercial airliners, imitation and reverse engineering are in fact extremely difficult and, according to some, not even feasible.

Footnote 153. See also Royce, "Current Problems", p. 5. This means that imitators will have to write those million lines of code we have discussed earlier and adapt it to the military platform and to its idiosyncratic requirements, as well as to each of its systems (engines, radar, etc.) and to each of its subsystems (missiles, hydraulic system, etc.) until they work perfectly. In contrast to laptops, a software crash, a freeze, or even a simple malfunctioning can be fatal for jet fighters. On the specificity of the software to the aircraft, Tomayko explains that "[t]he computer uses control laws specific to an aircraft to calculate the commands necessary to maintain stability and implement pilot desires. Control laws are the equations of motion that have to be solved to actively control an unstable aircraft. The values for these equations are specific to each aircraft design. That is why control laws embodied in electronic analog circuits make those circuits unusable in any other aircraft." Tomayko, *Computers Take Flight*, p. 25. With regard to the inherent difficulties of modifying software, Tomayko explains that "[s]oftware's flexibility is a bane as well as an advantage. It is too easy to change and very difficult to change correctly: fifty percent of all software modifications, including defect repairs, result in new defects." Tomayko, *Computers Take Flight*, p. 30. The problem with copying electronics emerged when this field was already in its infancy. As Tupolev noted when inspecting the *Superfortress*, which we discussed in fn. 138, "I cannot imagine how you will sort out all this tangle of wiring covering all of the machine, how you will ensure the linkage between the numerous sights and the weapons' remote control system, how you will tackle the control and navigation system." Gordon and Rigmant, *Tupolev Tu-4*, p. 17. Similarly, in the 1980s, it took Moscow longer to reverse engineer the IBM 360 than it took IBM to develop it *ex novo*. See Aaron L. Friedberg, "The United States and the Cold War Arms Race," in Odd Arne Westad (ed.), *Reviewing the Cold War* (London: Frank Cass, 2000), p. 230-231, fn. 58. The impossibility of observing and understanding the functioning of a military platform reflects a fundamental transition: the technological knowledge of how to design, develop, and produce a given weapon system cannot be separated from the very people who contributed to it. An advanced American drone, the RQ-170 *Sentinel*, was grounded in Iran in 2011. While Iran claimed it successfully reverse-engineered it, its replica seems a plastic mockup with no real engineering or electronics behind. See Dave Majumdar, "Iranian Copy of U.S. Unmanned Stealth Aircraft is a Fake," *USNI News* (May 12, 2014). On the challenges of imitating drones, see Gilli and Gilli, "The Diffusion." In February 2018, Israel shot down the alleged "knockoff" of the U.S. *Sentinel.* The Iranian drones is clearly not stealthy, as according to Israeli officers "[Israel maintained persistent intelligence of the drone as it took off from the Palmyra area of Syria, made its way through northern Jordan and entered Israeli airspace." Moreover, it is not powered by jet engines, as "from the video released by the Israel Defense Forces, you don't see any trails of hot air typical of jet-powered vehicles." Barbara Opall-Rome, "Israel Air Force Says Seized Iranian Drone is a Knockoff of US Sentinel," *Defense News* (February 12, 2018).

Footnote 154. See also Henderson and Clark, "Architectural Innovations," p. 28.

Footnote 155. For a discussion on how complexity and the resulting technological uncertainty affect written and oral communications, see for example Thomas E. Pinelli et al., "Technical Uncertainty and Project Complexity as Correlates of Information Use by U.S Industry-Affiliated Aerospace Engineers and Scientists: Results of An Exploratory

Investigation," *NASA Technical memorandum* 107693 (Bloomington, IN: Indiana University, 1993).

Footnote 156. See also Gholz, "Systems Integration for Complex Defense Projects", p. 53. This is particularly the case for weapon systems integration. This is why military officers are directly involved in the design and development processes. See Dombrowski and Gholz, *Buying*, pp. 44.

Footnote 157. Gholz, "Systems Integration for Complex Defense Projects", p. 52-53. As Gholz notes, "[p]eople involved in actual making things have a certain feel for the limits of their capabilities, for what changes will be easy and what will cost a fortune, and for the effects of unpredicted or unexplained interactions within a system."

Footnote 158. In this regard, Spinardi and co-authors have documented the problems that inter-firm exchange of electronic data posed in the case of the European cooperation project for the *Eurofighter Typhoon*. As they summarize, "standardisation of data form is not sufficient to enable the exchange of complex design data. Harmonization of the companies' working practices is also necessary." Spinardi, Williams and Graham, "Technical Data Interchange in the Eurofighter Project," p. 29. The designs and blueprints of the *Concord* that the Soviets obtained thorough industrial espionage "were [in fact] often indecipherable or not easily understood." Moon, *Soviet SST*, p. 5. Similarly, the Soviets experienced problems with understanding the instruction manuals of the B-29 *Superfortress*, given the use of slang. See Yefim Gordon and Vladimir Rigmant, *Tupolev Tu- 16 Badger: Versatile Soviet Long-Range Bomber* (Hersham, UK: Allan Printing Ltd. 2004), pp. 20-21.

Footnote 160. Henderson in this regard has shown that the "linear theory of innovation that projects a straightforward process from idea, to drawing, to prototype, to production [is] seriously misguided." Henderson, "Flexible Sketches and Inflexible Data Bases," pp. 449-450. See also Vincenti, *What Engineers Know*; Sheila Jasanoff (ed.) *States of Knowledge: The Co-Production of Science and Social Order* (New York, NY: Routledge, 2004); Nelson and Winter, *An Evolutionary*, chapter 4; Kirk Monteverde, "Technical Dialog as an Incentive for Vertical Integration in the Semiconductor Sector," *Management Science* vol. 41, n. 10 (1995), pp. 1624-1638; and Edward W. Steinmueller, "The European Software Sectoral System of Innovation," in Franco Malerba (ed.), *Sectoral Systems of Innovation: Concepts, Issues and Analyses of Six Major Sectors in Europe* (New York, Cambridge University Press, 2004), pp. 193-242.

Footnote 161. Mowery and Rosenberg note in fact that "the production and acquisition of detailed technical knowledge… are frequently joint activities." Mowery and Rosenberg, *Technology*, pp. 81-82. See also Wiebe Bijker, Thomas P. Hughes, Trevor Pinch (eds.), *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, Mass: The MIT Press, 1987). In order to retain experience, at times, countries decide to launch defense projects even though they know they will not be able to develop state-of-the-art technology. The case of a recently developed Japanese fighter demonstrator (the Mitsubishi Heavy Industry *X-2*) is informative. Japan is currently considering the development of an indigenous stealth fighter. Its demonstrator program "has [already] accomplished something important for the prospective fighter program…It has given engineers who worked on the F-2 [a Japanese fighter program from the early 1990s] a chance to pass on skills before retirement." Bradley Perret, "Japan's Ideal Fighter Would Have To Be Indigenous," *Aviation Week & Space Technologies* (October 14, 2016).

Footnote 162. This problem is particularly acute with regard to software engineering. Software development generally takes places over several years, and is then further upgraded over the course of its use. However, records of how the early software was developed are "often cryptic[…], never complete[…]." In fact, "[l]arge aerospace software systems […] commonly […] struggle with bad or missing documentation." See Royce, "Current Problems", p. 12. "Software documentation can be a contentious issue—it's hard to write and hard to keep current and accurate." Doe, "Current Practices," p. 28; see also p. 93. See also Tomayko, *Computers*, p. 40.

Footnote 163. In a large jet aircraft, for example, there are about 2 to 3 million fasteners. A minor variation in their density, by affecting the total weight of the system, can ultimately "shift the gravity center of the system, change the resonance frequency of the system, and induce undesirable vibration during operation that might even lead to premature failure." Wang, *Reverse Engineering*, pp. 266-268. Similarly, consider the problems of altitude for military aircraft. The U2 *Dragon Lady* was intended to operate above 70,000ft, higher than the range of Soviet anti-air defense systems of that time. However, during testing, seals of the engine valves and of the cockpit experienced unexpected oxidation. Later it was realized that rubber oxidizes when exposed to ozone, which the troposphere where the U2 was flying is laden of. While the solution was eventually (and incidentally) found, the problem was serious as it endangered both the survival of the pilot and the working of the engine (and hence the reliability of the very U2). See Rich and Yanos, *Skunk Works*, p. 138. This problem is particularly serious when it comes to software engineering: "when software fails, it invariably fails catastrophically." See Royce, "Current Problems", p. 11.

Footnote 164. As Lindsay and Cheung have noted, "the 'live' portion of data on an organization's network—current, valid, meaningful, revisited, operational data—is usually small compared to the amount of data stored. Old versions of documents, working drafts, discarded plans, and normal data errors abound on corporate servers. This mess essentially functions as disinformation for the naïve spy who collects it. Understanding which bits are meaningful requires participation in meetings, ongoing conversations, laboratory interactions, and other embodied moments in the life of an organization." This is consistent with Kristie Macrakis's account of Eastern German espionage, in that, as she concluded: "The amount of material gathered […] was overwhelming." See Kristie Macrakis, "Does Effective Espionage Lead to Success in Science and Technology? Lessons from the East German Ministry for State Security," *Intelligence and National Security* Vol. 19, n. 1 (2004), p. 73.

Footnote 165. The W76 is a nuclear payload that sits atop the Trident II missiles carried by America's *Ohio*-class submarines. As such, it represents an important part of the country's nuclear arsenal. The refurbishment of the aging W76s has taken much longer than was originally anticipated because once the engineers cracked open the old warheads they encountered a substance codenamed 'Fogbank.' And they had no idea how to replicate it." We would like to thank Austin Long for having pointed to us the case of Fogbanks, which we did not know. This problem applies more broadly to the replication of materials. The properties of a given material (such as strength, malleability, creep, ductility) depend on its chemical structure. Its chemical structure, in turn, is a function of the production process. Extremely small and subtle variations in the production process are sufficient to alter the chemical structure of a given material, and, therefore, of is properties (by small and subtle, we mean differences in temperature, time, electro-magnetic field, etc. of the production process). While modern laboratory technologies permit to identify the chemical composition of a material, they will not be sufficient for reverse engineering it: without detailed knowledge about the production process that delivers a specific material, one will not be able to develop an exact copy. As Wang puts it, "reverse engineering does not duplicate an identical twin to the original part because it is technically impossible." Wang, *Reverse Engineering*, p. 13. See also the discussion on page 12. We would like to thank Claudia Santini for having made us better appreciate the importance of process engineering.

Footnote 169. See also Nelson and Wright, "The Rise and Fall of Technological Leadership," p. 1950.

Footnote 173. As Alic adds: "The people who designed steam engines, tableware or bicycle also supervised their manufacture. A singe person could, in principle, design a product and build it – or design a product and specify the production methods for others to follow, perhaps even design the rolling mills, forging hammers, and machine tools needed. Design and manufacturing could be linked in one person's head." Nikolas Tesla's own words about his approach to inventions are quite illuminating: "I do not rush into constructive work. When I get an idea, I start right away *to buil it up in my mind*. I change the structure, I make improvements, I experiment, I run the device in my mind. It is absolutely the same to me whether I operate my turbine in thought or test it actually in my shop. It makes no difference, the results are the same. In this way… I can rapidly develop and perfect an invention, without touching anything." Quoted in W. Bernard Carlson, *Tesla: Inventor of the Electrical Age* (Princeton, NJ: Princeton University Press, 2013), p. 9. Similarly, consider that Thomas Edison wrote his investigation of incandescent lighting in a single page. See Tell, "Integrating," p. 60. Consider also that in 1908, the specifications for the purchase of the Wright Military Flyer was one-page long. See Anderson, *The Airplane*, p. 185.

Footnote 174. Two examples from the military realm are Robert Whitehead, the British inventor of the self-propelled torpedo, and John Holland, the Irish inventor of the modern submarine. Whitehead migrated to the Austro-Hungarian Empire and Holland to the United States, taking with them their knowledge of underwater munitions and submarines, respectively. Edwyn Gray, *The Devil's Device: Robert Whitehead and the History of the Torpedo* (Annapolis, MD: Naval Institute Press, 1991); Richard Knowles Morris, *John. P. Holland, 1841-1914: The Inventor of the Modern Submarine* (Columbia, SC: University of South Caroline Press, 1988). Another prominent case is that "aerodynamics [which] may be said to have come to America in the person of Theodor von Karman", in the words of Mowery and Rosenberg. David C. Mowery and Nathan Rosenberg, *Paths of Innovation: Technological Change* *in 20th Century America* (New York, NY: Cambridge University Press, 1998), p. 64. See also Paul A. Hanle, *Bringing Aerodynamics to America* (Cambridge, MA: MIT Press, 1982).

Footnote 175. He adds "With technologies growing more complicated, and production volumes expanding, the scope of operations exceeded the grasp of any one person. Specialized groups designed and developed the product – be it an automobilie, a sewing machine, a camera. Other specialists laid out the factories, specified manufacturing processes, supervised production employees. Integration of design and production became a collective responsibility rather than an individual task. Hierarchy followed." Alic, "Computer-Assisted Everything?", p. 364.

Footnote 177. In the second half of the 1930s "Bush [himself] conceded that the individual inventor's power had ebbed." In "[Bush's] youth, the lone inventor – eccentric, ingenious, part tinkerer and part entrepreneur – set the pace for American technology. Eight of ten U.S. patents were granted to individuals at the turn of the century. Edison was the archetype of these innovations. By the eve of the Depression, however, the lone inventor was fading into myth. In his place stood the colorless industrial laboratory, the new locus of invention." Zachary, *Endless Frontier*, p. 17. See also Schumpeter, *Capitalism, Socialism and Democracy*, pp. 133-134.

Footnote 178. Johnson is "one of the most honored and highly successful aeronautical engineers, designers, and builders of his or any other time [a] fact that is only partially documented by some fifty awards and honors." Leo P. Geary, "Foreword" in Kelly, p. viii. Rich described Johnson as follows: "I had never known anyone so expert at every aspect of airplane design and building. He was a great structures man, a great designer, a great aerodynamicist, a great weights man. Rich and Yanos, *Skunk Works*, p. 129.

Footnote 181. After seeing the sketch of the F-117, Johnson entered the office of Ben Rich, which recalled: "Kelly kicked me in the butt – hard too. Then he crumpled up the stealth proposal and threw it at my feet. 'Ben Rich, you dumb shit,' he stormed, 'have you lost your goddam mind? This crap will never get off the ground,'" hinting at the unusual shape of the aircraft – not intended to maximize its aerodynamics but its stealth. Johnson also thought that a previous aircraft by Skunk Works had a lower radar cross section than future F-117 would have. Rich and Yanos, *Skunk Works*, p. 32.

Footnote 184. The software of the F-117 was an adaptation of the software of the F-16, which in turn drew extensively from the software developed for the F-8, itself a derivative (for about 60%) from the Apollo program. Tomayko explains that "getting all the numbers right was a learning experience. The software developers [of the F-8 software] were limited to fixed decimal point arithmetic, which required scaling by hand to achieve the greatest accuracy, again by some trial and error." See pp. 43, 53-54. On the importance of single individuals, as Vincenti explains, "For every Kelly Johnson […] there are thousands of useful and productive engineers designing from combinations of off-the-shelf technologies that are then tested, adjusted, and refined until they work satisfactorily." See Vincenti, *What Engineers Know*, p. 8. Harry Hillaker himself admitted that while flattered by his title "the "Father of the F-16", "other people can take credit with what happened [with the F-16]. My interest in airplanes is the external shape. I am not interested in what inside, except as it affects the outside shape." Eric Hehs, "Father of the F-16: Hillaker Talks – Interview Part II," *Code One* Vol 6., no. 1 (April 1991), p. 23. There is little reasons to believe that this trend will be reversed any time soon. Consider digital signal processing (DSP), "one of the most powerful technologies that will shape science and engineering in the twenty-first century." As a textbook on the topic summarizes it, "Revolutionary changes have already been made in a broad range of fields: communications, medical imaging, radar & sonar, high fidelity music reproduction, and oil prospecting, to name just a few. Each of these areas has developed a deep DSP technology, with its own algorithms, mathematics, and specialized techniques." Consistent with the theory we develop in this article, "[t]his combination of breath and depth makes it impossible for any one individual to master all of the DSP technology that has been developed." Steven W. Smith, *The Scientist & Engineer's Guide to Digital Signal Processing* (Burlington, MA: Elsevier, 2003), p. 1.

Foonote 185. Roos, Jones and Womack note the difference between the diffusion of mass production and lean production and suggest that "[t]he difference, we must emphasize, is… that [Japanese managers] collectively possess many years of experience and know-how in making lean production work consistently in assembly plants." They add the conclusion of a "senior executive" from a Japanese company who "emphasized in an interview, 'We believe that our production system, with its many nuances, can be learned by anyone… but it takes ten years of practice under expert guidance'." Roos, Jones and Womack, *The Machine That Changed the World*, p. 249, 283-285.

Footnote 186. For example, the development of the XP-80 jet fighter prototype (1940s) required 120 people (of these, 23 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 engineers. Johnson, *Kelly*, pp. 161-162.

Footnote 188. Even in scientific research, there is evidence of these dynamics taking place as illustrated by the systematic increase in co-authorship for academic articles.

Footnote 190. See also Alic, "Managing U.S. Defense Acquisition," pp. 14-16. For a discussion about the limitation of computer-assistance in design, see Kathryn Henderson, "Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering," *Science, Technology, & Human Values* 16, no. 4 (1991), pp. 448-73. For more technical discussions of such limitations, see Randal E. Bryant, et al. "Limitations and Challenges of Computer Aided Design Technology for CMOS VLSI," *Proceedings of the IEEE*, Vol. 89, no. 3 (March 2001), pp. 341-365; and Jeong-Taek Kong, "CAD for Nanometer Silicon Design Challenges and Success," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 12, no. 11 (November 2004), pp. 1132-1147. We would like to thank Pietro Monsurrò for suggesting the last two references. The case of the UK Astute class nuclear ballistic missiles submarine is revealing in this regard. "[T]he first year of the program was beset with problems one of the biggest was the introduction of 3D Computer Aided Design (CAD) software. Although the British at Barrow had used 3D CAD software for the design of some surface ships, these designs did not compare to the complexity of a densely packed nuclear submarine. Previous submarine designs had been produced in 2D by hundreds of draughtsmen; wooden mock-ups were then used to understand the layout of the submarine and the access routes for pipes and cables. The CAD software required extensive modification before it could be used to design a submarine, which was difficult because of the shortage of UK designers with CAD experience. As a result of the delay, physical construction of HMS Astute began with very few complete drawings and those that were produced by the CAD process were to a level of detail with which the shipyard workers were completely unfamiliar." See James Jinks and Peter Hennessy, *The Silent Deep: The Royal Navy Submarine Service Since 1945* (London, UK: Allen Lane, 2015), p. 617. We thank Alexander Lanozska for this reference.

Footnote 192. This is what Alan Turing called "Lady Lovelace's Objection", after Ada Lovelace's understanding of the limits of computing machines. On Lady Lovelace, see Walter Isacsoon, *The Innovators: How a Group of Hackers, Geniuses, and Geeks Created the Digital Revolution* (New York, NY: Simon & Schuster, 2014), pp. 7-33.

Footnote 196. Earlier versions of the F/A-18 experienced "sharp roll" problems because "one wing [would stall] before the other." John Alic, "Technical knowledge, and experimental Learning", p. 434.

Footnote 198. It is important to stress that, allegedly, "computational fluid dynamics (CFD) cuts down on very expensive wind tunnel testing." Alic, "Computer-Assisted Everything?," p. 365. And yet, the prime contractor had to carry out wind tunnel and later in-flight testing "of plausible-seeming alternatives based on experience with other aircraft extensive ground and in flight testing." Alic, "Technical Knowledge and Experiential Learning", p. 434. On how wind tunnels still play a fundamental role, see for example Thierry Dubois, "Wind Tunnels Have Future In Digital Age, Europeans Say," *Aviation Week & Space Technology* (May 11, 2017).

Footnote 199. As Accenture's Paul Daugherty and H. James Wilson note, "AI is giving researchers and product developers a remarkable boost… [enabling them] to mine the data from past tests to uncover new insights and to conduct virtual experiments to test any hypothesis more quickly." However, all this "requires a shift in the employee skills needed." More precisely, and coherently with Alic's words, "employees must become better at conceiving more innovative products." Daugherty and Wilson, *Reimagining Work in the Age of AI*, p. 76. Interestingly, we know that intelligent machines underperform human beings in some tasks, including conceptualization. See Russ Altman *et al.*, "Artificial Intelligence and Life in 2030: One Hundred Year Study on Artificial Intelligence (AI100)," *Report of the 2015 Study Panel* (Stanford, CA: Stanford University, 2016). See also Microsoft, *The Future Computed: Artificial Intelligence and its role in society* (Seattle, WA: Microsoft, 2018); and Agrawal, Gans and Goldfarb, *Prediction Machines.*

Footnote 202. For instance, thanks to both its domestic growth as well to the adoption of the Tresidder-Harvey in the late 19th century, German metallurgy industry could produce high structural strength steel that was particularly appropriate for boilers, turbines, armored plates and long-range guns. Similarly, Germany reached first-class standards in both its electric and chemical industries, whose product were necessary for the production of fire control, communications and propellants. Ssee also Chandler, *Scale and Scope*, pp. 393-597; Sophie-Charlotte Fischer, "Artificial Intelligence: China's High-Tech Ambitions, *CSS-Analyses in Security Policy*, No 220 (February 2018); and Elsa Kania, "Much ado about Huawei," Australian Strategic Policy Institute Blog (27 Mar 2018).

Footnote 209. See also Lawrence Sondhaus, *Preparing for Weltpolitik: German Sea Power Before the Tirpitz Era* (Annapolis, MD: Naval Institute Press, 1997) and in particular pp. 150-226.

Footnote 212. This decision influenced by the performance of U.S aerial and naval platforms in the 1991 Gulf War, as it spurred Chinese strategists' interest in hi-tech military transformation and, in 1998, China adopted a pro-innovation and efficiency-enhancing reform of its defense industrial base. See also John Frankenstein, "China's Defense Industries: A New Course?," in James Mulvenon and Richard H. Yang (eds.), *The People's Liberation Army in the Information Age* (Santa Monica, CA: RAND Corporation, 1999), pp. 187-216; Paul H. B. Godwin, "Compensating for Deficiencies: Doctrinal Evolution in the Chinese People's Liberation Army: 1978-1999, in Mulvenon and Yang (eds.), *Seeking Truth from Facts*, pp. 87-118; Michael Pillsbury (ed.), *Chinese Views of Future Warfare* (Washington, DC: National Defense University Press, 1997); Bates Gilli and Lonnie Henley, *China and the Revolution in Military Affairs* (Carlisle, PA: Strategic Studies Institute, 1996).

Footnote 215. According to Sanders and Wiseman, over "the last 20 years, China has benefited significantly from 'follower's advantage.' Its military aviation industry has accessed the innovations of others via coproduction, espionage, and reverse engineering while making limited developments in genuinely new technology." See Saunders and Wiseman, "Buy, Build, or Steal," p. 48.

Footnote 216. *Dreadnought* was the end-point of the evolution in shipbuilding that had started 50 years earlier with armored wooded, and that had gone through broadside ironclads, casemate ships and finally the pre-dreadnoughts barbette and turret ships. See Brodie and Brodie, *From Crossbow*, p. 162. See also Bernard Brodie, *Sea Power in the Machine Age* (Princeton, NJ: Princeton University Press, 1941), pp. 226-227; and Gardiner, *Steam*, pp. 79-104.

Footnote 216. "[E]ven though it has been officially adopted by the PLAAF," as Dave Mujandar has noted, "[t]he J-20 is still under development." Majumdar, "China's New J-20 Stealth Fighter Has Officially Entered Service."

Footnote 218. See also Paul M. Kennedy, *The Rise of the Anglo-German Antagonism, 1860-1914* (Amherst, NY: Humanity Books, 1980).

Footnote 220. While in the age of sail, solid shots hardly sank warships and were primarily aimed at killing the enemy's onboard crew, with the emergence of explosive shells and steel hulls, single shots could incapacitate, and possibly even directly sink a major warship. See Lawrence Sondhause, *Naval Warfare, 1815-1914* (New York, NY: Routledge, 2001); Tucker, *Handbook*; Brodie, *Sea Power in the Machine Age.*

Footnote 221. See also Norman Friedman, *British Battleships of the Victorian Era* (Annapolis, MD: Naval Institute Press, 2018).

Footnote 223. See also William Hovgaard, *Modern History of Warships: Comprising a Discussion of Present Standpoint and Recent War Experiences* (London: E. & F. Spon, 1920); Friedman, *Fighting,* pp. 189-213; Friedman, *Battleship*, p. 54-83*;* John Roberts, "Warships of Steel: 1879-97", in Gardiner (ed.), *Steam*, pp.95-111; John Roberts, "The Pre-Dreadnought Age 1890-1905, in Gardiner (ed.), 112-133.

Footnote 225. See also Weir, *Building the Kaiser's Navy*, p. 12.

Footnote 226. See also Brown, *Warrior to Dreadnought*, pp. 180-90; and Dodson, *The Kaiser's Battlefleer*, pp. 23-71. This was facilitated by the stabilization of warship designs, following the introduction of the first pre-*Dreadnought* battleship.

Footnote 227. The *Sachsen*-class ironclad, for instance, "displayed flaws," had a "tendency to roll," and were slower than their "preceding armored frigates." Similarly, the pre-*Dreadnought* battleship *Brandenburg*'s guns were "too near the deck and caused blast damage when fired", while "the secondary armament was weak by the standards of the time." Dodson, *The Kaiser's Battlefleet*, p. 25. With respect to the problems of other German pre-*Dreadnought* battleships, see Robert Gardiner (ed.), *Conway's All the World's Fighting Ships, 1860-1905* (New York, NY: Mayflower Books, 1979), p. 247.

Footnote 228. Friedman, *Fighting the Great War at Sea*, pp. 73–101, 195–213; and Weir, *Building the Kaiser's Navy*, pp. 33–34. See also Michelle Murray, "Identity, Insecurity, and Great Power Politics: The Tragedy of German Naval Ambition Before the First World War," *Security Studies* 19, no. 4 (2010): 656-88; and John Asquilla, "A study in Technology Strategy: The Curious Case of Alfred von Tirpitz," *Comparative Strategy* 36, no. 2 (2017): 143-52.

Footnote 230. See also Weir, *Building the Kaiser's Navy*, pp. 33-34, 56.

Footnote 231. See also and Friedman, *Fighting*, pp. 122-23.

Footnote 233. See also Friedman, *Fighting the Great War at Sea*, pp. 104–187.

Footnote 235. See also Friedman, *Fighting*, p. 197.

Footnote 237. Tirpitz did not try to promote a concentration of German companies' investments and thus achieve superior and faster results. Weir, *Building*, p. 29.

Footnote 238. This was due also to Tirpitz's initial opposition to the all-big-gun battleship and to his later repeated attempts to keep down costs and capabilities. Friedman, *Fighting the Great War at Sea*, p. 197.

Footnote 240. At the same time, autonomously from Tirpitz, some German companies started working either on a foreign design (the Swiss Zoelly system) or with foreign partners for the indigenous development of turbines. For example, Allgemeine Electrizitäts Gesellshaft (AEG) partnered with the U.S. Curtiss Company. See Weir, *Building*, pp. 29, 96-98.

Footnote 241. The 1911 *König Albert* battleship of the *Kaiser*-class, for instance, incorporated turbines produced by Schichau, a German company, that not only exceed their designed power on trials, but also matched the speed of contemporaries British *Bellerophon*- (1909) and *St Vincent*-class battleships (1910), and even outperformed in horsepower those of the subsequent *Orion*-, *Neptune* and *Colossus*-classes. Parkinson, *Dreadnought*, p. 177. See also Weir, *Building*, pp. 86-91. Gardiner, *Conway's All the World's Fighting Ships, 1860-1905*, p. 242.

Footnote 243. See also Friedman, *Fighting*, pp. 188-213.

Footnote 245. Calber increased from 11 to 15 inches between 1909 and 1916. Data refers to *Nassau*-class and *Bayern*-class respectively. For instance, upon examining World War I equipment, in "1921, US Navy Lt. W R Furlong concluded after an official visit that the lifetime of German guns was about five times that of their US counterparts." Similarly, a "US attaché visiting the British Woolwich Arsenal in 1923 […] was told that [German] gun steel was better than anything the British had – more homogeneous and tougher." Friedman, *Naval Weapons of World War One*, p. 127.

Footnote 246. Krupp engineers introduced in 1895 Krupp-Cemented Plate steel, a process that yielded stronger steel than the Harvey method. Tucker, *Handbook*, p. 214. For a broader discussion, see Wolz, *From Imperial*, p. 104; and John Brooks, *The Battle of Jutland* (Cambridge, UK: Cambridge University Press, 2016), pp. 541-577.

Footnote 247. Friedman, *Fighting*, p. 123. Apparently, von Tirpitz was interested in extending neither the range nor the rate of fire as this permitted him, on the one hand, to anchor his strategy on the employment of torpedoes and, on the other, to keep range of fire in line with visibility in the North Sea, where he expected to encounter the British fleet. Friedman, *Naval Firepower*, p. 158. Before World War I, even the procurement bureaucracy of the Royal Navy "no longer understood what was at issue" in this realm. See Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p.4.

Footnote 250. The Royal Navy entered World War I with an analogic fire-control system, the *Dreyer* based on the *Dumeresq* rangefinder. Recent investigations have shown that the system was outstanding and far ahead than its main competitor, the *Pollen* system. The new German range-finder was a *Dumaresq*-equivalent. Friedman, *Naval Weapons of World War One*, pp. 23–26. See also Pugh, *The Cost of Seapower*, p. 44.

Footnote 253. The British and German systems were based on different design each yielding different advantages. Brooks, *Dreadnought Gunnery and the Battle of Jutland*, p. 218.

Footnote 256. German machinery worked relatively well during the engagement, especially if one considers Germanys' inferior coal that reduced its engines' power and lack of preparation against condeseritis, i.e. "leaks in the condenser tubes through which sea water was pumped to condense the exhaust steam from the turbines." Brooks, *The Battle, p. 473.* Specifically, the "Germans developed effective gunnery equipment and techniques, and they tested individual ship gunnery extensively." Conversely, until 1913, many "officers seem to have had the feeling that their fleet was untested and untrained as a fleet." For example, "the

Germans never seem to have appreciated the problem of command of a large formation," although things were apparently better planned at Jutland. Friedman, *Naval Weapons*, p. 123.

Footnote 263. Brooks further explains that "[e]ach had distinct advantages. The British range plots could easily identify and discount individual anomalous ranges and graphically compare observed and predicted ranges." Conversely, "German stereoscopic range-finders could cope better with partially obscured targets. […] On average their 3-metre instruments, in part due to their better-trained operators, were more accurate and had smaller spreads than the British 9-foot coincidence range-finders. These gave two benefits. First, the German system did not need range plotting to eliminate individual anomalous ranges. Second, it could use a form of range-finder control to follow the range as its rate changed due to an alteration of course. See Brooks, *The Battle*, p. 505. This being said, the Imperial German Navy did not possess some British technology (like a *Dreyer* Table) that, probably, "would have been very helpful" in combat. Friedman, *Naval Weapons*, p. 127.

Footnote 265. See also David J. Lynch, "How the Skunk Works Fielded Stealth," *Air Force Magazine* (November 1992) and Maj Gen Mark Barrett, USAF (Ret.) with Col Mace Carpenter, USAF (Ret.), *Survivability in the Digital Age: The Imperative for Stealth* (Arlington, VA: The Mitchell Institute for Aerospace Studies Air Force Association, 2017) Shape aims at reducing the edges of an aircraft, given that they reflect radar beams. The materials used are "radar absorbing", which further reduce the reflection of radar beams. Other features intended to reduce the observability to radar of an aircraft include internal weapon bays (missiles are stored internally, rather than externally like in previous fighters, as they would add edges to the aircraft), and the shielding of engine nozzle from radar beams. Obviously, stealth technology is intended to reduce also other observable signatures of an aircraft such as visual, contrails, engine smoke and acoustic. The observability to radar is measured through Radar Cross Section (RCS): "a measure of the power reflected back to a radar received from a target." Edward Lovick, JR., *Radar Man: A Personal History of Stealth* (Bloomington, IN: IUniverse, 2010), p. 15, fn. In practical terms, the RCS of target is "the size of a sphere which would reflect the same amount of radar energy as the aircraft […] measured. The RCS in square meters is then the area of a circle of the same diameter as this imaginary sphere." Richardson, *Stealth*, p. 27. For an accessible and very systematic treatment of stealth technology, see the series of articles written by Dan Katz. Dan Katz, "Physics And

Progress Of Low-Frequency Counterstealth Technology," *Aviation Week & Space Technology* (August 25, 2016); Dan Katz, "Measuring Stealth Technology's Performance," *Aviation Week & Space Technology* (June 28, 2016); Dan Katz, "The 'Magic' Behind Radar-Absorbing Materials For Stealthy Aircraft, *Aviation Week & Space Technology* (Oct 28, 2016); Dan Katz, "State Of Counterstealth Technology On Display At Airshow China," *Aviation Week & Space Technology* (Jan 17, 2017); Dan Katz, "The Physics And Techniques Of Infrared Stealth," *Aviation Week & Space Technology* (July 7, 2017); Dan Katz, "Next Steps In Stealth: From Hopeless Diamonds To Cranked Kites," *Aviation Week & Space Technology* (August 1, 2017); Dan Katz "State Of Stealth: Part 7—The Future Of Survivability," *Aviation Week & Space Technology* (Sep 8, 2017).

Footnote 266. For a discussion on the importance of the engines for the J-20, see for example Rick Joe, "China's Stealth Fighter: It's Time to Discuss J-20's Agility Continuing the debate: Is the J-20 agile enough to be an air superiority fighter?" *The Diplomat* (December 07, 2018), https://thediplomat.com/2018/12/chinas-stealth-fighter-its-time-to-discuss-j-20s-agility/. For a discussion of heat emissions and infrared tracking, see Katz, "The Physics And Techniques Of Infrared Stealth."

Footnote 267. Modern weapon systems depend entirely on their onboard computers and software. In the case of the F-22, for instance, the central computer systems is intended to ensure that it sees, shoots and kills an enemy before the latter does. Such "first-look, first-shoot, first kill" capability depends on advanced sensors providing automatic long-range enemy detection, geolocation, high-confidence identification and accurate target tracking. For this to be possible, multiple onboard sensors collect information and this "multisensor information must be fused or correlated into a consistent, valid, integrated track file. This is done automatically by the sensor track fusion algorithms and the 'smart' sensor-tasking algorithms which are tailored to support each [tactical] requirements." Each target track file, "is continually and automatically updated without pilot intervention." Brower, "Lockheed F-22 Raptor."

Footnote 270. See also Medeiros, Cliff, Crane and Mulvenon, *A New Direction for China's Defense Industry*, pp. 1-49; 154-80.

Footnote 273. The list of foreign companies include General Electric, Pratt & Whitney, Snecma (now Safran), Rolls-Royce, Boeing, Airbus, Rockwell Collins, Honeywell International and Eaton Corporations.

Footnote 274. According to Cliff and co-authors, since "many aviation technologies are inherently dual-use," these interactions with foreign firms "are also contributing to China's capability to produce military products." "There is no question, therefore, that foreign involvement in China's aviation manufacturing industry is contributing to the development of China's military aerospace capabilities." Cliff et al., *Ready for Takeoff*, p. 37. An additional strategy China has relied on in order to improve "the performance of [her] military-aviation sector has been to leverage the capabilities of the civilian-aviation sector, such as using the fabrication of components for commercial aircraft to improve China's military-aircraft production capabilities." Medeiros et al., *A New Direction*, p. 177. See also Government Accountability Office (GAO), *Export Controls: Sensitive Machine Tool Exports to China* (Washington, DC: Government Accountability Office, 1996); Government Accountability Office, *Export Control: Sale of Telecommunication Equipment to China* (Washington, DC: Government Accountability Office, 1996).

Footnote 276. Bill Sweetman, "China's J-20 Stealth Fighter Begins Taxi Tests," *Aviation Week & Space Technology* (Jan 3, 2011), pp. 18-19. Allegedly, there have been "at least 30,000 hacking incidents, more than 500 significant intrusions in DoD [Department of Defense] systems, at least 1600 DoD computers penetrated, and more than 600,000 user accounts compromised, in addition to over 300,000 user ID/passwords and 33,000 U.S. Air Force officer records compromised. These hacks, in turn, gave China 50 terabytes of data about the F-35, and other information about U.S. stealth bombers and fighters (the B-2 *Spirit* and the F-22), missile navigation and tracking systems, and possibly also information China has been eager to obtain for long time such as "radar design (the number and types of modules) [and] detailed engine schematics (methods for cooling gases, leading and trailing edge treatments, and aft deck heating contour maps)."Franz-Stefan Gady, "New Snowden Documents Reveal Chinese Behind F-35 Hack," *The Diplomat* (January 27, 2015).

Footnote 277. See also Larry M. Wortzel, "Hearing on Enforcement of Federal Espionage Laws," *Testimony before the Subcommittee on Crime, Terrorism, and Homeland Security of the House Committee on the Judiciary* (U.S. House of Representatives, January 29, 2008); and Carl Roper, *Trade Secret Theft, Industrial Espionage, and the China Threat* (London, UK: CRC Press, 2013), Appendix C; Michael Brown and Pavneet Singh, *China's Technology Transfer Strategy: How Chinese Investments in Emerging Technology Enable A Strategic Competitor to Access the Crown Jewels of U.S. Innovation Updated with 2016 and 2017 Data* (Washington, DC: Defense Innovation Unit Experimental (DIUx), January 2018); John Hemmings, "It's not Just Rolls-Royce: China is Stealing Every Technology That Isn't Nailed Down," *The Daily Telegraph* (June 16, 2018); Ellen Nakashima, "In A First, A Chinese Spy is Extradited to the U.S. After Stealing Technology Secrets, Justice Dept. Says," *The Washington Post* (October 10, 2018).

Footnote 278. See also David A. Fulghum and Robert Wall, "Russians Admit Testing F-117 Lost in Yugoslavia," *Aviation Week & Space Technology* (October 8, 2001), pp. 80-81. The article cited in the footnote can be found at: https://www.telegraph.co.uk/news/worldnews/asia/china/8277090/Chinas-stealth-aghter-based-on-US-technology.html.

Footnote 279. See also Larry M. Wortzel, *China's Military Potential* (Carlisle, PA, Strategic Studies Institute, 1998); Wendy Frieman, "Arms Procurement in China: Poorly Understood Processes and Unclear Results," in Eric Arnett (ed.), *Military Capacity and the Risk of War: China, India, Pakistan, and Iran* (Oxford: Oxford University Press, 1997).

Footnote 280. In the "1970s, the Xi'an Aeroengine Grop received a licence from Rolls-Royce to manufacture the Spey Mk 202 turbofan engine. However, until very recently, Chinese manufacturers were unable to produce satisfactory examples of this type of engine." Medeiros, *A New Direction*, p. 170.

Footnote 281. The Chinese program at that time was the F-10, now called J-10 program, and was a derivative of the Israeli *Lavi* – in turn, a derivative of the U.S. F-16 Fighting Falcon. Allen, Krumel and Pollack, *China's Air Force*, p. 155; Government Accountability Office (GAO), *Export Controls: Sensitive Machine Tool Exports to China* (Washington, DC: Government Accountability Office, 1996); Government Accountability Office, *Export Control: Sale of Telecommunication Equipment to China* (Washington, DC: Government Accountability Office, 1996).

Footnote 286. According to some sources, China bought the design of the MiG 1.44 Fighter from Russia, which in turn can be detected in some external features of the J-20. See John Reed, "Did The J-20 Come From This MiG?," *Military.Com* (19 Aug 2011).

Footnote 287. The articles cited in the footnote can be found, respectively, at https://www.popsci.com/china-stealth-aghter-new-engine; and https://www.economist.com/china/2018/02/15/china-will-soon-have-air-power-rivalling-the-wests.

Foonote 288. As an anonymous Chinese source admitted six months before the J-20 was officially commissioned, "[t]here are still a series of technical problems that need to be tackled [on the J-20], including the reliability of its […] engines, [the plane's] control system, stealth coat and hull materials and infrared sensor." See Chan, "China's J-20 Stealth Fighter Joins the People's Liberation Army Air Force." Five months after the J-20 entered service, two independent anonymous sources within the Chinese military admitted that rising tensions in the South China Sea pushed China to commission the J-20 ahead of time. Since the initially intended engines still suffer of significant technical problems, the J-20 is powered by older and inferior engines. See Chan, "Why China's First Stealth Fighter Was Rushed Into Service With Inferior Engines." The two articles cited in the footnote can be found, respectively, at https://www.scmp.com/news/china/article/2077732/ chinas-j-20-stealth-aghter-oies-aghting-forces-says-state-media; and https://www.scmp.com/news/china/diplomacy-defence/article/2130718/ why-chinas-arst-stealth-aghter-was-rushed-service.

Footnote 289. The articles cited in the foonote can be found, respectively, at https://www.businessinsider.com.au/the-similarities-between-the-j-20-heads-up-display-and-that-on-the-f-22-are-striking-2012-6; https://www.popsci.com/chinas-j-20-stealth-fighter-officially-enters-service.

Footnote 290. In discussing the results of their analysis (to date, probably the most rigorous and detailed assessment of the RCS of the J-20), Pelosi and Kopp note that "[t]he aft fuselage, tailbooms, fins/strakes and axi-symmetric nozzles are not compatible with high stealth performance." They conclude that unless non-stealthy features in the rear and in the sides are corrected, the J-20 "could at best deliver robust Very Low Observable performance in the nose aspect angular sector." According to a senior scientist of Lockheed Martin, these problems have a deeper origin as "it's apparent from looking at many pictures of the [J-20] that the [Chinese] designers don't fully understand all the concepts of [stealth]" design. Alex Lockie, "Here's How the F-35 Stacks Up to Russia and China's 5th-Generation Aircraft," *Business Insider* (Feb. 23, 2017). At recent air shows, the J-20 displayed several of the unstealthy features Pelosi and Kopp discussed in their 2011 assessment, including "two ill-fitting access panels on its upper fuselage between the engines." These panels projected "perhaps 1 cm (0.4 in.) from the surrounding structure" thus increasing the RCS of the J-20. The authors explain that these panels "were serrated to disperse radio energy, they looked like permanent features, not some kind of temporary addition." Moreover, "[o]ther features that did not look very stealthy included bulges for lights above and below the wingtips;" and third that the J-20 "has six [additional] aerodynamic surfaces… and their edges are not aligned." Finally, "the engine nozzles remain conventional, not designed to control reflections." Tail booms like those in U.S. stealth aircraft "shield the nozzles from radars beam." Bradley Perrett, Dan Katz and Graham Warwick "J-20 At Zhuhai Shows Unstealthy Features: China Shows Off Two J-20s at the Zhuhai Air Show," *Aviation Week & Space Technology* (Nov 4, 2016), p. 24-25. In September 2017, Engineering Sofrware, Research and Development Inc. (esrd.com) released data allegedly showing the RCS of the J-20 as captured by Taiwanese radars. The military Twitter account Intellipus sarcastically commented that "the J-20's RADAR Cross Section is somewhere North of the Motherships from Independence Day, in reference to the significant reflections – especially in the rear section. See respectively https://twitter.com/alert5/status/903763379814150145 and https://twitter.com/intellipus/status/913411999673016320. Similarly, India claimed that it could easily detect the J-20 in flight. Alex Lockie, "China's J-20 Stealth Jet Has Taken to the Skies — but India Says its Fighters Can Spot It Easily," *Business Insider* (May 29, 2018). Some have wondered whether, in both instances, the Chinese military on purpose augmented artificially the RCS of the J-20 (through a Luneberg lens, for example).

Footnote 291. According to some observers, the unstealthy features of the J-20 on the sides and rear reflect its mission: rather than an-superiority fighter like the F-22, it might be intended as an interceptor (aimed to take down supporting aircraft, like tankers or Airborne Early Warning and Control aircraft) or as an air-to-ground striker (intended to penetrate enemy air defenses, like the F-117). Accordingly, the emphasis is on frontal stealth, while sides and rear have been neglected as less relevant. This view is not supported by facts. Whether this is a strategic choice reflecting Chinese military doctrine or a pragmatic decision resulting from technical difficulties in developing a stealth air-superiority fighter is hard to say. One is obviously left wondering why would China decide to develop a less ambitious fighter than it actually could, given all the information it obtained through industrial and cyber-espionage. An air-superiority fighter like the F-22 can in fact serve also as an interceptor and as an air-to-ground striker. See Bill Sweetman, "J-20 Stealth Fighter Design Balances Speed And Agility," *Aviation Week & Space Technology* (Nov 10, 2014), p. 57. Earlier assessment provided support to the thesis that the J-20 is not an air superiority fighter. However, as of 2017, new size assessments suggest that the J-20 is only slightly larger than the F-22 (10%), and hence it might be in the end an air-superiority fighter. Some have also pointed out that the weapon bay is too small to carry air-to-ground or anti-ship missiles, while others have stressed that its external sensors – as of August 2018 – would permit only air-to-air targeting and forward situational awareness. For a full discussion, see Bradley Perrett, "J-20 Appears At Zhuhai Air Show," *Aerospace Daily & Defense* (Nov 1, 2016); Bill Sweetman, "China Does Stealth: How Far Along is China's J-20?? *Defense Technology International* (Jan 1, 2012); Carlo Kopp and Peter Goon, "Chengdu J-XX [J-20] Stealth Fighter Prototype: A Preliminary Assessment," *Air Power Australia* Technical Report APA-TR-2011-0101. Carlo Kopp and Peter Goon, "The Strategic Impact of China's J-XX [J-20] Stealth Fighter," Air Power Australia Technical Report APA-TR-2011-0101 (January 3, 2011); and Nate Jaros, "Analysis: Chengdu J-20, The Chinese Raptor?," Fighter Sweep (September 24, 2016). For a criticism of the view that the J-20 is intended to serve as an interceptor or air-to-ground striker, see PLA Real Talk, "J-20: Striker or Interceptor" (December 27, 2015), available at: http://plarealtalk.com/2015/12/27/j-20-striker-interceptor/; Tyler Rogoway, "High-Quality Shots Of Unpainted Chinese J-20 Stealth Fighter Offer New Capability Insights," *The Drive* (July 31, 2018), available at http://www.thedrive.com/the-war-zone/22534/high-quality-shots-of-unpainted-chinese-j-20-stealth-fighter-offer-new-capability-insights; and discussions among twitter accounts that provide open source intelligence on Chinese military technology: https://twitter.com/RickJoe_PLART/status/929114543090941952; https://twitter.com/xinfengcao/status/929004663440998400; and finally https://twitter.com/Aviation_Intel/status/1024488061231456262.

Footnote 292. It is important to stress that the degree to which canards affect radar cross section is not settled. On the one hand, Sweetman notes: "While some observers have suggested that canards are incompatible with stealth, an engineer who was active in Lockheed Martin's early Joint Strike Fighter efforts says the final quad-tail configuration was no stealthier than the earlier canard-delta design." Sweetman, "J-20 Stealth Fighter Design," p. 57. On the other, military journalist David Axe explains that "Canards can add stability to highly maneuverable fighters meant to pull hard turns at low speed; at high speed, canards are generally useful for reducing airframe vibrations. In any event, canards are generally indicative of a less-than-harmonious design requiring "bolt-on" fixes. And as they add radar-reflecting edges, they're usually not stealthy." David Axe, "China's Jet Fighter Surprise," *War is Boring* (June 16, 2013). Consistent with this argument, all the aircraft designs with canards considered in the development of the F-22 were deemed less stealthy ("moderate observable level") in comparison to designs without canards ("low observable level"). See R. M. Engelbeck, *Investigation into the Impact of Agility on Conceptual Fighter Design* (Washington, D.C.: National Aeronautics and Space Administration, 1995), figure 4.1, p. 48; see also figure 3.1-4, p. 18, and p. 49. This being said, there are reasons to doubt the effectiveness of the J-20 for deep strike operations that transcend whether canard affect frontal stealth or not. In this regard, it is important to emphasize first that "[b]alanced, all-aspect signature reduction is the most important advantage an aircraft has in the duel with the defending IADS [integrated air defense systems]." The reason is that an aircraft intended for deep strike operations is at constant risk of being detected, identified and tracked by radars (operating at different bands and at different angles and providing overlapping coverage) in time to be shot at by surface-to-air missiles (SAM). When ingressing the theater of operation, front aspect signature reduction would enhance the aircraft survivability. However, when egressing, detectability from the rear would expose the aircraft to enemy's SAM. For this reason, aircraft designs that maximize only front aspect radar reduction, to the detriment of side aspect and rear aspect (so-called "Pacman shape", for the resemblance between the shape of radar reflections and the 1980s arcade game) seem to be at disadvantage for deep strike missions when compared to those that minimize both front and rear signature ("bowtie shape") and all aspect signature ("fuzzball"). This does not mean that front aspect reduction is not important, it can still be employed for air-to-ground operations, but its technical limitations require more advanced tactical and operational planning, in conjunction with (among others) electronics counter-measures. See Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, VA: Mitchell Institute Press, 2010), p. 53, 47-49, 49-53. Pelosi and Kopp confirm that this is in fact the case for the J-20. On the one hand, the reflection on the side of the J-20 is greater "than otherwise necessary due to the use of smooth area ruling rather than discrete geometrically flat area segments." On the other, "[t]he axisymmetric nozzle design is not viable for aircraft intended to penetrate an IADS, as the aircraft will frequently be painted in the aft hemisphere by radars operating across a wide range of bands." Pelosi and Kopp, "A Preliminary Assessment." In September 2017, pictures of a J-20 with an indigenous thrust-vectoring engine (the WS-10) appeared online. Richard D Fisher Jr. "Military Capabilities Images show China's J-20 Possibly Equipped With New Engines," *Jane's Defence Weekly* (September 6, 2017). The engine has features aimed at reducing rear radar reflections (serrated afterburner nozzle). Some believe that this step shows China has "mastered [one of] the major parts of [fifth generation] fighter technology." See Lin and Singer, "China's Stealth Fighter." At that time, this conclusion seemed unwarranted. The indigenous Chinese engines still retained an axysimmetric design (that would expose the aircraft from radar and infrared detection from the rear). Moreover, that they are less powerful than the Russian engines China had previously relied on. Information that leaked out in February 2018 confirmed this skepticism. See fn. 299-306.

Footnote 294. In the words of a Lockheed Martin analyst who worked on the F-117, the four most important aspects of stealth are in fact "shape, shape, shape and materials." Denys Overhol quoted in Axe, "7 Secret ways America's Stealth Armada Stays Off the Radar." Available at https://www.wired.com/2012/12/steath-secrets/. See also Katz, "Physics And Progress Of Low-Frequency Counterstealth Technology." For a more extensive discussion, see Bahret, "The Beginnings of Stealth Technology."

Footnote 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 been going through a lot of trial and error in order to fix possible design problems of the J-20. See Sweetman, "J-20 Stealth Fighter Design." http://aviationweek.com/zhuhai-2014/j-20-stealth-fighter-design-balances-speed-and-agility; and Feng Cao, "China Unveils More Capable Stealth Fighter Prototype," *USNI News* (March 19, 2014), https://news.usni.org/2014/03/19/china-unveils-capable-stealth-fighter-prototype.

Footnote 297. The articles cited in the footnote can be found, respectively, at https://thediplomat.com/2012/12/the-long-pole- in-the-tent-chinas-military-jet-engines; and http:// aviationweek.com/defense/opinion-china-s-radar-and-missile-work-means-more-aghters.

Footnote 298. One of the highlights of the China Air Show in Zhuhai in November 2018 was a J-10 powered by a WS-10 capable of thrust vector control, which showed that China has developed this technology.

Footnote 299. A second sources confirmed the explosion, and attributed it to several complicated reasons, "with one being the quality control of [the engine's] single-crystal turbine blades, the key component for such a powerful turbofan engine." Chan, "Why China's First." The name of this engine is Xian WS-15.

Footnote 300. The article cited in the footnote can be found at https://www.scmp.com/news/china/military/article/2172993/china-reveals-j-20-stealth-fighters-missile-carrying-capability.

Footnote 301. The same source claimed that it is "so embarrassing to change engines for such an important aircraft project several times… just because of the unreliability of the current […] engines. It is the long-standing core problem among home-grown aircraft." Chan, "Why China's First."

Footnote 302. According to observers, with the AL-31, the J-20 looked significantly underpowered. Tyler Rogoway, "China's J-20 Stealth Fighter Stuns By Brandishing Full Load Of Missiles At Zhuhai Air Show," *The Drive* (November 11, 2018), http://www.thedrive.com/the-war-zone/24841/chinas-j-20-stealth-fighter-stuns-by-brandishing-full-load-of-missiles-at-zhuhai-air-show. The article cited in the footnote can be found at https://www.scmp.com/ news/china/military/article/2171987/chinas-new-j-20-stealth-aghter-engine-no-show-zhuhai- air-show.

Footnote 303. With the current engines, the capabilities of the J-20 "will [in fact] be severely limited, affecting its maneuvrability and fuel efficiency as well as its stealthiness at supersonic speeds." Quoted in Chan, "Why China's First." Already in 2016, China's Defense Ministry publicly admitted that there is a "definite gap" between Chinese military technology and some developed countries. An anonymous Chinese military expert confirmed that "Chinese fighter jets could not perform as well as American warplanes because of inferior engine technology." Quoted in See Siva Govindasamy, "Not Top Gun Yet: China Struggles with Warplane Engine Technology," Reuters News (January 29, 2016).

Footnote 304. See also Bradley Perrett, "Four High-Bypass Turbofans Under Development In China, *Aviation Week & Space Technology* (May 6, 2013). According to a Chinese private consulting company, over the next 30 years, China might be ready to invest additional 300 billion to rectify the problems that still plague its domestic turbofan engine industry. Richard Fisher "Can China Break the Military Aircraft Engine Bottleneck?," *Flight Global* (May 27, 2015), https://www.flightglobal.com/news/articles/analysis-can-china-break-the-military-aircraft-engine-412424/. The article cited in the footnote can be found at https://www.scmp.com/news/china/ article/2053741/china-powers-military-jet-engine-tech-wean-itself-russian-imports.

Footnote 305. An anonymous military source maintained that China "needs more time to overcome [the problems of the WS-15 engine] after countless experiments and tests." Chan, "Why China's First." See also Chan, "China Reveals J-20 Stealth Fighter's Missile Carrying Capability." As Sweetman acknowledges "cyber-espionage is potentially the most valuable addition to spycraft since the advent of signals intelligence…. But given that, [he asks] why does engine technology represent such a stumbling block [for China]?" Consistent with our theory, he explains, "The underlying reason is that the design and manufacture of high-performance, reliable combat engines in the West rely on a sophisticated, large, but tightly controlled base of suppliers, feeding only four primes with the demonstrated ability to deliver such engines. The supply chain incorporates advanced technologies and a knowledge base that is mostly unique to turbine engines, focusing on high-temperature metal alloys and processes for designing and fabricating critical components such as blades, disks and shafts. An important point, however, is that the supply chain has not been dominated by military-engine business for decades, and today, the market for commercial engines—which drives the same critical technologies to deliver performance and durability—dwarfs the defense business." Bill Sweetman, "Engine Tech, Cyber-Espionage Key To China's Progress," *Aviation Week & Space Technology* (Nov 5, 2012). According to Cliff and co-authors, for example, "It took decades for China to master the production technology for the [Rolls-Royce engine]" it received in the 1970s. See Cliff et al., *Ready for Takeoff,* p. 64.

Footnote 306. The article cited in the footnote can be found at https://www.flightglobal.com/news/articles/chinas-j-20-set-to-receive-indigenous-engine-435075/.

Footnote 307. According some experts, this will happen soon. See, for example, Lin and Singer, "China's Stealth Fighter May Be Getting a New Engine." According to a Macau-based military observer, it will take three to eight years for further developments. Quoted in Chan, "Why China's First Stealth Fighter Was Rushed into Service with Inferior Engines." According the Asia Managing Editor at *FlightGlobal*, it will take twenty to thity years for China to have "a viable military engine." Quoted in Siva Govindasamy, "Not Top Gun Yet: China Struggles with Warplane Engine Technology," Reuters, Jnauary 28, 2016, https://www.reuters.com/article/china-military-engines-idUSL3N14C4KM.

Footnote 308. Similarly, Richard Bitzinger stresses China's "limited indigenous technological capabilities relative to the West," especially "in areas such as propulsion and defense electronics."Bitzinger *et al.*, "Locating," p. 203.

Footnote 309. According to Dr. Carlo Kopp, the J-20 will need at least 40,000-50,000 lbs. thrust engines to have the agility required for close air combat. The engine (WS-10) China has temporarily mounted on the J-20, however, has only 15,000 lbs. thrust, while the new engine (WS-15) it is developing might have 30,000 to 40.000 lbs. thrust. See respectively, Carlo Kopp, "An Initial Assessment of China's J-20 Stealth Fighter," *China Brief* Vol XI, N. 8 (May 6, 2011); Lin and Singer, "China's Stealth Fighter;" and Waldrom, "China's J-20."

Footnote 310. See also Richard A. Bitzinger et al. "Locating China's Place in the Global Defense Economy,," Policy Brief, No. 28 (San Diego: Institute on Global Conflict and Cooperation, University of California San Diego, September 2011), p. 203; Justin Bronk quoted in Alex Lockie, "How China's Stealthy Nnew J-20 Fighter Jet Compares to the US's F-22 and F-35," *Business Insider*, (Nov. 1, 2016); and Mark B. Schneider, "Professional Nnotes: The U.S. F-35 versus the PRC J-20," *Proceedings Magazine*, Vol. 143, Non. 10 (October 2017).

Footnote 314. For this reason, software has become a "complexity sponge." See Mili and Tchier, *Software Testing*, p. 6. Herry Hillaker, the "Father of the F-16," has summarized the issue as follows: "There is no question in my mind that fly-by-wire made aircraft design much easier. Before fly-by-wire, you had a big debate about whether to configure airplanes for performance or for flying qualities. With fly-by-wire, both sides are happy. The tradeoff has been eliminated. Lockheed's F-117 Stealth is an extreme example. The plane represents everything you would not do for both performance and flying qualities. But the design works because it has a flight control system." Eric Hehs, "Father of the F-16: Hillaker Returns – Interview Part II," *Code One* Vol 6., no. 2 (April 1991), p. 15.

Footnote 315. See also Mili and Tchier, *Software Testing*, p. 6.

Footnote 317. That Chinese aerospace engineers have given priority to aerodynamics rather than to stealth (as described above) supports this conclusion. Flight control seems to be a major problem also for the J-15, as it is alleged to be behind several fatal crashes. See Minnie Chan China is Working on a New Fighter Jet for Aircraft Carriers to Replace Its J-15s," *South China Morning Post* (July, 5 2018), https://www.scmp.com/news/china/diplomacy-defence/article/2153803/china-working-new-fighter-jet-aircraft-carriers-replace. One important aspect to keep in mind, however, is that the J-15 is produced by Shenyang while the J-20 is produced by Chengdu. With regards to data-fusion, Majumdar has summarized the issue as follows: "while it is possible that the Chinese aircraft might have decent sensors—Air Force officials have suggested that the J-20 lacks the 'sensor fusion' and networking to be as effective as the F-22 or F-35. One area that the Chinese are almost certainly lacking is what Air Combat Command commander Gen. Herbert 'Hawk' Carlisle once described [...] as "spike management." Fifth-generation aircraft such as the F-22 and F-35 have cockpit displays that indicate to the pilot the various angles and ranges from which their aircraft can be detected and tracked by various enemy radars. The pilots use that information to evade the enemy by making sure to avoid zones where they could be detected and engaged. It is a technology that took decades for the United States to master—through a lot of trial and error." See Gen. Herbert 'Hawk' Carlisle quoted in Dave Majumdar, "The Reason Why America's F-35 Would Crush China's J-20 Stealth Fighter in Battle," *The National Interest* (August 10, 2016). At the China Airshow in Zhuhai in November 2018, two J-20s flew with the weapon bay open, thus showing the missiles it can potentially carry. Journalist Tyler Rogoway summarized what is possible to infer from the pictures and videos available. Precisely, he noted that the F-22 will soon have a special capability (lock-on after launch) with the upgraded version (Block II) of its air-to-air missile (AIM-9X). The pictures of the Air Show shows the J-20s carrying also two small missiles outside of the weapon bay, ready to be fire. Rogoway asks: "If China loves copying the US when it comes to weapons systems, why not just build something similar for the J-20 when it comes to deploying its short-range air-to-air missiles? The answer is quite simple, lock-on after launch capability is not an easy one to achieve. It is technologically complex, requires deep systems integration (software architecture permitting), and robust testing using live missiles, and thus it is expensive. China, being the resourceful and cunning folks that they are, figured out a way to employ any new or relatively archaic high-off-bore-sight short ranged air to air missile while keeping the jet's aerodynamics relatively intact (doors closed during prolonged maneuvering while the missile hangs out on its rail) while also minimizing the impact a 'deployed missile' has the J-20's low radar cross-section." Tyler Rogoway,"China's J-20 Stealth Fighter Stuns By Brandishing Full Load Of Missiles At Zhuhai Air Show," *The Drive* (November 11, 2018). Available at http://www.thedrive.com/the-war-zone/24841/chinas-j-20-stealth-fighter-stuns-by-brandishing-full-load-of-missiles-at-zhuhai-air-show). In January 2019, news outlet revealed that China is working on a "two-seat" version of the J-20. This would be intended to serve as a tactical stealth bomber. From this information, it is admittedly difficult to infer China's capabilities. Yet, when we compare it with the U.S. experience with stealth fighters, we cannot rule out that the possibility that problems with automation and data-fusion have informed this decision. In fact, all U.S. stealth fighters are capable of carrying out air-to-ground missions and are single-seated – whether air-to-ground was their primary mission, such as for the F-117; an ancillary one as for the F-22; or one of many, such as for the multirole F-35. That China, in 2019, has to take a different path is revealing. See Andrew Tate, "China may be developing first two-seat stealth combat aircraft," *Jane's Defence Weekly* (January 18, 2019), https://www.janes.com/article/85813/china-may-be-developing-first-two-seat-stealth-combat-aircraft.

Footnote 318. One Chinese aircraft (the J-10) displays "strong similarities to the Israel Aircraft Industry […] Lavi and the [European] fighter Typhoon." Medeiros, *A New Direction*, p. 162. Yet, this happened to be an extremely slow project (started in 1988, entered service in 2006) as China "confronted considerable difficulties in moving prototypes into production." Bitzinger *et al.*, "Locating", in Cheung, *Forging*, p. 172. Not surprisingly, China has had limited success exporting these advanced weapon systems abroad. Richard A. Bitzinger, "Why hardly anyone wants to buy Chinese weapons," *Asia Times* (September 7, 2016).

Footnote 319. The article cited in the footnote can be found at https://nationalinterest.org/feature/china-stole-fighter-russia-its-coming-the-south-china-sea-17087

Footnote 320. Roblin add that "[p]roduction has lagged far behind demand, and quality control remains a big issue with more engines returned to plant than actually produced! Reports also suggest that [Chinese engine] can't generate quite as much thrust as the [Russina one], nor raise it as quickly. Either way, the [Chinese engine's] reliability and thrust remain major problems not just for J-11s, but for China's stealth fighter program as well. The actual performance of the J-11B remains obscure too, as public sources simply repeat the statistics for the original Su-27SK."

Footnote 321. The article cited in the footnote can be found at https://www.wired.com/2013/03/developing-warplanes-is-hard/.

Footnote 323. On China claiming the J-11 is superior to the Su-27, see Dave Majumdar, "China Upset at Being Called Out for Reverse Engineering Su-33," *Flight Global* (7 December, 2012). On why the purchase of 24 Su-35 questions the narrative that China has closed the gap in fifth generation fighters, see Dave Majumdar, "If the J-20 Stealth Fighter Is So Amazing Why Is China Buying Russia's Su-35?" November 2, 2016. That the display of these aircraft has not been translated to Mandarin but they will be in its original form, Cyrillic, gives credence to the interpretation that they were bought in order to copy parts of them. See "Chinese Su-35s' avionics will display in Cyrillic script," *Alert5* (November 10, 2016). Available at: 5http://alert5.com/2016/10/11/chinese-su-35s-avionics-will-display-in-cyrillic-script/. The article cited in the footnote can be found at http:// aviationweek.com/combat-aircraft/china-has-11-oanker-versions-more-possible.

Footnote 324. The article cited in the footnote can be found at https://mic.com/articles/20270/china-j-15-fighter-jet-chinese-officials-defend-new-fighter-as-chinese-original-but-questions-remain.

Footnote 325. Fully loaded, the J-15 could carry only two YK-83K anti-ship missiles and two PL-8 air-to-air missiles. Partially loaded, the J-15 could carry four additional bombs, but would still not be able to carry a medium range PL-12 air-to-air missile. See "Chinese Media Takes Aim at J-15 Fighter Archived, *Defense News* (September 28, 2013).

Footnote 326. See also Gabe Collins and Andrew Erickson, "China's J-15 No Game Changer," *Diplomat*, June 23, 2011, https://thediplomat.com/2011/06/chinas-j-15-no-game-changer/.

Footnote 327. As one observer has noted, "so many J-15s have crashed and burned that China is developing a new carrier jet, the J-31." Cited in Michael Peck, "Russia Is Mocking China For Screwing Up The Fighter Jet They Stole," *The National Interest* (September 27, 2018). In addition to the crashes, it is clear China experienced significant problems with this aircraft given that between 2012 and 2015, it was able to produce only 10 of these aircraft. See Choi Chi- yuk, "Fatal Crash of Chinese J-15 Carrier Jet Puts Question Mark Over Troubled Programme," *South China Morning Post* (June 27, 2017). Moreover, the J-15 is "the heaviest active carrier-based fighter jet in the world but the sole carrier-based fighter in the People's Liberation Army Navy." Cited in Minnie Chan, "China's Aircraft Carrier Conundrum: Hi-tech Launch System for Old, Heavy Fighter Jets," *South China Morning Post* (November, 19 2017). An insider source noted that "China has so far still failed to develop a more advanced and powerful carrier-based fighter jet to match the Type 002 carrier." Cited in Minnie Chan, "Trade Tensions with the United States Blow Hole in Budget for China's Newest Aircraft Carrier," *South China Morning Post* (November, 27 2017). Finally, that China has been working on so many different types of 4th generation fighters (J-10, J-11, J-15 and several derivatives for each) is further evidence of the problems these aircraft still have. In fact "the [Chinese] air force and navy remain quite dissatisfied with the modernity of their fighters."Perrett, "China Has 11 Flanker Versions," p. 50. As Parett adds, "That leaves open the question of what will succeed the J-10. The best answer, so far, is 'something better than the J-31.' Although that Shenyang Aircraft type is often listed alongside the J-20 as China's other low-observable fighter, it so far seems to be no more than a technology demonstrator. Despite the J-31's stealth shaping and internal weapons carriage, the air force has not been persuaded that the J-31 is superior enough to the J-10 to justify halting production of the latter and introducing yet another new type." The article cited in the footnote can be found at https://nationalinterest.org/blog/buzz/chinas-aircraft-carriers-have-big-problem-fatally-flawed-fighter-planes-25072

Footnote 328. The article cited in the footnote can be found at http://www.chinasignpost.com/2011/01/17/chinas-new-project-718j-20-fighter-development-outlook-and-strategic-implications/.

Footnote 331. China actually started working on stealth technology much earlier. Already in 1987, a Chinese radio claimed that "It will not be long before out country can make our own stealth aircraft." Richardson, *Stealth*, p. 93.

Footnote 331. Among others, "tooling refurbishment" would cost about $228million; "production requalification" for components and raw materials would cost $1.218 billion; $5.768 billion would ne necessary to redesign four subsystems; and $1.156 billion would be required for other associated "restart costs," along with $1.498 billion in "additional government costs." United States Air Force, *F-22A Production Restart Assessment.*

Footnote 334. Saunders and Wiseman, "Buy, Build or Steal," p. 48. As they concluded, "The ability to reach the technology frontier across a range of related civilian and dual-use modalities […] is not necessarily transferable to the military aviation realm. Even if the technical knowledge and industrial capacity exist, opportunity costs involved with developing single-use military technologies might prove too great." On this, some have noted that the J-20 will take much longer to enter mass production than most optimistic prospects suggests. An article in *The Asia Times*, for instance, has reported that "AVIC's plant in Chengdu, Sichuan province, has been scrambling to churn out more of the fighters as orders continue to pile up. That is because the aerospace conglomerate is held back by a host of technical hurdles, parts-supply issues and a shortage of top-flight workers, so much so that producing such a cutting-edge aircraft is a remarkable logistical and engineering feat in itself under the current circumstances." See "PLA's J-20 fighters years away from mass production," *The Asia Times* (July 31, 2018).

Footnote 335. Posen noted that the "[weapon] systems needed to command the commons require significant skills in systems integration […] where the U.S. defense industry excels." These skills in turn, "depend[…] on decades of expensively accumulated technological […] experience embodied in the institutional memory of public and private military research and development organizations." Posen, "The Command of the Commons," p. 10. See also Ashton B. Carter with Marcel Lettre and Shane Smith, "Keeping the Technological Edge," in Ashton B. Carter and John P. White (eds.), *Keeping the Edge: Managing Defense For the Future*

(Cambridge, MA: Belfer Center for Science and International Affairs, 2001), pp. 130-163.

Footnote 337. In other words, "the rate at which wealth can be transformed into power" – to borrow from Mark Brawley – has changed. See Brawley, "The Political Economy of Balance of Power Theory," p. 80. For a broader discussion on the defense industrial base, see Keith Krause, *Arms and the State: Patterns of Military Production and Trade* (Cambridge: Cambridge University Press, 1995); and Andrew L. Ross "Full Circle: Conventional Proliferation, the International Arms Trade, and Third World Arms Exports," in Kwang-il Baek, Ronald D. McLaurin, and Chung-in Moon, eds., *The Dilemma of Third World Defense Industries: Supplier Control or Recipient Autonomy?* (Boulder: Westview Press, 1989), pp. 1-31.